# Modelling Supply Chain Resilience in Industrialized Construction: A Hong Kong Case

E.M.A.C. Ekanayake
17902595r@connect.polyu.hk
PhD Candidate, The Hong Kong Polytechnic University
Geoffrey Q.P. Shen, M.ASCE – Corresponding Author
geoffrey.shen@polyu.edu.hk
+852 27665817
Chair Professor of Construction Management, The Hong Kong Polytechnic University
Mohan M. Kumaraswamy, M.ASCE
mohan@hku.hk
Honorary Professor, Department of Civil Engineering, Faculty of Engineering, University of Hong Kong
Emmanuel K. Owusu, Ph.D
emmanuel.k.owusu@connect.polyu.hk
Postdoctoral Fellow, The Hong Kong Polytechnic University
Abdullahi B. Saka
abdullahi.saka@connect.polyu.hk
PhD Candidate, The Hong Kong Polytechnic University

**Abstract**

Given the heightened imperatives for Supply Chain Resilience (SCR) in Industrialized Construction (IC) in Hong Kong, this study modelled the dynamic impact of Supply Chain Vulnerabilities (SCV) and Supply Chain Capabilities (SCC) on IC supply chains. The data collected through expert surveys, interviews and case studies were analyzed using Social Network Analysis (SNA) and System Dynamics Modelling (SDM) to develop the research models. On-site assembly was identified as the most vulnerable supply chain phase, and 'anticipation' as the most influential capability. Further, the use of an interoperable, smart software package and other suggested strategies were shown to enhance IC's resilient capabilities. As key practical contributions, these findings provide evidence-based pointers to initiate well-focused performance-enhancing measures to achieve SCR in IC. Moreover, this is the first initiative to explore the potential applications of SDM and SNA to assess IC supply chain dynamics targeting a goal of enhanced resilience. This study, therefore, contributes substantially to the IC and SCR knowledge domains. This should also motivate and provide pointers to scholars pursuing similar industry-specific improvements in other jurisdictions too.

**Keywords:** Supply Chain Resilience (SCR); Industrialized Construction (IC); Social Network Analysis (SNA); System Dynamics Modelling (SDM); Supply Chain Vulnerabilities (SCV); Supply Chain Capabilities (SCC)

## Introduction

Organizations are presently experiencing and envisaging prolonged Supply Chain Vulnerabilities (SCV) arising from COVID-19 (McKinsey Global Institute, 2020). Since many organizational supply chains are interconnected, disruptions may cascade across global supply chains, and their impacts may accumulate, amplify and even become catastrophic. For instance, the COVID-19 pandemic triggered dramatic material shortages worldwide (Golan et al., 2020). In the United States, similar financial stress arose after the 2008 financial crisis (Golan et al., 2020). Further, country and region lockdowns shrunk production supply chains in most countries, especially in Japan (Inoue et al., 2020). Focusing on the construction industry, key supply chain disruptions were aggravated by the shortage of labor and key-personal, dynamic changes in the work environment (Raoufi and Fayek, 2020), and material shortages. More specifically, North American construction supply chains experienced major delays and disruptions due to social distancing at site, productivity losses, material shortages, and logistic and supply delays (Raoufi and Fayek, 2020). Supply and logistic disruptions are seen in Hong Kong too. Hence, this recent pandemic further compels organizations of the need to rethink their plannning and decision making to address and overcome these tumultuous vulnerabilities.

In this context, 'supply chain resilience' has been introduced as a game-changing supply chain management goal that opens up robust pathways to withstand SCV (Zavala et al., 2018). Further, supply chain resilience is a better alternative to traditional risk management practices (Zavala et al., 2018). Besides, adequate and appropriate Supply Chain Capabilities (SCC) must be deployed to achieve such resilience (Pettit et al., 2019). Therefore, many leading economies and industries worldwide have attempted to design and deploy resilience strategies in their industrial supply chains (Ekanayake et al., 2020a). However, supply chain resilience is jurisdiction and industry-specific, given the different configuration and characteristics of each supply chain (Ekanayake et al., 2020a).

As a leading economic contributor, the HK construction industry has also focused on strategies and methodologies to reduce supply chains' vulnerability levels. Industrialized Construction (IC) has steadily gained popularity in the HK construction industry over the recent decades, first coming into prominence in public housing. IC provides an environment-friendly, better quality, cleaner, and safer working environment (Li, 2016). The recent IC progression to modular integrated construction enables the on-site assembly of volumetric units or modules, yielding advantages of reduced construction time, significantly reduced on-site labor, better quality, enhanced safety and productivity and reduced exposure to external services with greater sustainability (Xu et al., 2020). However, IC supply chains' inherent complexity and fragmented nature often lead to disruptions and even some reduced performance levels (Ekanayake et al., 2020a).

IC supply chains are usually more sophisticated and complex than in traditional construction, since IC is based on incorporating modern advances in offsite manufacturing and on-site assembly. Further, the necessarily specific IC supply chain phases of factory-manufacturing, logistics and on-site assembly (Ekanayake et al. 2020a) contribute to supply chain fragmentation. Also, the types of manufactured units, corresponding supply chain configurations and levels of IC supply chains' vulnerability differ across jurisdictions. For example, Singapore has developed 'pre-engineered prefinished volumetric construction' based on 'bigger' pre-engineered volumetric units while a different module assembly process is used in Japan. Consequently, the types and levels of vulnerabilities in the supply chain's manufacturing and delivery of such different unit types would thereby differ (Ekanayake et al. 2020a). In the HK context, all the prefabricated units are transported from Mainland China; hence supply chains are commonly affected by transportation and cross-border logistics-related vulnerabilities (Ekanayake et al., 2019) compared to some other jurisdictions (as discussed in detail in the forthcoming sections of this paper). This necessitates strong and more resilient IC supply chains in HK than in other jurisdictions as the industry needs to cope with significant cross-border logistic associated vulnerabilities. Moreover, suitably focused jurisdiction-specific studies are critical in detecting appropriate SCC imperatives to ameliorate jurisdiction-specific supply chain vulnerabilities. Apart from the above, the HK context necessitates enhancing the resilience capability of IC supply chains to address the current performance conundrums faced by the industry.

In light of this background and rapidly changing conditions, this study aimed to assess the dynamic impact of SCV and SCC targeting resilient supply chains in IC in HK and to propose strategies to enhance supply chain resilience in IC. Hence, this study first evaluated the dynamic impact of SCV in each supply chain phase. Then, this study examined and modelled the potent influence of relevant SCC towards enhancing resilience abilities in IC in HK through a system dynamics modelling approach.

Finally, a set of useful strategies to introduce and/or upgrade resilient practices in IC supply chains is proposed based on the HK case study findings. Therefore, the forthcoming sections of this paper present the theoretical foundation of this piece of research, followed by a conceptual framework, research methods employed in model development and validations, a discussion with comparative case studies, proposed strategies to uptake and/or upgrade supply chain resilience in IC, and finally, the conclusions that include research limitations and suggested ways forward.

**Theoretical Foundations and the Conceptual Framework**

IC supply chains span a much longer process and time-frame than in conventional in-situ construction as they straddles across two production environments. Further, IC supply chains require longer periods for potential error reduction for achieving greater dimensional accuracy and arranging prefabrication lead times to fit on-site construction schedules. IC supply chains are, therefore, inherently more vulnerable to potential disruptions (Luo et al., 2019). Further, the higher the number of IC supply chain tiers, the less the supply chain visibility, making it more difficult to identify and respond to emerging risks. Single supplier dependency or the absence of substitute suppliers, is another disruptive cause (McKinsey Global Institute, 2020) that afflicts the construction sector. Besides, in HK, IC supply chains are profoundly affected by the distant location of the manufacturing yards, invariably in mainland China, due to higher labor cost in HK, specialisations and economies of scale. Further, the logistics phase of IC supply chains is usually subject to significant disruptions in transportation and customs clearance of the prefabricated components (Ekanayake et al., 2020a). Temporary protection of precast units, including to ensure water tightness during transportation, is another challenging task. Mechanical failures, malfunctions of cranes and misplacement or damage of modules on storage sites are common highly disruptive events that IC face during on-site assembly (Li et al., 2018). Coupled with the inherent complexity and the IC supply chains' fragmented nature, these further multiply and amplify vulnerabilities across the supply chain network.

Existing risk management practices are evidently unable to foster more resilient supply chains (Pettit et al., 2019). In extant studies, each risk is identified individually and separately during risk management processes, thereby neglecting any interactions of risks, with inadequate consideration for sudden and unanticipated disturbances, since the focus is more on discrete anticipated events. Therefore, dynamic supply chains need ‘constant vigilance’ to detect potential SCV. In this respect, resilience would provide a good solution by enriching IC supply chains with capabilities to adapt, mitigate, reduce or avoid SCV. Moreover, supply chain resilience can only be enhanced by improving the appropriate SCC (Pettit et al., 2013), which also enhances the IC supply chains' adaptive capacities. Moving beyond the SCC of flexibility and efficiency, organizations currently access technological advancements through the internet of things and digital platforms. However, the accumulated and interactive complexities when combining and applying some such recent developments, often inject more robust strategies for survival. Many organizations are still at the early stages of their efforts to realise these technological capacities, connecting the entire value chain with a seamless data flow (McKinsey Global Institute, 2020).

Delving deeper, supply chain resilience aligns with the ‘Dynamic Capability View’. It supports the explanation of SCC in dynamic and uncertain environments by utilizing appropriate resources and capabilities to respond to dynamic changes (Chowdhury and Quaddus, 2017). Hence, this study postulates that supply chains need to create dynamic capabilities to withstand SCV under tumultuous supply chain environments to boost IC's performance in HK. Building on these assumptions, this study employed system dynamics modelling to investigate the dynamics of SCC, targeting resilient IC supply chains in HK. System dynamics modelling provides an effective mechanism to discover, elucidate, and measure interrelationships and dynamics among the elements of a model (Wang et al., 2018). Besides, system dynamics modelling is ideal for evaluating the consequences of implementing new strategies (Wang et al., 2018). It can be effectively used in estimating the improvements in supply chain performance due to supply chain resilience and SCC initiation. Studies by Olivares-Aguila and ElMaraghy (2020), Kochan et al. (2018), Bueno-Solano and Cedillo-Campos (2014) used the same system dynamics modelling in evaluating dynamic supply chain disruptions. The focus of previous studies was, therefore, on assessing the dynamic impact of one or more SCV and hence, lacks full consideration of the entire dynamic system encompassing the supply chain with its influential SCV and SCC.

Given that resilience is an imperative in IC supply chains in HK and noting the research lacuna in modelling the supply chain resilience impact, this study investigates the effect of SCC in strategies to boost resilience in IC with the help of relevant modelling techniques such as system dynamics and social network analysis, depending on the material being probed. After specific detailed precursor studies, Ekanayake et al. (2020a) previously identified five SCV constructs, i.e. economic, technological, procedural, organizational, production-based components incorporating 24 critical SCV variables; and also nine SCC constructs, i.e. resourcefulness, flexibility, anticipation, dispersion, capability, adaptability, efficiency, financial strength and visibility, incorporating 41 critical SCC variables (Ekanayake et al., 2020b), in respect of IC supply chains in HK. These were built upon for further data collection and model development as appropriate to this study and explicated further in the forthcoming sections. Since fortification of resilience requires new initiatives, these findings led to suggest strategies to enhance supply chain resilience in IC in HK based on two comparative case studies and the results generated from the dynamic modelling of IC supply chains.

