MODELING SUPPLY CHAIN RESILIENCE IN INDUSTRIALIZED CONSTRUCTION IN HONG KONG

EKANAYAKE MUDIYANSELAGE ANUSHIKA CHATHURANGI EKANAYAKE

PhD

The Hong Kong Polytechnic University

2022

The Hong Kong Polytechnic University

Department of Building and Real Estate

Modeling Supply Chain Resilience in Industrialized Construction in Hong Kong

Ekanayake Mudiyanselage Anushika Chathurangi Ekanayake

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

June 2021

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

Signature ____________________

Name of Student Ekanayake Mudiyanselage Anushika C E

Abstract

A highly volatile and interconnected global market, the ever-changing demands of clients and fierce competition amongst major suppliers necessitate a strategic shift towards a modern supply chain management strategy that prioritizes Supply Chain Resilience (SCR). This is because organizational supply chains are increasingly fragile; hence, more susceptible to unforeseen crises, as vividly demonstrated by catastrophic disruptions to global supply chains by COVID-19 as this thesis is being compiled. Organizations face disruptions even under normal conditions. All these disruptions endanger an organization's ability to perform effectively. Moreover, the growing complexity of the global supply chains and their increased vulnerability to disruptions have threatened the long-term success and survival of organizations and sometimes their parent industries too.

In response, SCR enables organizations to respond effectively during disruptions with the swift and stable restoration of supply chains following disruptions. Besides, resilient supply chains are less vulnerable to disruptions and are also more capable of handling any vulnerabilities that do trigger problems. Focusing on the construction industry in Hong Kong, construction supply chains have weathered various disruptions over the years. Further, the construction industry is unique, and the supply chain configurations of most construction projects are distinctive. Although Industrialized Construction (IC) practices in Hong Kong have introduced innovations through safe, clean and efficient construction methods for the construction industry, IC supply chains are still drastically affected by the inherent supply chain disruptions. Since IC is developed by incorporating advances in offsite manufacturing practices, IC supply chains are more complicated than in traditional construction and IC straddles the supply chain phases of manufacturing-factory, logistics and onsite assembly. Especially in Hong Kong, all the prefabricated units are transported from Mainland China. Hence, the supply chains are

widely affected by transportation and cross border logistics-related vulnerabilities compared to the other countries.

In this regard, SCR prioritization can be introduced as a game-changing supply chain management strategy, which by directing addressing specific resilience issues, should surpass or out-perform traditional risk management practices by opening up robust pathways to withstanding important Supply Chain Vulnerabilities (SCV) of IC in Hong Kong. Further, it is crucial for IC organizations to build more resilient supply chains through enhanced Supply Chain Capabilities (SCC) to effectively respond to escalating threats since the construction industry is a key economic driver. Moreover, supply chain networks vary according to their geographical context in different ways that can shape their types and levels of vulnerability. Recent Government initiatives for increasing IC in Hong Kong accentuated the need for a focused study to investigate: (a) IC supply chain behavior, strengths and weaknesses in Hong Kong and (b) how to enhance the resilience capabilities of IC supply chains to address the current performance conundrum faced by the Hong Kong industry. These foregoing needs, taken together, establish the imperative for enhancing SCR practice in IC in Hong Kong, although not yet even explored in the international IC literature to which these research outcomes would also, therefore, contribute.

Given this background and rapidly changing conditions, this study aimed to develop and propose strategies to enhance supply chain resilience in IC through developing a dynamic model to assess SCR in IC in Hong Kong. Further, four research objectives were established to achieve the research aim as (i) to identify supply chain vulnerabilities and capabilities as critical measures of supply chain resilience in industrialized construction, (ii) to develop mathematical models to assess supply chain vulnerabilities, supply chain capabilities and their correlational impacts, (iii) to develop a dynamic SCR evaluation model for IC in Hong Kong via probing and assessing relevant supply chain vulnerabilities and capabilities, and (iv) to propose strategies to enhance supply chain resilience in IC in Hong Kong.

To achieve research Objective 1, this study first conducted two comprehensive and systematic literature reviews on SCC and SCV targeting SCR in IC. These reviews enabled the identification of 37 vulnerabilities and 58 capability measurement items in the IC context. A questionnaire was developed to further probe these identified SCV and SCC, and thereby, to achieve Objective 2. In addition, semi-structured interviews, frequent site visits to the construction sites and document reviews were conducted to gather additional related data. Subsequent factor analysis facilitated the grouping of the identified SCV under five underlying categories and SCC measurement items under nine capability components. Twenty-four SCV and forty-one supply chain capability measurement items that remained after the factor analysis were regarded as critical measures in realizing SCR in IC in Hong Kong. This study next proceeded with developing mathematical models to assess SCV and SCC separately as specific to the IC in Hong Kong using fuzzy synthetic evaluation. Besides, the correlational impacts of SCV and SCC were modeled using the partial least squares structural equation modeling to explore their interactions under the phenomena of SCR. These models are the first known mathematical evaluation models developed for assessing SCR in the construction industry.