A theoretical framework (Fig.1.) was developed for the above purpose, including SCV constructs and SCC constructs which are the two main categorical measures established in the literature, highlighting that supply chain resilience could be realised through maintaining an appropriate balance between SCV and SCC. SCV hamper the smooth performance of IC supply chain processes, hence shown as a negative link. In contrast, SCC strengthen the resilient IC supply chains, hence shown as a positive link. On the other hand, SCC are the counter balancers of SCV, hence indicated by another negative link. Fig.1., thus, represents a generic overview of how the individual vulnerability and capability categorical measures (which are the indicators of supply chain resilience) affect the entire supply chain process of IC. The theoretical relationships depicted in Fig.1. are examined later in the study to establish how these vulnerability and capability indicators collectively impact each supply chain phase and entire supply chain of IC and how the negative impacts can be strategically extirpated.

**[Please insert Fig.1. here]**

## Research Methods and Data Analysis

### Research Methods

A comprehensive and robust research methodology was clearly needed based on the foregoing theoretical foundations and conceptual framework so as to elicit, analyze and unveil the key components and underlying dynamics in developing resilient supply chains by a focused study of fundamental concepts, overarching principles and current best practices, along with their strengths and weaknesses. Fig.2. depicts the research questions derived, the research methods used and the flow, and research outcome in line with each research activity of this study to improve readers' understanding. Accordingly, this study adopted a mixed-method approach, with an empirical questionnaire survey and case study being the main data collection techniques.

**[Please insert Fig.2. here]**

Therefore, a questionnaire was developed by including vulnerability and capability measures which were ascertained following the comprehensive literature review as appropriate to IC in HK. Before proceeding with the sampling and data collection, the questionnaire was tested for the relevance and comprehensiveness of the questions, language structure and understandability. Four academic professors who are experienced with IC practices in HK and possess vast relevant knowledge on research and industry practice of IC supply chains were approached in this questionnaire testing and confirmed the questionnaire's suitability for data collection. After that, the pilot testing of the data collection tools was done with three academics and two industry practitioners with research experience in IC. They were considered the experts on the subject matter because they each had more than 20 years of experience and vast knowledge in handling IC projects (Ekanayake et al., 2020a). Then, the questionnaire survey was administered to solicit the views of industry experts who are working or worked in IC projects in HK. Purposive sampling: a non-probability sampling (Zhao et al., 2014) was used to obtain a representative sample for this study (Chan et al., 2018).

Further, this study also used a snowball sampling method to obtain a valid and expanded sample size, enabling rich data gathering through social networks as employed in previous construction management studies by Zhang et al. (2011) and Chan et al. (2018). Seventy-six responses from relevant experts were obtained with special efforts to account for the respondents' busy schedules. This sample size is considered adequate for the analysis (Sproull 2002) since a sample size of 30 is representative of any group (Ott and Longnecker, 2015) and adequate to develop significant conclusions in a subject area of this nature (Owusu et al., 2020). Besides, the 76-response rate is higher than the response rates obtained in some of the previous survey-based construction management studies (Adabre and Chan 2019; Owusu et al. 2020; Darko and Chan 2018). Fig.2. presents the survey respondents' profile, highlighting that these respondents possess managerial level experience of IC projects and justifying that their responses are valid. Many project engineers who were assigned to the manufacturing factory were also involved in this study to enable rich data gathering. At the same time, all the respondents were asked to provide their answers considering all the supply chain phases to maintain consistency of the data collected. A purposive sampling approach facilitated selecting suitable respondents (the project professionals who are experienced and knowledgeable on the supply chain process of prefabricated housing construction) for this study. These respondents in Fig.2. were identified by exploring their business profiles, attending seminars related to IC conducted by them, and industry-based contacts. Indeed, the number of such experts in HK with ‘managerial level experience on IC projects’, (i.e. the total population from which this sample is drawn) is itself not large, further justifying the reliability and representativeness of findings derived from the sample of 76. All necessary details regarding questionnaire development, factor exclusion in pilot studies, respondent selection, and expert survey are explicated in detail in the precursor studies of Ekanayake et al. (2020a, 2020b).

Without limiting to the deductive research approach, semi-structured interviews were also used in data collection as the element of interpretivism was found useful, indeed important, in seeking and providing industry-based justifications for the quantitative results. Therefore, all the respondents were contacted face-to-face or through online interviews. A brief description of the survey was conveyed at the beginning of the interviews, including the requirements of this data collection. They were then requested to fill the questionnaire. During the survey, experts’ views were solicited on; (I) SCV measures and (II) the SCC measures, which enable successful withstanding of the associated SCV. The experts were also asked to assign a score to rate the importance of each capability variable and the criticality of each vulnerability variable based on their probability of occurrence and the level of severity. All these data covered all the IC supply chain phases, and the experts separately identified the SCV associated with each supply chain phase. The interview discussions were useful in verifying the questionnaire responses. In order to optimize the results, the outliers were removed from the sample (Bakker et al., 2014), while data normalization was conducted in factor selection for analysis as discussed in the precursor studies of Ekanayake et al. (2020a, 2020b).

Owing to the nature of the anticipated outcomes, which drove the accomplishment of research objectives, three main tools were employed. The mean ranking approach was first employed to conduct a descriptive analysis to determine vulnerability and capability measures' criticalities using their average weight scores derived from the questionnaire survey (Ameyaw et al., 2017). This was followed by examining the relative criticalities or impacts of SCV on each supply chain phase using the network analysis approach. Thereafter, simulation of the accumulated impacts of SCV and the appropriate SCC measures was conducted using the system dynamics modelling approach to help instigate appropriate measures to achieve resilient supply chains in IC in HK.

*Why Social Network Analysis?*

Social network analysis is a comprehensive paradigmatic method that considers social structures as systems by direct examination of resource allocation patterns in the social systems (Scott and Carrington, 2011). It is specific to network theory and has emerged as a key research technique in sociology and has become a popular topic of speculation and study (Yang et al., 2015; Chinowsky et al., 2008; Chinowsky et al., 2010). Besides, this method facilitates easy access to the data, simplicity of design, limited sample size, and decisional and interactional analysis (Tichy et al., 1979). Given that, the theory has also been successfully applied in construction supply chain management studies to examine stakeholder risks and their associated interactions in complex green building projects (Yang et al., 2015), risks and opportunities in the supply chain information sharing process (Colicchia et al., 2019), and to model constraints for the on-site assembly process of prefabrication housing supply chains (Gong et al., 2019). These studies, therefore, have justified social network analysis as an effective method to explore the influence of a wide-ranging array of risk factors in construction supply chains. There, the social network theory regards a project as a system that consists of diverse relationship links and investigates the cause and effects of relationship structure (Scott, 2000). Individual actors in a social network are the nodes while the links detect the relationship between two nodes (Lin, 2015). In this context, this study adopted social network analysis to analyze the vulnerability levels of the principal supply chain phases of IC, namely factory-prefabrication, logistics, and on-site assembly.

*Why System Dynamics Modelling?*

System dynamics modelling was introduced by Professor Jay Forrester in 1958, using computer simulation technology and feedback control theory as means of quantitative analysis of multifaceted real-world systems (Li et al., 2014; Ajayi, 2016). This is a multidisciplinary research tool that has been widely used in project management, decision sciences, and construction management domains, among others. Dynamic modelling of construction activities enabled identifying solutions for several complex problems where non-linear relationships and multiple interdependent connections existed (Sterman, 1992). Further, system dynamics modelling can correlate several factors and enable experiments within a controlled environment (Love et al., 2000). As an advanced research tool, system dynamics modelling facilitates managing complex processes, relying upon its feedback loops and connections. Thus, the modelling process is highly dependable upon the captured interactions among the variables. Thereby, system dynamics modelling enables the examination of the behavior of a complex system over time with changes in the variables. Hence, the construction industry has employed system dynamics modelling to examine productivity, waste management, construction safety, and forensic project management (Li et al., 2014). Although this method is widely used to analyze project dynamics and complexities (Khan et al., 2016), there were no known attempts to analyze resilience in construction practices using system dynamics modelling principles. Given the aforementioned importance of such a research study and in response to the research lacuna identified, system dynamics modelling is employed in this study to investigate the accumulated impacts of SCV and SCC components to help instigate appropriate measures to achieve resilient supply chains in IC in HK.

**Data Analysis**

The descriptive statistics of the expert survey of all the underlying components of this study are given in Table 1. These components include all the variables considered in the social network analysis and system dynamics modelling. SCV constructs include all the negative variables that hamper and retard SCR. SCC constructs include all the positive variables which encourage and enable resilience. According to the mean score figures, the topmost critical components are organizational SCV and efficiency as an SCC. Thus, following this appreciation of the relative impacts of all the negative constructs on the supply chain, the development of the system dynamics model is intended to unveil and point to potential strategies for uplifting IC supply chains' resilience. Before the system dynamics modelling, this study intended to identify the most critical supply chain phases considering the impact of negative constructs, namely economic, technological, procedural, organizational and production-based SCV. Hence, social network analysis was conducted, and the process is described further as follows.

**[Please insert Table 1 here]**

*Social Network Analysis Model*

The data collected through the expert opinion survey (as illustrated above) were used to develop a social network analysis model. The industry experts were asked to identify the SCV affecting each supply chain phase, and they were asked to score the vulnerability of each SCV at each supply chain phase using values of 0 or 1. If any vulnerability has a considerable direct impact on any supply chain phase, the respondents stated 1 for the vulnerability under the specific phase. If there is no such considerable impact, 0 was assigned. The total scores received for each vulnerability under each phase were considered in social network analysis and presented as percentage values in Table 1. Each phase's vulnerability level was calculated by taking the summation of scores received for all the vulnerabilities under each phase through social network analysis. Thereby, a vulnerability matrix was developed, including supply chain phases with SCV as the main nodes. This matrix was imported to the Netminer 4 software, and a two-mode network analysis was conducted to derive the results shown in Fig.3. The node shapes denote the types of SCV (circles) and supply chain phases (squares), respectively, whereas the arrow thickness reflects the degree of influence between the nodes.

The node size reflects the level of vulnerability of each supply chain phase. Further, 'degree' as one of the key measures in social network analysis was used to explain the results. This measure detects the count of the number of ties to other actants in this network by reflecting the immediate features of node connections (Luo et al., 2019). Hence, the measure of 'degree' enabled identifying the most critical phases of IC supply chains, considering the highest values of degree. The results of social network analysis are further elaborated in the discussion section.

**[Please insert Fig.3. here]**

*System Dynamic Model*

*Model development*

The application of the system dynamics modelling in this study facilitates understanding of how the IC supply chain process responds to the interactions and the changes or the dynamic behavior of SCV (negative constructs). Moreover, it is employed to explain the supply chain system's behavior under suggested propositions of the SCC strategies formulated to mitigate SCV in the IC process. Therefore, this approach, helps to evaluate the relative feedbacks of the supply chain system. Also, the model is intended to suggest effective avenues to enhance supply chain resilience. As found in the data collection, all three phases of IC supply chains contain SCV. These SCV are grouped under five constructs, and each of these constructs includes other underlying dimensions that retard resilient performance in IC. Also, the SCC can be grouped under nine constructs representing the relevant underlying factors in each construct. Therefore, each underlying factor's relationship between these appropriate constructs was first established using the Partial Least Squares Structural Equation Modelling (PLS-SEM) (Ajayi, 2016). Thereby, the relationships between the factors were modelled through the use of Vensim 8.1.0 software.