Following these foregoing outcomes, a dynamic model to assess SCR in IC in Hong Kong was developed with the use of the system dynamics modeling technique. It is the first known system dynamics model in the relevant literature on this topic. Having thereby realized study Objective 3, the vulnerability levels of each supply chain phase were modeled and evaluated by applying social network analysis technique. This is the first known initiative to apply this social network analysis technique to assess the dynamics of IC supply chains in the pursuit of resilience. The developed system dynamics model for achieving SCR in IC was further verified and analyzed

using two-comparative case studies, after which useful strategies to boost SCR in IC in Hong Kong were proposed as the key research outcomes of this significant study, thereby achieving research Objective 4 and fulfilling the overall research aim.

Moreover, this study contributed to improving IC practices not only by initiating SCR assessment models but also by proposing useful strategies for the effective uptake of SCR practices in Hong Kong. In addition to this contribution to practice, supply chain management and related theories were enriched by unveiling how the several research methods deployed in this study, such as fuzzy synthetic evaluation, partial least squares-structural equation modeling, system dynamics modeling, and the social network analysis, could be effectively applied to analyze SCR imperatives in the construction research domain. These key research contributions would inform both industry practitioners and researchers on how to deploy and improve SCR in IC practices in Hong Kong, thereby also helping to address the acute disruptions as well as the general performance conundrums debilitating the industry. Finally, these synergistic theory-practice thrusts could help develop resilient and sustainable construction supply chains in IC processes, which could, in turn, drive value-enhanced performance in IC in Hong Kong.

Keywords: Industrialized Construction; Supply Chain Resilience; Supply Chain Vulnerabilities; Supply Chain Capabilities; Fuzzy Synthetic Evaluation, Partial Least Squares Structural Equation Modeling (PLS-SEM); System Dynamic Modeling; Social Network Analysis; Hong Kong.

Publications

Refereed Journal Papers – directly from this research

1. **Ekanayake, E.M.A.C.**, Shen, G.Q., Kumaraswamy, M.M., Owusu, E.K. and Abdullahi, S., 2021. Modelling Supply Chain Resilience in Industrialized Construction: A Hong Kong Case. *ASCE Journal of Construction Engineering and Management*. 147(11). 10.1061/(ASCE)CO.1943-7862.0002188.
2. **Ekanayake, E.M.A.C.,** Shen, G.Q., and Kumaraswamy, M.M., 2021. A Fuzzy Synthetic Evaluation of Capabilities for Improving Supply Chain Resilience of Industrialized Construction: A Hong Kong Case Study. *Production Planning & Control.* DOI: 10.1080/09537287.2021.1946330.
3. **Ekanayake, E.M.A.C**., Shen, G. and Kumaraswamy, M.M., 2021. Identifying supply chain capabilities of construction firms in industrialized construction. *Production Planning & Control*, 32(4), 303-321, DOI: 10.1080/09537287.2020.1732494.
4. **Ekanayake, E.M.A.C.,** Shen, G.Q., Kumaraswamy, M.M., Owusu, E.K. and Xue, J., 2021. Capabilities to Withstand Vulnerabilities and Boost Resilience in Industrialized Construction Supply Chains: A Hong Kong Study. *Engineering, Construction and Architectural Management.* DOI: 10.1108/ECAM-05-2021-0399.
5. **Ekanayake, E.M.A.C.,** Shen, G.Q., Kumaraswamy, M.M. and Owusu, E.K., 2021. A Fuzzy Synthetic Evaluation of Vulnerabilities Affecting Supply Chain Resilience of Industrialized Construction in Hong Kong. *Engineering, Construction and Architectural Management*. DOI 10.1108/ECAM-12-2020-1010.
6. **Ekanayake, E.M.A.C.,** Shen, G. and Kumaraswamy, M.M. 2021. Supply Chain Resilience: Mapping the Knowledge Domains through a Bibliometric Approach. *Built Environment Project and Asset Management Journal*, DOI 10.1108/BEPAM-03-2020-0040.
7. **Ekanayake, E.M.A.C.,** Shen, G.Q., and Kumaraswamy, M.M., 2020. 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.
8. **Ekanayake, E.M.A.C.,** Shen, G.Q., Kumaraswamy, M.M. and Owusu, E.K., 2020. 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.