*Causal loop diagram*

A causal loop diagram visualizes the cause-and-effect relationships between the variables in a model by articulating the interrelationships of various elements that create a system (Ajayi, 2016). This diagram includes nodes and links where nodes refer to the variables and links represent the variables' relationships. Supply chain resilience in IC in this study is measured in two dimensions; namely; i) mitigating the impact of the significant negative constructs of SCV and ii) increasing the effectiveness of SCC measures. As a result, in the causal loop diagram, two distinct constructs were discussed. Thus, the two main loops considered here are 1) the positive indicators (+): SCC, which enhance the resilience and accumulate the impact of resilient supply chains, and 2) the negative indicators (-): SCV, which retard the performance of supply chains. Hence, the negative loops commence with five SCV constructs, which lead to acute disruptions in IC supply chains in HK. Therefore, the positive loops are the nine SCC constructs that facilitate the successful withstanding ability of SCV. However, these SCC have a negative influence on SCV constructs. All these interactions are depicted in the CLD given in Appendix 1. The variables within the respective constructs are also indicated and represented by the nodes, and their relative dependencies are presented using the links. Based on their positive or negative influence on the loop, the link arrows are given the signs of (+) or (-) on the arrowheads.

*Stock and flow diagram*

A stock and flow diagram is another possible method of presenting causal relationships between variables in system dynamics modelling (Coyle, 1996). According to Ajayi (2016), stock and flow diagram is an algebraic representation that can be run on a computer since it is written in equations and computer coding. Hence, stock and flow diagram facilitates quantitative analysis and mathematical simulation of a model without just limiting to evaluation through tracing of the causal and use trees (Wang et al., 2018). The causal loop diagram was converted to a stock and flow diagram thereafter using Vensim software to simulate dynamic relationships of various strategies in achieving resilient supply chains in IC. The stock and flow diagram is presented in Appendix 2, and all the notations used are described in Table 2.

**[Please insert Table 2 here]**

As shown in Appendix 2, the variables in the stock and flow diagram include stocks, flows, auxiliary variables, and constant indicators. The stock and flow diagram allows input of mathematical equations and weighting scores to the model to simulate each variable's impact on the model separately and as a whole. In order to conduct appropriate quantitative analysis, the respective indices of each measurement items were first established. Thereby, the impacts of adopting different strategies for achieving resilient IC supply chains were simulated.

*Data collection and analysis for model simulation*

After constructing the stock and flow diagram, two cases were selected to conduct a comparative case study and as the model simulation inputs. Both Case A and Case B were public housing construction projects in HK. These cases are representative of IC projects in HK, given that; (a) the largest IC client develops these projects in HK providing public housing for over 50% of its residents, (b) the main contractors of Case A and Case B are reputed, top graded and well-experienced contractors in the field of IC sector in HK with project teams possessing management skills similar to other experienced IC project teams, and (c) all the public housing projects are very similar except for site conditions, with the floor plan, structure type, assembly cycle, and volume and types of precast components being the same for each of a few standard designs. This justifies the generalization from the case study. The only difference between the selected cases is that Case A does not have its inhouse manufacturing company.. However, the contractor in Case B has its own prefabrication yard in Mainland China, and hence, all the supply chain phases are linked under one Building Information Modelling (BIM) platform. Table 3 presents further details about the two projects.

**[Please insert Table 3 here]**

All the required data from the selected cases were collected through unstructured interviews with six project professionals, including project managers of each selected case, document reviewing, and conducting site visits together with a questionnaire survey. The questionnaire was designed to capture the level of application of SCC strategies and the level of vulnerability due to supply chain disruptions. Supply chain vulnerability and capability measures which were confirmed in the PLS-SEM analysis (Ekanayake et al., 2020c), were included in the questionnaire. All the respondents were asked to rank the level of SCC application and the vulnerability level on a range of 0% to 100%, which indicates 0% as the least to 100% as the highest. Besides, all the project-specific details, lessons learnt, and the firms' individual arrangements were captured in the interviews and helped propose strategies to enhance supply chain resilience practices in IC in HK.

In calculating a relative importance value for each vulnerability and each capability, the following steps were used by following the study of Ajayi (2016).

(I) First, the data collected from the main questionnaire survey was used to develop a PLS-SEM model, reflecting the interconnections between SCV and SCC as presented in Ekanayake et al. (2020c). PLS-SEM has computed a weighting score for each link (relationships) within the constructs. For instance, it has developed weights for each variable within the economic SCV construct appropriate to the relevant construct. Similar findings emerged for all the capabilities and the vulnerabilities. This method allows more justifiable values as these values are generated from a statistical tool compared to the mean score weightings. Hence, the relative weights for each variable were calculated using the factor weights ($w_{x_i}$) assigned by PLS-SEM analysis as in Equation 1.

$$R_{x_i} = \frac{w_{x_i}}{\sum_{j=1}^{n} w_{x_j}} \qquad (1)$$

$R_{x_i}$ denotes the significance index of element $x_i$, indicating the extent to which $x_i$contributes to its latent variable. $w_{x_i}$ is the factor weight derived from PLS-SEM.

For instance, considering, the latent factor "Production-based SCV-PBSCV" where $x_1$= QL, $x_2$ = SDM, $x_3$ = LS, $w_{x_1}$ = 0.89, $w_{x_2}$ = 0.89, and $w_{x_3}$ = 0.75. As per Equation 1, the relative weight of QL, [$R_{QL}$] = 0.89/2.53 = 0.35.

(II) Thereafter, the application levels of first-order latent variables such as PBSCV, ESCV and other constructs were computed using the following Equation 2.

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

Where, $AL(X)$ = application level of the latent factor X, $L_{x_i}$= application level of sub-element $x_i$ contributing to the latent factor X. $R_{x_i}$= the significance index of sub-element $x_i$ as calculated using Equation 1.

(III) Then, this study computed the significance index of all the latent variables using the following Equation 3 in order to understand each construct's significance towards achieving the resilient IC supply chains.

$$R_{X_i} = \frac{w_{X_i}}{\sum_{j=1}^{n} w_{X_j}} \quad (3)$$

In Equation 3, $R_{X_i}$ denotes the significance index of the latent variable $X_i$, which can be a vulnerability or capability construct. $w_{X_i}$ is the absolute weight derived from PLS-SEM analysis for each construct. $\sum_{j=1}^{n} w_{X_j}$ reflects the sum of absolute weights for all the constructs with respect to their associated vulnerability or capability category.

(IV) Accordingly, the impacts of vulnerabilities and capabilities were computed using the following Equation 4 and Equation 5, considering their relative impacts on the contributing factors and their level of application.

$$SCV = AL_{ESCV} \times R_{ESCV} + AL_{TSCV} \times R_{TSCV} + AL_{PSCV} \times R_{PSCV} + AL_{OSCV} \times R_{OSCV} + AL_{PBSCV} \times R_{PBSCV} \quad (4)$$

$$SCC = AL_{FLE} \times R_{FLE} + AL_{RES} \times R_{RES} + AL_{CAP} \times R_{CAP} + AL_{ADA} \times R_{ADA} + AL_{FIS} \times R_{FIS} + AL_{DIS} \times R_{DIS} + AL_{VIS} \times R_{VIS} + AL_{EFF} \times R_{EFF} + AL_{ANT} \times R_{ANT} \quad (5)$$

$SCV$ is the combined impact of all the vulnerabilities, whereas $SCC$ denotes all the capability measures' combined impact. Relevant $AL$ and $R$ values were calculated using Equation 2 and Equation 3.

(V) Finally, the balancing impact of SCC and SCV towards achieving supply chain resilience in IC in HK, which is RSCIC, was derived as appropriate to this study using the correlation suggested by Pettit et al. (2013). All these values were input into the model, indicating the units as 'Dmnl' since the data input was measured in a scale or a percentage. Prior to the simulation run, the model was then tested for its accuracy (Ding et al., 2016; Senge, 1990).

*Model testing and validation*

The validity test is performed to ensure that the model reflects definite scenarios (Richardson and Pugh, 1981), and model validation is essential in system dynamics modelling (Sterman, 2000). The series of tests performed to review and highlight the validity of the model are; 1) the boundary adequacy test, which confirms whether all the essential concepts and structures are considered in the model (Qudrat-Ullah & Seong, 2010); 2) parameter verification test which confirms whether the parameter value is consistent with the system knowledge by means of numerically and descriptively (Ajayi, 2016); 3) dimension consistency test that verifies the measurement units in any equation is consistent (Sterman, 2000; 4) extreme condition test which confirms whether the model behavior is consistent at extreme cases of 0% and 100% implementation of all the strategies (Ajayi, 2016); and 5) structure verification test which verifies whether the model represents real-life relationships and interconnections as well as the actual system simulated (Ding et al., 2016). Test 1 was verified by interviewing two industry experts who earlier assisted in this data collection. The other four tests were performed in the Vensim software; hence, the model parameters were successfully verified. Thereby, base run simulation and the sensitivity analysis were conducted on the Vensim model to derive the study results. The results are further elaborated in the next section.

**Results and discussion**

**Vulnerability analysis of supply chain phases**

This section presents the outcomes generated and consequential discussions based on social network analysis of the IC supply chains in this study. Fig.4. presents an overarching view of the collective impact of vulnerabilities affecting each supply chain phase. Here, N-V stands for the normalized values of the degree of impact. Hence, it is seen as the dynamic relative impact of SCV on the supply chain phases. According to Fig.3. and Fig.4., the manufacturing phase and the on-site assembly phase are more (highly) vulnerable phases in IC supply chains. The logistics phase is also marginally vulnerable in terms of supply chain disruptions. However, none of the phases was immune from SCV.

**[Please insert Fig.4. here]**

The manufacturing and the on-site assembly phases are highly susceptible to labor-related issues, which are very significant in IC. Loss of skilled labor is a highly influential factor that reduces the performance of the IC. Hoisting of prefabricated components requires the support of trained and skilled labor. Otherwise, more time would be required; assembly quality will be downgraded, and many safety problems may arise. Further, the disruptions due to supply-demand mismatch and outsourcing problems are also associated with these two phases. Machinery or equipment breakdowns are also allied to the manufacturing and assembly phases. During the assembly, tower crane and hoist breakdowns are common. However, having alternative equipment on stand-by incurs unnecessary costs; hence, sound maintenance agreements are preferred in real practice. Industry market pressures and economic policy changes are other influential vulnerabilities in these two phases. Besides, quality loss is the most significant vulnerability that each supply chain phase faces. Beginning from the factory, tolerance issues should be avoided and require three more inspections of the units as opined by experts. Several trial liftings and mockups are needed even at the site, with further demands on skilled labor to reduce vulnerabilities.

The implications of new regulations affect all three supply chain phases since regulatory changes impact highly on cross-border logistics. As shown in Fig.3., logistics phase is different from the other two phases since there are distinct vulnerabilities associated with the logistics phase. These include transport disruptions, including port stoppages. According to the experts, even custom clearance is a complex task since there are many documents, and it is quite difficult to get permissions for high-technology items such as modular units. Further, the transportation of oversized precast units needs special attention. The units are mostly transported during the night using less trafficked routes to avoid accidents, heavy traffic and other disruptive causes. Therefore, although the vulnerability is slightly less in the logistics phase, there are many significant SCV to be addressed in this phase, requiring project stakeholders' attention.

**Dynamics of capabilities in achieving resilient supply chains**

To understand the optimal approach for achieving resilient supply chains in IC in HK, various scenarios were modelled using the system dynamics approach as explicated above. This modelling process involved two scenarios, (I) evaluating the influence of SCV and SCC using two cases and (II) evaluating the impacts of various SCC strategies on overall performance. Accordingly, the scenario models were performed using the SyntheSim Simulate function of the Vensim software. Fig.5. shows the output generated for supply chain resilience levels in Case A and Case B. As shown in Fig.5., the performance level of Case A is around 40%, whereas Case B's performance is more than 50%. There are numerous reasons behind this significant difference in supply chain resilience values.

**[Please insert Fig.5. here]**

In Case B, it is possible to identify the proper integration (vertical integration) of supply chain phases as the main contractor is handling all three supply chain phases under one roof by consolidating supply chain flexibility. The contractor in Case B has its in-house manufacturing factory in Mainland China, and they also handle logistics and on-site assembly. Hence, the entire supply chain phases are integrated with their Building Information Modelling (BIM) based system, enabling collaborative information exchange among the supply chain members compared to Case A. With this arrangement, there are fewer disruptions in Case B as it avoids outsourcing of prefabricated components and better co-ordination.

Most importantly, this method facilitates an overwhelming solution for improved quality since tolerance issues are detected successfully and in advance through this system. Therefore, taking necessary actions are quicker, avoiding variations and rework. Further, supply chain integration enables production postponement whenever it is essential and prevents overstocking prefabricated units at sites. Maintaining an adequate stock at the site is highly crucial since the construction sites in HK are congested, making on-site logistics more complex. However, Case B is at high risk in 'risk-sharing' due to its integrated supply chain mechanism.

On the other hand, in Case A, the contractor uses an RFID enabled platform for tracking and tracing the prefabricated units from the manufacturing factory to the assembly. This approach has increased real-time visibility of the supply chain and enhanced tracing of supply chain logistics. Also, there are two quality managers, one assigned at the manufacturing factory and the other at the assembly site, to avoid quality issues. This arrangement incurred additional costs, while the project was unable to fully control tolerance issues with this arrangement. In addition, Case A has already faced tower crane breakdowns during operations which prompted a back-up maintenance agreement with a company. Although this project has faced safety accidents, they were not severe, as they were near misses, including dropping segments, small tools, and small equipment. In the IC assembly process, safety issues arise from lifting operation failures, heavy lifting, untidy and uncomfortable working environment, installation accidents, and unloading of precast elements (Ekanayake et al., 2020a). Finally, more or less, all these capabilities and vulnerabilities contributed to achieving resilient supply chains in both Case A and B, where Case B is leading with its significant withstanding ability of SCV. However, both the projects need to initiate robust strategies to reach the 100% level of supply chain resilience, as suggested in the next section of this study.

**[Please insert Fig.6. here]**

The analysis was next conducted for scenario II, evaluating the impact of each SCC construct on overall performance. For each of the SCC strategies, implementation levels were raised to 100% to assess their overall effects on supply chain resilience while maintaining all the other strategies at the baseline levels (graph of project A), as presented in Fig.6. The baseline scenario of this study yielded approximately 40% of supply chain resilience, as shown in Fig.6. However, all the strategies contributed to increased resilience. Simultaneously, the results suggested that anticipation can make the highest impact on supply chain resilience implementation, providing the ability to detect potential disruptions. In this construct, therefore, there should be adequate provisions for the deployment of tracking and tracing tools (Li et al., 2018), quality control and intensive training (Ekanayake et al., 2020b).

Further, as separate strategies, all the capability constructs contribute to increasing resilience up to 50%, which is a significant improvement. The least contribution is towards the construct of dispersion because IC practices in HK always encourage a greater extent of distributed decision making in their current practice. Besides, all the SCC strategies' dynamic impact contributes to reaching resilience up to 90% with the dynamic impacts of SCV as depicted in Fig.6. Perfect performance is only achievable with the 100% implementation of all the strategies applicable to the HK context. Moreover, based on the elicited expert opinions, the case study findings and the simulation results, this study offers the following strategies to install and/or upgrade supply chain resilience practices in IC in HK as explicated in the forthcoming section.

**Strategies to uptake supply chain resilience in IC in HK**

Shortfalls were identified in supply chain resilience approaches and practices in the IC sector. Unsurprisingly, the industry still suffers from numerous acute supply chain disruptions due to SCV. Therefore, useful strategies to introduce and/or upgrade supply chain resilience in IC in HK were solicited from the project professionals (the experts) involved in Case A and Case B using semi-structured interviews during the case study process. The suggested strategies can be explicated as follows as arising from the case study findings and the simulation results of this research. Moreover, it is discussed in this section how the identified supply chain vulnerabilities can be tackled and reduced and how the proposed supply chain capability measures can be strengthened using these strategies as below.

*Development of a smart software package*

Building information modelling (BIM) has been widely used in construction processes over the years. According to the experts, BIM is a must in conducting IC processes efficiently. It enables clash analysis and provides early warning signals before disruptions occur and even before construction takes place. Delving deeper, BIM facilitates project planning. In IC supply chains, it enables effective pre-planning of assembly cycles, assembly mock-ups, and other installation processes to avoid on-site disruptions and provide a safe working environment. Since construction sites in HK are congested, planning site logistics requires careful attention. BIM makes this process easier and more effective. Besides, BIM links all three supply chain phases together by introducing one platform where all the project professionals can input their contributions, making supply chain processes flexible and visible. Beginning from detailed production plan development, manufacturing area arrangement, finishing and storage at the factory can be linked with other supply chain processes to avoid component queuing at the site and manage production buffer time.

More recently, linking Radio Frequency Identification (RFID) technology with BIM has improved supply chain coordination and visibility of material flows, specifically in the pursuit of Industry 4.0 (Chen et al., 2020). Most importantly, this method enables detailed look-ahead plans by deploying promising opportunities for accurate tracking and matching of dynamic site needs with material supply. Hence, even the proper integration of BIM and RFID will boost supply chain visibility needed for resilience in IC. Besides, seamless communication and coordination among multiple stakeholders through improved information interoperability between supply chain processes will yield another underlying benefit from this integration. During prefabricated component production, execution, and control, this BIM and RFID integration will help overcome lack of accurate information, information misuse, low productivity, weak responses towards changes, excessive resource waste, and enable component quality certification. Precise selection of prefabricated units and knowing the amount to transport is essential to avoid disruptive stock management and to maintain appropriate production lead times, which is possible through RFID assisted BIM implementation.

Further, cross-border logistics between Mainland China and HK will become more efficient through real-time information visibility and traceability. Supply chain members can track and trace the RFID readings of prefabricated components throughout the entire logistics. Hence, they can pre-identify disruptive situations where necessary actions can be taken to avoid delays and excessive queuing. Thus, it will be easier to address poor information sharing, lack of dynamic control and inefficient supply chain management through BIM and RFID while realising 'just in time delivery' of prefabricated components. Complex IC site logistics are likely to trigger acute disruptions due to limited space, safety risks at the site during heavy and high lifting, lack of real-time locations of components, workers and equipment and ineffective on-site data location. Such on-site disruptions often trigger a series of problems through the entire project supply chain. Therefore, enabling a BIM and RFID integrated supply chain communication and coordination platform will encourage effective site coordination and seamless communication at the site to allow just in time delivery of components. This integration would enable the precise and visual monitoring of on-site progress and trigger alarms on potential time and cost vulnerabilities. Error-free assembly and improvement of on-site productivity are also allied with these technological advancements. In addition, mobile checkpoints and mobile checking, which are available with this system, add more flexibility to the IC process.

Linking Geo-Information System (GIS) to an integrated BIM system would significantly improve emergency response and crisis management in IC supply chains (Irizarry et al., 2013) with its improved visual monitoring ability and supply chain traceability. For example, proper vehicle scheduling without vehicle queuing or buffering and error matching between tractors and trailers is feasible with this technology in IC. Further, disturbance-free and waste-free task allocation, including task allocation to vehicle drivers, are added to the associated merits. Most importantly, real-time traceability of vehicles facilitates accurate and frequent vehicle tracking, identifying and assessing road traffic, and timely determination of vehicle breakdowns or delays at supply chain points. Therefore, these SCC demonstrate success in withstanding associated SCV in IC in HK while clearing avenues towards supply chain resilience.

In a recent development, Min (2019) identified that the integration of 'Blockchain' concepts with supply chain management offers promising accountability and visibility to supply chains. Further, blockchain technology enables data security in the supply chain process. Hence, the integration of BIM and blockchain will enhance the IC supply chain process's data security by providing an innovative collaboration platform for IC project professionals. Besides, this arrangement would enhance financial security and improve cash flow by enabling smooth and certain cash flow management and milestone payment arrangement systems. It would be easy to track materials offsite, work done, and materials on-site through the system and provide healthy cash flows for contractors without payment delays.

Therefore, introducing a BIM+RFID+GIS+Blockchain integrated software package would be highly beneficial for enhancing supply chain resilience in IC while offering promising avenues to improve SCC of involved organizations. Further, this novel integrated system will enable quality assurance and frequent quality checking through online inspection. Tolerance issues will be better controlled with this enhanced supply chain management, which would effectively withstand associated vulnerabilities. Further, remote inspection and record-keeping will also be advantageous since this avoids liability issues and provides frequent testing of concrete components, plumbing and drainage network, waterproofing, and joints. In addition, planning time for quality checks, enabling adequate buffers, and efficient resource allocation (e.g., inspectors) are also feasible with reduced disruptions. Online inspection is critical during this Covid-19 pandemic situation. Indeed, a technical circular issued by Building Department on 07 Feb 2020 was on adopting online inspection. Therefore, the envisaged smart software package would be useful not only in conducting important online inspections but also in quick, collaborative decision making based on inspection outcomes to overcome disruptive triggers in IC. Therefore, based on the relevant literature, opinions of industry experts, and case study findings, this study identifies the development and use of a smart software package to manage IC supply chains as the first initiative to enhance IC supply chains' resilient capacity in HK.

*Enhance interoperability of software used*

While the aforementioned smart software package is vital in achieving supply chain resilience in IC, interoperability of this software should be enhanced to realize the targeted benefits. For instance, blockchain technology is relatively new to the construction industry, and the developed software is limited. Therefore, these software packages should be customized as appropriate to the IC context and should match existing software in use. An organizational software system's capacity should be adequate to share, exchange, and use supply chain information without causing disruptions such as system breakdowns, data loss or misinterpretations. The most challenging task here is integrating all these useful software with the organizations' existing enterprise resource planning systems. Therefore, there is a need to enhance the interoperability of the software used, encouraging supply chain resilience in IC.

*Extensive use of appropriate technology*

As a result of higher labor cost and loss of skilled labor in HK, IC components' manufacturing is done in Mainland China. In these circumstances, automated production lines will make the supply chain process more resourceful and efficient. Since computer-aided-design, robotic arms and laser cutting techniques are available in general; this study suggests developing and deploying suitable computer-aided manufacturing, labor robots, and automated manufacturing processes to enhance resilient practices in IC itself. On the other hand, it is worth reducing accidents and enhancing site safety. Providing adequate appropriately positioned cameras to oversee tower crane operations, arranging high-resolution cameras to have clear images of lifting and site storage, frequent monitoring through mobile phones and laptops, structurally designed anchorage points, auto-retractable harness to reduce the risk of fall and increase maneuvering would add adequate safety and security to reduce potential threats. Besides, planning for on-site installation phase is the biggest challenge as it involves the high lifting of extensively heavy materials. Therefore, trial lifting and a considerable number of mockups should be conducted to avoid tolerance issues and safety hazards. In line with this scenario, artificial intelligence and virtual reality techniques can be applied to perform simulations. This will reduce safety hazards and on-site mockups. Further, these simulation models can be used to train labor since intensive training is required for skilled labor engaged with on-site installation of prefabricated components to avoid safety hazards and improve work efficiency.