9. **Ekanayake, E.M.A.C**., Shen, G.Q., Kumaraswamy, M.M. and Owusu, E.K., 2020. Identifying supply chain vulnerabilities in industrialized construction: an overview. *International Journal of Construction Management*, pp.1-14. DOI:10.1080/15623599.2020.1728487.
10. **Ekanayake, E.M.A.C.,** Shen, G. and Kumaraswamy, M. 2019. "Mapping the knowledge domains of value management: a bibliometric approach", *Engineering, Construction and Architectural Management*, 26(3), pp. 499-514. https://doi.org/10.1108/ECAM-06-2018-0252.

Refereed Journal Papers – from other projects during my PhD

11. Xin, J., Shen, G.Q., and **Ekanayake, E.M.A.C**., 2021. Improving Construction Industrialization Practices from a Socio-Technical System Perspective: A Hong Kong Case. *International Journal of Environmental Research and Public Health*. 18, 9017. https://doi.org/10.3390/ijerph18179017.
12. Xue, J., Shen, G.Q., Yang, R.J., Zafar, I. and **Ekanayake, E.M.A.C**., 2020. Dynamic Network Analysis of Stakeholder Conflicts in Megaprojects: Sixteen-Year Case of Hong Kong-Zhuhai-Macao Bridge. *ASCE Journal of Construction Engineering and Management*, 146(9), p.04020103(1-16).
13. Sirimewan, D.C., Samaraweera, A., Manjula, N.H.C. and **Ekanayake, E.M.A.C.**, 2020. A guideline for sustainable irrigation water management: a case of a developing country. *Intelligent Buildings International,* 13(2), pp.129-141. DOI: 10.1080/17508975.2020.1809982.
14. Xue, J., Shen, G.Q., Yang, R.J., Zafar, I., **Ekanayake, E.M.A.C**., Lin, X. and Darko, A., 2020. Influence of formal and informal stakeholder relationship on megaproject performance: a case of China. *Engineering, Construction and Architectural Management*. 27(7), 1505-1531, DOI: 10.1108/ECAM-07-2019-0353.
15. Zafar, I., Shen, G.Q., Zahoor, H., Xue, J. and **Ekanayake, E.M.A.C.,** 2019. Dynamic Stakeholder Salience Mapping Framework for Highway Route Alignment Decisions: China Pakistan Economic Corridor as a Case Study. *Canadian Journal of Civil Engineering*. 47(11), 1297-1309.
16. Xin, J., **Ekanayake, E.M.A.C.,** and Shen, G.Q., 2021. Critical Policy Drivers in Modular integrated Construction Projects in Hong Kong. *Building Research and Information*. (Accepted for publication).
17. Sirimewan, D.C., Samaraweera, A., Manjula, N.H.C., Rameezdeen, R., Rodrigo, M.N.N., and **Ekanayake, E.M.A.C.**, 2021. Application of socio-technical systems theory for sustainable water management of irrigation systems, *Engineering, Construction and Architectural Management*. (Under Review).

18. Xue, J., **Ekanayake, E.M.A.C.**, and Shen, G.Q., 2021. Stakeholder resilience modeling of relationship management in megaprojects: the case of Hong Kong – Zhuhai – Macao Bridge. *International Journal of Project Management*. (Under Review).

Conference Publications – directly from this research

1. **Ekanayake, E M A C**., Xue, J, Shen, G Q and Kumaraswamy, M M (2021) Dynamic Supply Chain Vulnerability Analysis of Hong Kong-Zhuhai-Macao Bridge Construction: A Topic Modelling Approach In: Scott, L and Neilson, C J (Eds) Proceedings of the *37th Annual ARCOM Conference*, 6-7 September 2021, UK, Association of Researchers in Construction Management, pp. 491-500.
2. **Ekanayake, E. M. A. C.,** Xue, J., Shen, G. Q. P. and Kumaraswamy, M. 2021. Dynamic supply chain capability analysis of Hong Kong-Zhuhai-Macao bridge construction: A topic modeling approach. In: Sandanayake, Y.G., Gunatilake, S. and Waidyasekara, K.G.A.S. (eds). Proceedings of the *9th World Construction Symposium*, 9-10 July 2021, Sri Lanka. [Online]. pp. 268-279. DOI: https://doi.org/10.31705/WCS.2021.23. Available from: https://ciobwcs.com/papers/.
3. **Ekanayake, E. M. A. C.,** Shen, G. Q. P. and Kumaraswamy, M. 2020. Resilient Supply Chains in Industrialized Construction: A Hong Kong Case Study. In proceedings of the *CRC2020 Conference.* 08-10 March 2020 at Arizona State University, Tempe, Arizona. The USA.
4. **Ekanayake, E. M. A. C.,** Shen, G. Q. P. and Kumaraswamy, M. 2019. Managing Vulnerabilities and Capabilities for Supply Chain Resilience in Industrialized Construction. In proceedings of the *ARCOM2019 Conference*. 02-04 September 2019 at Leeds Beckett University, Leeds, United Kingdom. pp.811-820.