*Maintaining in-house prefabrication yard and increased use of modular units*

According to the findings of system dynamics modelling, and as explicated above, the organization with its prefabrication yard is more resilient to SCV than the other. In the case studies, the higher the vertical integration, the lower the cost implication, lower the outsourcing and lower the vulnerability level. On the other hand, more demand for and use of modular units reduces construction duration, labor cost, and workmanship issues while increasing quality, site safety and environmental protection. Further, as modular integrated construction is a recent innovative development in HK, if an organization can fulfil the current market demand, it will enhance the organizational capacity, market position and reputation for customer satisfaction, all of which are clearly needed to absorb industry and market pressures.

*Uptake policy support*

Implementation of these supply chain management strategies is not possible without policy support (Liu et al., 2018). That is why researchers examined the impact and effectiveness of policy support towards achieving supply chain resilience in different industries (Mancheri et al., 2019; Liu et al., 2018). Therefore, it is clear that promotional policies should be influential in achieving supply chain resilience in IC in Hong Kong, although this is not yet explored to date. These policy drivers and enablers could arise from regulative policies, which could be based on public procurement law, mandatory government policies, and housing policies, IC policies; standardised policies of regional prefabricated construction standards, design level standards, quality standards, technical and construction method standards;

managerial policies of risk management, research and development, safety policies, performance management and supply-chain policies; and sustainable policies of green construction, waste management, environmental conservation, carbon emissions mitigation, and energy conservation. The above policy implications are expected to encourage and promote supply chain resilience uptake and improvements in IC in HK.

## Conclusions, limitations and ways forward

This study was formulated to investigate the dynamic impact of SCV and SCC in achieving supply chain resilience in IC in HK. First, this study identified the level of vulnerability of each supply chain phase of IC through social network analysis modelling. Accordingly, the on-site assembly phase is the most vulnerable to the associated SCV, and the logistics phase faces identical SCV compared to the other supply chain phases. Then, this study developed a causal loop diagram, stock and flow diagram, and ran the simulation using system dynamics modelling to investigate SCC dynamics in realizing resilient supply chains in IC. The study found that there is still room for improvement under the SCC of anticipation, flexibility, financial strength, and resourcefulness, indicating that their practice should be improved and would then be highly influential in fulfilling resilience requirements. Visibility, efficiency, capacity and adaptability show their moderate influence targeting resilience. At the same time, dispersion was perceived to have the least requirement for improvement as the industry has already employed dispersion measures to a greater extent in current practice.

Two comparative case studies conducted using two real-time IC projects enabled identifying and appraising the real-life practices of IC supply chains in HK. The findings suggested that Case B is more resilient than Case A because of the supply chain's inherent capabilities, such as vertical integration, less outsourcing, higher modular product design, higher safety and security, and the use of innovative technology. Besides, it was found out that there is a more structured and focused long-term approach needed to achieve supply chain resilience in IC; hence, the first set of useful strategies were proposed to move forward. These strategies comprise: (i) development of a smart software package, (ii) enhance interoperability of software used, (iii) extensive use of appropriate technology, (iv) maintaining in-house prefabrication yard and increased use of modular units, and (v) uptake policy support.

Reinforcement of these strategies would facilitate robust approaches to develop more resilient supply chains with its associated benefits of value and performance enhanced supply chains in IC in HK.

Although this study offers a significant contribution to the IC knowledge domain, some perceived limitations of this study are worth noting. The sample size of 76 was fully justified in the research method section. Still, a bigger sample size may facilitate more sensitive models as the optimal sample size cannot be precisely determined. The results are based on two comparative case studies in HK due to time resource and access constraints. More projects can be included in the sensitivity analysis to generate better and more comparable results. Further, the nature of supply chains and their dynamics differ in diffrent industrial contexts and jurisdictions. Also, the length of supply chains can impact on the resilience, e.g., shipping products from Mainland China to HK is different to shipping from Mainland China to North America. Hence, the developed models are the best fit for the IC context in HK. Given HK's specific socio-economic background, these models' parameters and calibration cannot be directly generalized for other cities. However, similar studies may be replicated in other country contexts and industry contexts by following the now proven research methodology initiated and proposed in this research to ascertain the generalized results while drawing lessons to be learned from different country contexts. On the other hand, this study presents an overall picture of the IC supply chain process without focusing on specific IC categories or types (such as precast construction, prefabricated components assembly, modular integrated construction). This is because during the survey and the interviews, authors asked all the experts to provide their responses based on their overall experiences in IC projects in HK, which should cover all types of IC products used in HK. Therefore, this fundamental, hence essential first study can next be further built upon to focus separately on each IC category to generate more specific research outcomes in each IC 'sub-sub-sector' if IC is taken as a sub-sector of the HK Construction sector.'

Further, this data collection was conducted just before the emergence of the Covid-19 pandemic situation. Therefore, similar system dynamics modelling can be undertaken to determine the impact of Covid-19 on IC supply chains in HK itself, when resilience imperatives may increase while conditions may also change. Furthermore, in future studies, similar simulations should be conducted to update the knowledge domain of supply chain resilience in IC while proposing robust and timely strategies to boost resilient practices with policy-makers and industry leaders' support. Besides, supply chain resilience aspects can be linked with construction firms' organizational behavior and behavioral aspects, which could be another substantial research direction to conduct dynamic simulation studies. Moreover, the potentially cascading impacts of all SCV, together with strategies to balance the system interdependencies and these cascading impacts, could be developed, modelled, and analyzed using real case studies to develop more robust results. Although this may initially seem like a complex combination of daunting tasks, such exercises could draw on examples from the methodology developed in this study.

System dynamics modelling has been used in a few previous studies to analyze supply chain disruptions. Still, those studies were limited to assessing the dynamic impact of one of the SCV, or a few of SCV and, hence, lacked consideration of the supply chain's entire dynamic system with its influential SCV and SCC. The other available supply chain resilience models do not even consider the dynamics of the entire supply chain system and are not validated through such real-time case studies. Besides, there is no known attempt to develop a dynamic supply chain resilience model in IC or even in the construction industry. Therefore, this is the first study conducted to assess the dynamics of the entire supply chain system considering the interactions and combined impacts of both SCV and SCC. In this regard, this study significantly contributes to the supply chain resilience knowledge domain by initiating system dynamics modelling in supply chain resilience analysis. Indeed, this study contributes significantly to research in prefabricated construction by proposing the first dynamic assessment model of supply chain resilience targeting value-enhanced IC supply chains.

Moreover, the model developed for assessing supply chain disruptions in each supply chain phase is the first application of social network analysis in the supply chain resilience knowledge domain in vulnerability analysis. Furthermore, this is the first attempt to assess each IC supply chain phase's vulnerability level. Besides, proposing the first set of useful strategies to uptake and improve resilience in IC supply chain practices is highly beneficial to uplift project performance. Therefore, this study substantially contributes to the theoretical and practical knowledge creation and dissemination in supply chain resilience in IC research domains. Finally, this study confirms supply chain resilience to be a timely and important imperative for developing policy and strategic objectives and protocols to boost supply chain performance in IC in HK, as well as other jurisdictions or countries where construction industries now face acute challenges due to totally unforeseen and unprecedented disruptions that have significantly aggravated existing performance shortfalls.

**Data Availability Statement**

All data, models, and code generated or used during the study appear in the submitted article.

**Acknowledgement**

The research described in this paper is supported by the National Natural Science Foundation of China (Grant No.71671156) and the Research Institute for Sustainable Urban Development of the Hong Kong Polytechnic University. The authors also wish to gratefully acknowledge the HK Ph.D. Fellowship Scheme and The Hong Kong Polytechnic University contributed to the preparation of this paper. The authors gratefully acknowledge the survey respondents and anonymous reviewers for their significant contribution to draft and improve this paper.

**References**

Adabre, M.A. and Chan, A.P. 2019. Critical success factors (CSFs) for sustainable affordable housing. *Building and Environment*, 156, 203-214.

Ajayi, S., 2016. *Design, procurement and construction strategies for minimizing waste in construction projects* (Doctoral dissertation). University of the West of England, Bristol

Ameyaw, E. E., Pärn, E., Chan, A. P., Owusu-Manu, D. G., Edwards, D. J., and Darko, A. 2017. Corrupt practices in the construction industry: Survey of Ghanaian experience. *Journal of Management in Engineering, 33*(6), 05017006.

Bakker, M. and Wicherts, J.M., 2014. Outlier removal, sum scores, and the inflation of the type I error rate in independent samples t tests: The power of alternatives and recommendations. *Psychological methods*, 19(3), 409-427.

Bueno-Solano, A. and Cedillo-Campos, M.G., 2014. Dynamic impact on global supply chains performance of disruptions propagation produced by terrorist acts. *Transportation research part E: logistics and transportation review*, 61, 1-12.

Chan A.P.C., Darko A., Olanipekun A.O., and Ameyaw E.E., 2018 Critical barriers to green building technologies adoption in developing countries: the case of Ghana, *Journal of Cleaner Production*. 172, 1067-1079.

Chen, Q., Adey, B.T., Haas, C. and Hall, D.M., 2020. Using look-ahead plans to improve material flow processes on construction projects when using BIM and RFID technologies. *Construction Innovation*. 20(3), 471-508.

Chinowsky, P., Diekmann, J. and Galotti, V., 2008. Social network model of construction. *Journal of construction engineering and management*, 134(10), 804-812.

Chinowsky, P.S., Diekmann, J. and O'Brien, J., 2010. Project organizations as social networks. *Journal of construction engineering and management*, 136(4), 452-458.

Chowdhury, M.M.H. and Quaddus, M., 2017. Supply chain resilience: Conceptualization and scale development using dynamic capability theory. *International Journal of Production Economics*, *188*, 185-204.

Colicchia, C., Creazza, A., Noè, C. and Strozzi, F., 2019. Information sharing in supply chains: a review of risks and opportunities using the systematic literature network analysis (SLNA). *Supply chain management: an international journal*. 24/1(2019), 5-21

Coyle, R.G., 1996. *System dynamics modelling: a practical approach* (Vol. 1). CRC Press.

Darko, A. and Chan, A.P.C. 2018. Strategies to promote green building technologies adoption in developing countries: The case of Ghana. *Building and Environment*, 130, 74-84.

Ding, Z., Yi, G., Tam, V.W. and Huang, T., 2016. A system dynamics-based environmental performance simulation of construction waste reduction management in China. *Waste Management*, *51*, 130-141.

Ekanayake, E.M.A.C., Shen, G.Q., Kumaraswamy, M.M. and Owusu, E.K., 2020a. Critical Supply Chain Vulnerabilities Affecting Supply Chain Resilience in Industrialized Construction in Hong Kong. *Engineering, Construction and Architectural Management*. DOI 10.1108/ECAM-06-2020-0438.

Ekanayake, E.M.A.C., Shen, G.Q., and Kumaraswamy, M.M., 2020b. Critical Capabilities of Improving Supply Chain Resilience in Industrialized Construction in Hong Kong. *Engineering, Construction and Architectural Management*. DOI 10.1108/ECAM-05-2020-0295.

Ekanayake, E. M. A. C., Shen, G. Q. P., Kumaraswamy, M. and Owusu, E. K. 2020c. Impact of Capabilities on Withstanding Vulnerabilities in Achieving Supply Chain Resilience of Industrialised Construction: A Hong Kong Case Study. (*currently under review*)

Golan, M.S., Jernegan, L.H. and Linkov, I., 2020. Trends and applications of resilience analytics in supply chain modeling: systematic literature review in the context of the COVID-19 pandemic. *Environment Systems & Decisions*, 40, 222-243.

Gong, P., Teng, Y., Li, X. and Luo, L., 2019. Modeling constraints for the on-site assembly process of prefabrication housing production: a social network analysis. Sustainability, 11(5), 1387

Irizarry, J., Karan, E. P. and Jalaei, F. 2013. Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. Automation in Construction, 31, 241-254.

Inoue, H., Murase, Y. and Todo, Y., 2020. The impact of supply-chain networks on interactions between the anti-COVID-19 lockdowns in different regions. Available at SSRN 3692937.

Khan, K. I. A., Flanagan, R., and Lu, S. L. 2016. Managing information complexity using system dynamics on construction projects. *Construction management and economics, 34*(3), 192-204.

Kochan, C.G., Nowicki, D.R., Sauser, B. and Randall, W.S., 2018. Impact of cloud-based information sharing on hospital supply chain performance: A system dynamics framework. *International Journal of Production Economics*, *195*, pp.168-185.

Li, C.Z., Hong J., Fan C., Xu X., and Shen G.Q. 2018. Schedule delay analysis of prefabricated housing production: a hybrid dynamic approach. *Cleaner Production*. 195,1533-1545.

Li, C. Z., Hong, J., Xue, F., Shen, G. Q., Xu, X. and Mok, M. K. 2016. Schedule risks in prefabrication housing production in Hong Kong: a social network analysis. *Journal of Cleaner Production*, 134, 482-494.

Li, C.Z., Xue, F., Li, X., Hong, J. and Shen, G.Q. 2018. An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Automation in construction,* 89, 146-161.

Li, Z., Shen, G.Q. and Alshawi, M., 2014. Measuring the impact of prefabrication on construction waste reduction: an empirical study in China. *Resources, Conservation and Recycling*, *91*, 27-39.

Lin, S.C., 2015. An analysis for construction engineering networks. *Journal of Construction Engineering and Management*, 141(5), p.04014096.

Liu, C.L., Shang, K.C., Lirn, T.C., Lai, K.H. and Lun, Y.V., 2018. Supply chain resilience, firm performance, and management policies in the liner shipping industry. *Transportation Research Part A: Policy and Practice*, *110*, 202-219.

Love, P.E.D., Mandal, P., Smith, J. and Heng L., 2000. Modelling the dynamics of design error induced rework in construction. *Construction Management and Economics,* 18(5), 567-574

Luo, L., Qiping Shen, G., Xu, G., Liu, Y. and Wang, Y., 2019. Stakeholder-associated supply chain risks and their interactions in a prefabricated building project in Hong Kong. *Journal of Management in Engineering*, *35*(2), 05018015.

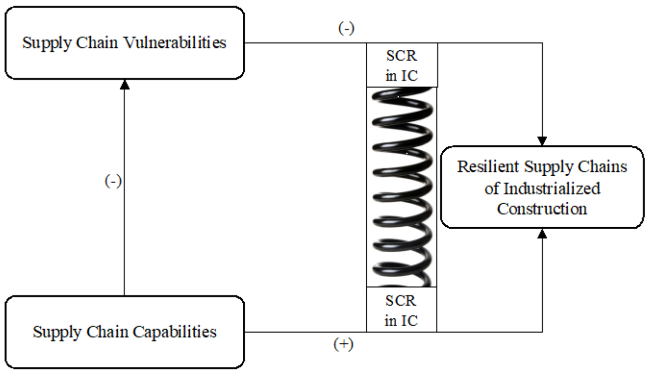
Mancheri, N.A., Sprecher, B., Bailey, G., Ge, J. and Tukker, A., 2019. Effect of Chinese policies on rare earth supply chain resilience. *Resources, Conservation and Recycling*, *142*, 101-112.

McKinsey Global Institute. 2020. (online) *Risk, resilience, and rebalancing in global value chains* from 06 August 2020, available at https://www.mckinsey.com/business-functions/operations/our-insights/risk-resilience-and-rebalancing-in-global-value-chains [Accessed: August, 2020]

Min, H. 2019. Blockchain technology for enhancing supply chain resilience. *Business Horizons*, 62(1), 35-45.

Olivares-Aguila, J. and ElMaraghy, W., 2020. System dynamics modelling for supply chain disruptions. *International Journal of Production Research*, DOI: 10.1080/00207543. 2020.1725171
Ott, R.L. and Longnecker, M.T. 2015. *An introduction to statistical methods and data analysis*, Nelson Education. Toronto.
Owusu, E.K.,Chan, A.P.,Hosseini, M.R. and Nikmehr, B. 2020. Assessing procurement irregularities in the supply-chain of Ghanaian construction projects: a soft-computing approach. *Journal of Civil Engineering and Management*, 26, 66-82.
Pettit, T.J., Croxton, K.L. and Fiksel, J., 2019. The evolution of resilience in supply chain management: a retrospective on ensuring supply chain resilience. *Journal of Business Logistics*, 40(1), 56-65.
Pettit, T.J.,Croxton, K.L. and Fiksel, J. 2013. Ensuring supply chain resilience: Development and implementation of an assessment tool. *Journal of Business Logistics,* 34, 46-76.
Qudrat-Ullah, H. and Seong, B.S., 2010. How to do structural validity of a system dynamics type simulation model: the case of an energy policy model. *Energy Policy*, *38*(5), 2216-2224.
Raoufi, M. and Fayek, A.R., 2020. Identifying Actions to Control and Mitigate the Effects of the COVID-19 Pandemic on Construction Organizations: Preliminary Findings. *Public Works Management & Policy*, 26(1), 47-55.
Scott, J. 2000. "Social network analysis: A handbook." *SAGE Publications*.
Scott, J. and Carrington, P.J., 2011. *The SAGE handbook of social network analysis*. SAGE publications.
Senge, P.M. 1990, The Fifth Discipline: The Art and Practice of the Learning Organization, Currency Doubleday, New York, NY.
Snyder, L.V. and Shen, Z.J.M. 2007. Managing disruptions to supply chains. *Frontiers of Engineering: Reports on Leading Edge Engineering from the 2006 Symposium*, National Academies Press, 139.
Sterman, J. D. 2000. *Systems Thinking and Modeling for a Complex World. Management*.
Sterman, J.D., 1992 "System dynamics Modelling for Project Management," Sloan School of Management, MIT (online). Available at: http://web.mit.edu/jsterman/www/SDG/project.pdf. [Accessed: July, 2020]
Tichy, N.M., Tushman, M.L. and Fombrun, C., 1979. Social network analysis for organizations. *Academy of management review*, 4(4), 507-519.
Wang, T., He, Q., Lu, Y., and Yang, D. 2018. How Does Organizational Citizenship Behavior (OCB) Affect the performance of megaprojects? Insights from a System Dynamic Simulation. Sustainability, 10(6), 1708.
Xu, Z., Zayed, T. and Niu, Y., 2020. Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore. *Journal of Cleaner Production*, *245*, 118861.
Yang, R. J., Zou, P. X. W., and Wang, J. 2015. "Modelling stakeholder-associated risk networks in green building projects." *International Journal of Project Management*, 34(1), 66–81.
Zavala, A., Nowicki, D. and Ramirez-Marquez, J. E. 2018. Quantitative metrics to analyse supply chain resilience and associated costs. Proceedings of the Institution of Mechanical Engineers, *Part O: Journal of Risk and Reliability*. 233(2), 186-199.
Zhang, B., Y. Le, B. Xia, and M. Skitmore. 2017. Causes of business to government corruption in the tendering process in China. *Journal of Management Engineering*. 33(2), 05016022.
Zhang, X.,Shen, L. and Wu, Y. 2011. Green strategy for gaining competitive advantage in housing development: a China study. *Journal of Cleaner Production,* 19, 157-167.
Zhao, X.,Hwang, B.G., Pheng-Low, S. and Wu, P. 2014. Reducing hindrances to enterprise risk management implementation in construction firms. *Journal of Construction Engineering and Management,* 141, 04014083.

**Fig 1**



Supply Chain Vulnerabilities
(-)
SCR
in IC
(-)
Resilient Supply Chains
of Industrialized
Construction
SCR
in IC
Supply Chain Capabilities
(+)

**Fig 2**

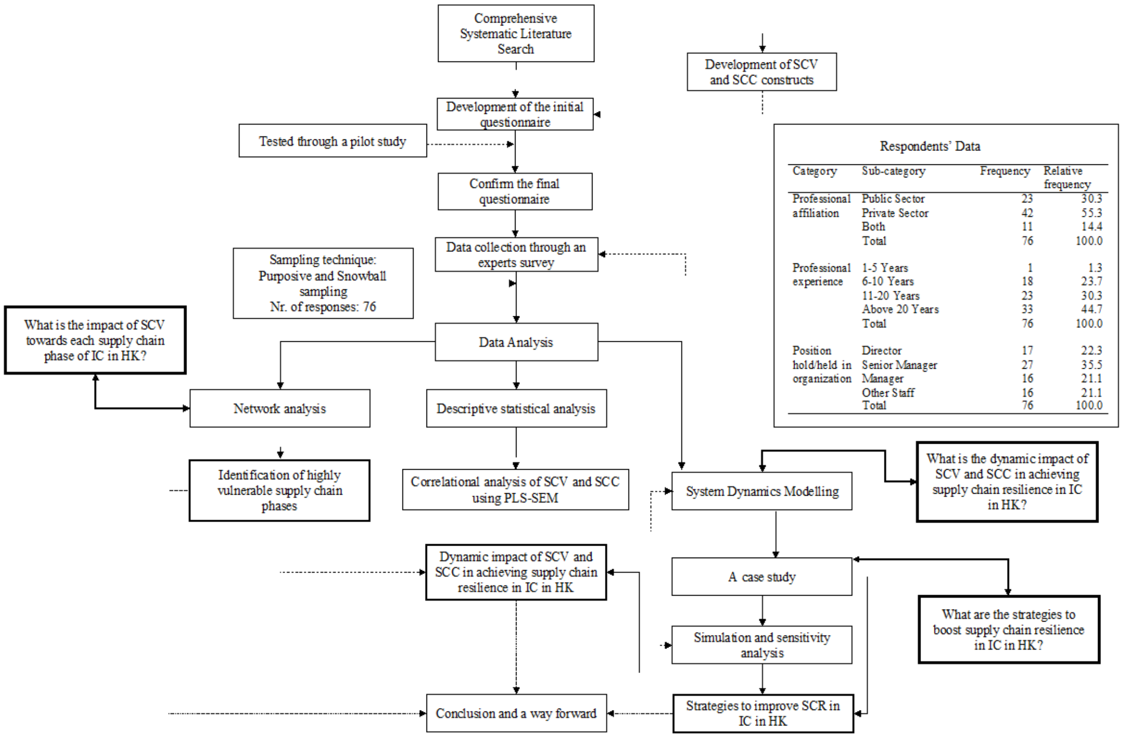

Comprehensive Systematic Literature Search
Development of SCV and SCC constructs
Development of the initial questionnaire
Tested through a pilot study
Confirm the final questionnaire
Data collection through an experts survey
Sampling technique: Purposive and Snowball sampling Nr. of responses: 76
What is the impact of SCV towards each supply chain phase of IC in HK?
Data Analysis
Network analysis
Descriptive statistical analysis
Identification of highly vulnerable supply chain phases
Correlational analysis of SCV and SCC using PLS-SEM
System Dynamics Modelling
What is the dynamic impact of SCV and SCC in achieving supply chain resilience in IC in HK?
Dynamic impact of SCV and SCC in achieving supply chain resilience in IC in HK
A case study
What are the strategies to boost supply chain resilience in IC in HK?
Simulation and sensitivity analysis
Conclusion and a way forward
Strategies to improve SCR in IC in HK
Respondents' Data
Category
Sub-category
Frequency
Relative frequency
Professional affiliation
Public Sector 23 30.3
Private Sector 42 55.3
Both 11 14.4
Total 76 100.0
Professional experience
1-5 Years 1 1.3
6-10 Years 18 23.7
11-20 Years 23 30.3
Above 20 Years 33 44.7
Total 76 100.0
Position hold/held in organization
Director 17 22.3
Senior Manager 27 35.5
Manager 16 21.1
Other Staff 16 21.1
Total 76 100.0

**Fig 3**

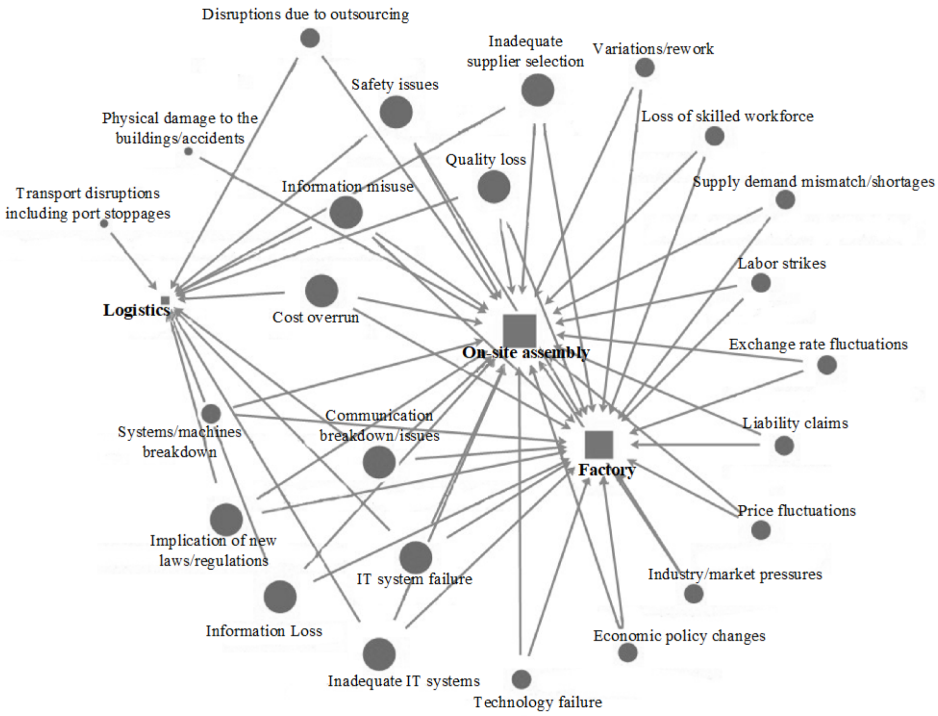
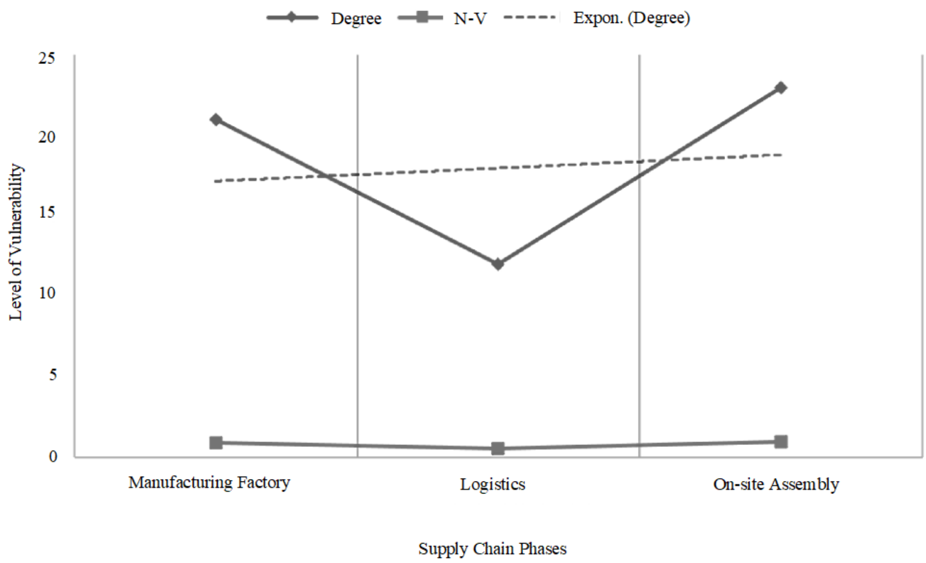

Disruptions due to outsourcing
Inadequate supplier selection
Variations/rework
Safety issues
Physical damage to the buildings/accidents
Loss of skilled workforce
Quality loss
Transport disruptions including port stoppages
Information misuse
Supply demand mismatch/shortages
Labor strikes
Logistics
Cost overrun
On-site assembly
Exchange rate fluctuations
Communication breakdown/issues
Systems/machines breakdown
Liability claims
Factory
Price fluctuations
Implication of new laws/regulations
IT system failure
Industry/market pressures
Information Loss
Economic policy changes
Inadequate IT systems
Technology failure

**Fig 4**



Degree
N-V
Expon. (Degree)
Level of Vulnerability
25
20
15
10
5
0
Manufacturing Factory
Logistics
On-site Assembly
Supply Chain Phases

**Fig 5**

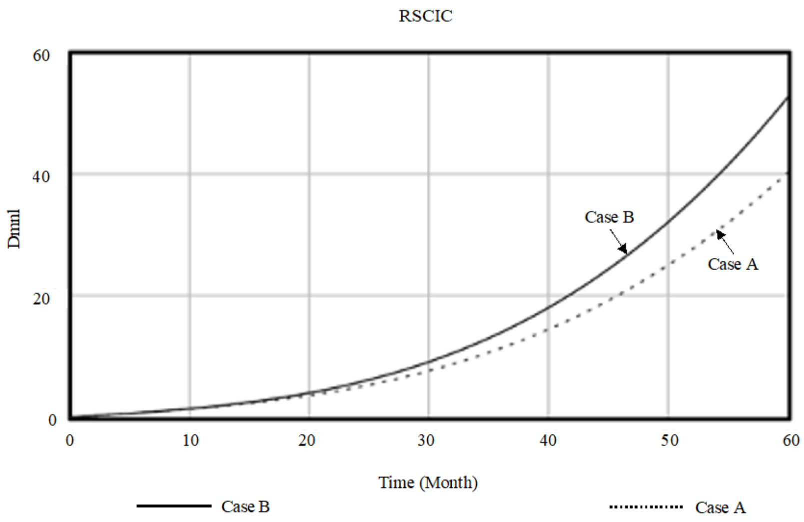
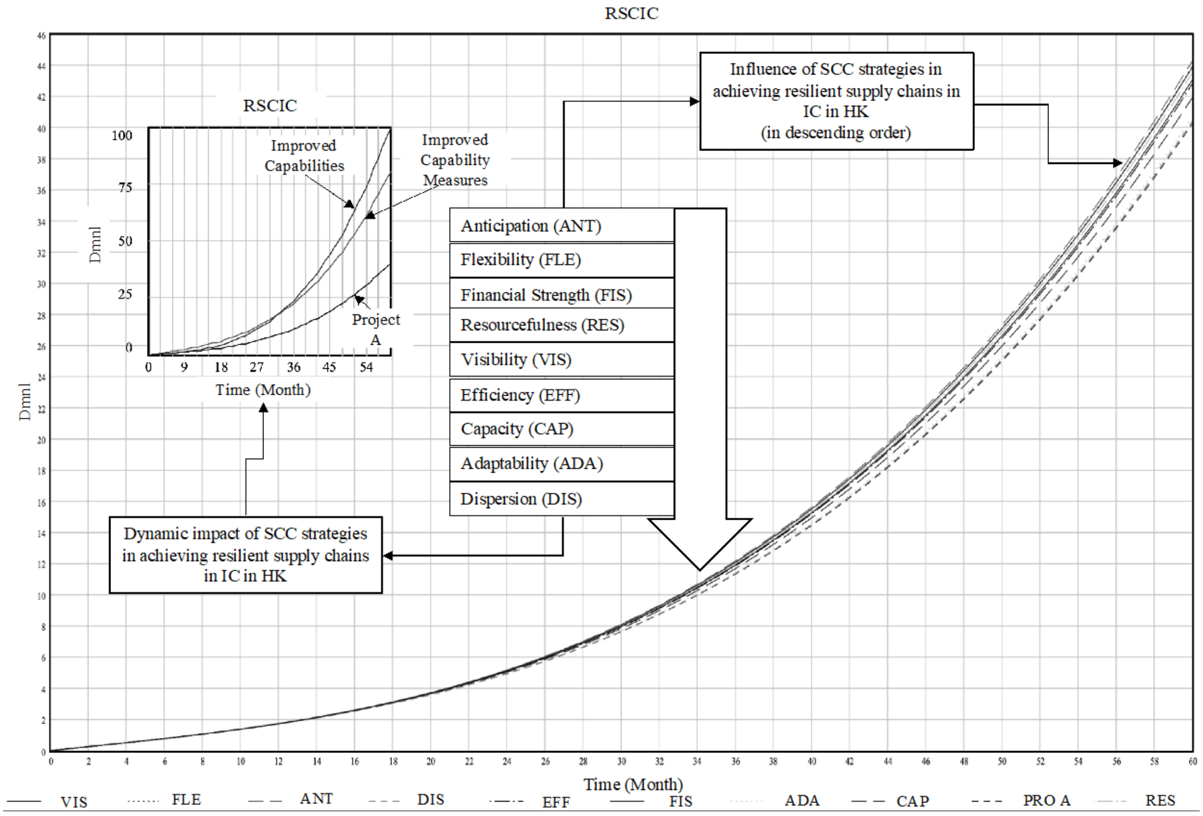

RSCIC
60
40
20
0
Dmml
0
10
20
30
40
50
60
Time (Month)
Case B
Case A
Case B
Case A

**Fig 6**



RSCIC
Influence of SCC strategies in achieving resilient supply chains in IC in HK (in descending order)
RSCIC
Improved Capabilities
Improved Capability Measures
Project A
Dmnl
Time (Month)
Anticipation (ANT)
Flexibility (FLE)
Financial Strength (FIS)
Resourcefulness (RES)
Visibility (VIS)
Efficiency (EFF)
Capacity (CAP)
Adaptability (ADA)
Dispersion (DIS)
Dynamic impact of SCC strategies in achieving resilient supply chains in IC in HK
Dmnl
Time (Month)
VIS
FLE
ANT
DIS
EFF
FIS
ADA
CAP
PRO A
RES

**Fig 7**

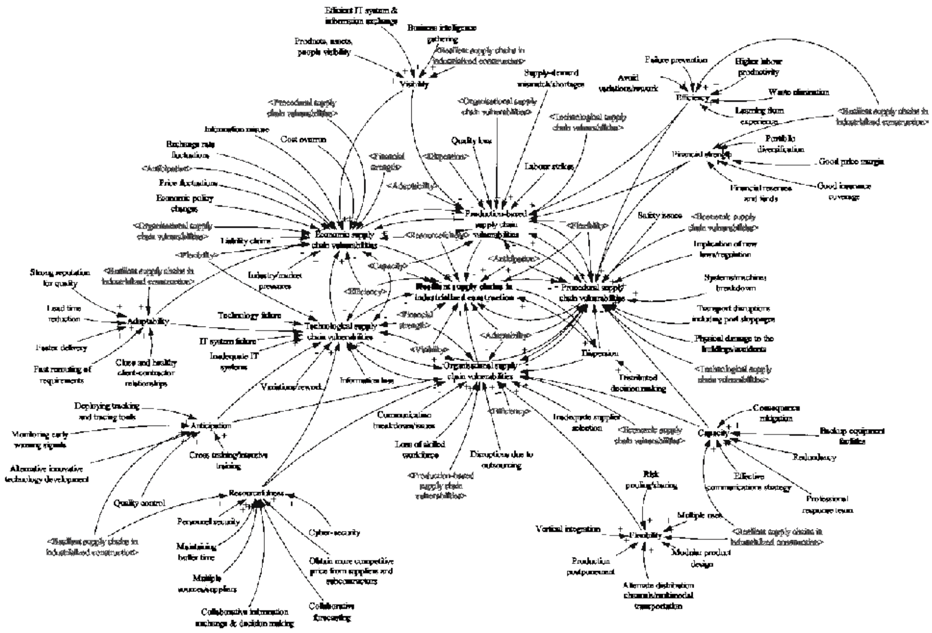

Efficient IT system & information exchange
Business intelligence gathering
Products, assets, people visibility
Visibility
<Procedural supply chain vulnerabilities>
Information misuse
Cost overrun
Exchange rate fluctuations
<Anticipation>
Price fluctuations
Economic policy changes
<Organisational supply chain vulnerabilities>
Liability claims
<Flexibility>
<Financial strength>
<Adaptability>
Economic supply chain vulnerabilities
Industry/market pressures
<Capacity>
<Efficiency>
Strong reputation for quality
Lead time reduction
Faster delivery
Fast remoulding of requirements
Close and healthy client-contractor relationships
Adaptability
Technology failure
IT system failure
Inadequate IT systems
Technological supply chain vulnerabilities
Variations/rework
Information loss
Deploying tracking and tracing tools
Monitoring early warning signals
Alternative innovative technology development
Anticipation
Cross training/intensive training
Quality control
Resourcefulness
Personnel security
Maintaining buffer time
Multiple sources/suppliers
Collaborative information exchange & decision making
Collaborative forecasting
Cyber-security
Obtain more competitive price from suppliers and subcontractors
Supply-demand mismatch/shortages
Quality loss
<Dispersion>
Labour strikes
<Technological supply chain vulnerabilities>
Production-based supply chain vulnerabilities
<Resourcefulness>
Resilient supply chains in industrialised construction
<Financial strength>
<Visibility>
Organisational supply chain vulnerabilities
Communication breakdown/issues
Loss of skilled workforce
Disruptions due to outsourcing
<Production-based supply chain vulnerabilities>
Failure prevention
Higher labour productivity
Avoid variations/rework
Efficiency
Waste elimination
Learning from experience
<Resilient supply chains in industrialised construction>
Financial strength
Portfolio diversification
Good price margin
Financial reserves and funds
Good insurance coverage
Safety issues
<Economic supply chain vulnerabilities>
Implication of new laws/regulation
Procedural supply chain vulnerabilities
Systems/machines breakdown
Transport disruptions including port stoppages
Physical damage to the buildings/accidents
Dispersion
Distributed decision making
Inadequate supplier selection
Capacity
Consequence mitigation
Backup equipment facilities
Redundancy
Effective communications strategy
Professional response team
Risk pooling/sharing
Multiple modes
Vertical integration
Flexibility
Modular product design
Production postponement
Alternate distribution channels/multimodal transportation

**Fig 8**

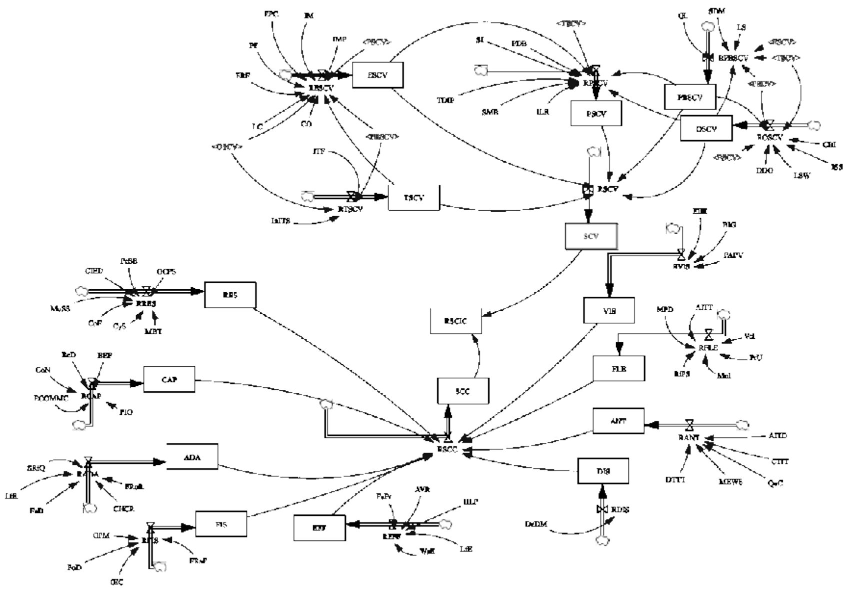


**Table 1:** Descriptive statistics of the determinants of supply chain resilience

| No | Code | Construct | Mean | N-Value | Score % for SNA | Rank |
|---|---|---|---|---|---|---|
| **1** | **SCV** | **Supply Chain Vulnerabilities** | | | | |
| 1.1 | ESCV | Economic SCV | 2.91 | 0.00 | 33.3 | 5 |
| 1.2 | TSCV | Technological SCV | 3.25 | 0.72 | 20.4 | 2 |
| 1.3 | PSCV | Procedural SCV | 3.23 | 0.67 | 22.2 | 3 |
| 1.4 | OSCV | Organizational SCV | 3.39 | 1.00 | 11.1 | 1 |
| 1.5 | PBSCV | Production-based SCV | 3.22 | 0.65 | 13.0 | 4 |
| **2** | **SCC** | **Supply Chain Capabilities** | | | | |
| 2.1 | RES | Resourcefulness | 4.05 | 0.07 | - | 8 |
| 2.2 | FLE | Flexibility | 4.10 | 0.40 | - | 4 |
| 2.3 | CAP | Capacity | 4.12 | 0.53 | - | 3 |
| 2.4 | ADA | Adaptability | 4.06 | 0.13 | - | 7 |
| 2.5 | EFF | Efficiency | 4.19 | 1.00 | - | 1 |
| 2.6 | FIS | Financial Strength | 4.18 | 0.93 | - | 2 |
| 2.7 | VIS | Visibility | 4.04 | 0.00 | - | 9 |
| 2.8 | ANT | Anticipation | 4.09 | 0.33 | - | 5 |
| 2.9 | DIS | Dispersion | 4.07 | 0.20 | - | 6 |
| **3** | | **Supply Chain Phases** | | | | |
| 3.1 | MAP | Manufacturing Phase | 4.12 | 0.41 | 37.5 | 2 |
| 3.2 | LOP | Logistics Phase | 3.87 | 0.00 | 21.4 | 3 |
| 3.3 | OAP | On-site Assembly Phase | 4.48 | 1.00 | 41.1 | 1 |

*Note: N-Value– Normalized values of construct means; SNA-Social Network Aanalysis*

**Table 2:** Descriptions of the model variables

| Variable Name and Abbreviation | Variable Name and Abbreviation |
|---|---|

| | | | |
|---|---|---|---|
| Resourcefulness | RES | Economic SCV | ESCV |
| Personnel security | PeSe | Exchange rate fluctuations | ERF |
| Collaborative information exchange & decision making | CIED | Price fluctuations | PF |
| Collaborative forecasting | CoF | Liability claims | LC |
| Cyber-security | CyS | Cost overrun | CO |
| Obtain more competitive price from suppliers and subcontractors | OCPS | Industry/market pressures | IMP |
| Multiple sources/suppliers | MuSS | Information misuse | IM |
| Maintaining buffer time | MBT | Economic policy changes | EPC |
| Flexibility | FLE | Technological SCV | TSCV |
| Vertical integration | VeI | Technology failure | TF |
| Production postponement | PrU | IT system failure | ITF |
| Alternate distribution channels/multimodal transportation | AlTT | Inadequate IT systems | InITS |
| Modular product design | MPD | Information loss | IL |
| Multiple uses | MuI | Variations/rework | VR |
| Risk pooling/sharing | RiPS | Procedural SCV | PSCV |
| Capacity | CAP | Safety issues | SI |
| Back-up equipment facilities | BEF | Implication of new laws/regulation | ILR |
| Redundancy | ReD | Systems/machines breakdown | SMB |
| Consequence mitigation | CoN | Transport disruptions including port stoppages | TDIP |
| Effective communications strategy | ECOMMC | Physical damage to the buildings/accidents | PDB |
| Professional response team | PIO | Organisational SCV | OSCV |
| Adaptability | ADA | Communication breakdown/issues | CBI |
| Strong reputation for quality | SRfQ | Loss of skilled workforce | LSW |
| Lead time reduction | LtR | Disruptions due to outsourcing | DDO |
| Faster delivery | FaD | Inadequate supplier selection | ISS |
| Close and healthy client-contractor relationships | CHCR | Production-based SCV | PBSCV |
| Fast rerouting of requirements | FRoR | Quality loss | QL |
| Efficiency | EFF | Supply-demand mismatch/shortages | SDM |
| Failure prevention | FaPr | Labour strikes | LS |
| Avoid variations/rework | AVR | Resilient supply chains in IC | RSCIC |
| Higher labour productivity | HLP | Financial Strength | FIS |
| Waste elimination | WaE | Good price margin | GPM |
| Learning from experience | LfE | Portfolio diversification | PoD |
| Visibility | VIS | Financial reserves and funds | FRaF |
| Efficient IT system & information exchange | EIiE | Good insurance coverage | GIC |
| Business intelligence gathering | BIG | Anticipation | ANT |
| Products, assets, people visibility | PAPV | Deploying tracking and tracing tools | DTTT |
| Dispersion | DIS | Monitoring early warning signals | MEWS |
| Distributed decision making | DeDM | Alternative innovative technology development | AITD |
| Cross training/intensive training | CTIT | Quality control | QuC |

**Table 3:** Details of the selected cases

| **Features** | **Description** | |
|---|---|---|
| | **Case A** | **Case B** |
| Project Type | New built public housing | New built public housing |
| Usage | Subsidized sale flats | Subsidized sale flats |
| Project duration | 24 months | 26 months |
| Scope of construction | 36 floors with amenities | 37 stories with amenities |
| Location | Tiu Keng Leng | Queen's hill |