Research Seminars Conducted

1. Conducted a research seminar on '**Modelling Supply Chain Resilience in Industrialized Construction: A Hong Kong Case**' at The Hong Kong Polytechnic university on 06th May 2021 from 12.30 PM to 2.00 PM. The seminar was organized by the Department of Building and Real Estate, Faculty of Construction and Environment, The Hong Kong Polytechnic University.

2. Conducted a research seminar on '**Sri Lankan Construction Industry and the Supply Chain Resilience**' at The Hong Kong Polytechnic university on 26th Feb 2019 from 6.30 PM to 8.30

PM. The seminar was organized by the Professional Services Advancement Support Scheme of The Hong Kong Polytechnic University together with Hong Kong Construction Association.

3. Conducted a research seminar on '**Probing the Future Prospects of Construction Industry in Sri Lanka under the Belt and Road Initiative**' at The Hong Kong Polytechnic university (online) on 02nd April 2020 from 6.30 PM to 8.30 PM. The seminar was organized by the Professional Services Advancement Support Scheme of The Hong Kong Polytechnic University together with Hong Kong Construction Association.

Honors and Awards

1. The Emerald Prize for the Best Theoretical or Methodological Paper was awarded for paper titled as "Dynamic Supply Chain Vulnerability Analysis of Hong Kong-Zhuhai-Macao Bridge Construction: A Topic Modelling Approach" at the 37th Annual ARCOM Conference.
2. Emerald Built Environment Project and Asset Management (BEPAM) Highly Commended Paper Award for paper titled as "Dynamic Supply Chain Capability Analysis of Hong Kong-Zhuhai-Macao Bridge Construction: A Topic Modelling Approach".
3. The HK$ 70,000 (Highest) Award from the 'Award and Funding Scheme for Recognizing the Research Outputs of Current Hong Kong PhD Fellowship (HKPFS) Students with good performance'.
4. 3rd place in 3 Minute Presentation Competition of 17th Academic Conference for Post-Graduate Students in Construction Management and Real Estate, jointly organized by The University of Hong Kong (HKU), The Hong Kong Polytechnic University (PolyU) and Shenzhen University (SZU).

Acknowledgements

The past four-year PhD study in the Department of Building and Real Estate, The Hong Kong Polytechnic University is a memorable academic journey in my life. There are many people behind the success of this journey who are gratefully remembered. Here, I would like to extend my sincere appreciation to all of them.

I am most grateful to the Research Grants Council and The Hong Kong Polytechnic University for offering me the precious PhD fellowship award and fully funding this research. My sincerest gratitude goes to my chief supervisor, Prof. Geoffrey Qiping Shen, who accepted me as a PhD student and provided continual and noble guidance through the whole research process. I must appreciate his patience, understanding and encouragement, which guided me to conduct research independently. He is always a motivating supervisor with leadership that allowed me to learn from him, even multi-tasking in my life. Therefore, I will forever be grateful to him. Also, I am indebted to my co-supervisor, Prof. Mohan M. Kumaraswamy, who first introduced me to Prof. Shen. Prof. Kumaraswamy also believed in me right from the start of this project and had guided me through every step. I know that I cannot thank him enough for all that he has done and the value that he added to my life. Therefore, I will forever be grateful to him, as well.

Next, my heartfelt gratitude goes to the Department of Building and Real Estate for providing financial support and equipment that were necessary to facilitate me to complete my research study. Also, thanks a lot, my dear colleagues, Kingsford, Emily, Irfan, Lizi, Verna, Amos, Emma, Jin, Shell, Jason, Boyu, Saka, and all my other colleagues as I would not complete my research smoothly without your great support. Further, I am also grateful to all the professionals who helped me during my research data collection in Hong Kong. My special thank goes to all the Sri Lankan friends in Hong Kong and all my friends around the world who were there for me throughout this roller-coaster journey.

Moreover, I want to extend my heartfelt gratitude to my late mother, father, brother and sister for their care, unconditional love and utmost encouragement. Last but not least, my love goes to my dear husband for sharing all my happiness and bearing all my sadness and offering me great freedom while motivating me to pursue my dream.

Table of Contents

List of Figures

List of Tables

Abbreviations

ADA	-	Adaptability
ANT	-	Anticipation
BIM	-	Building Information Modeling
RFID	-	Radio Frequency Identification
CA	-	Content Analysis
CAP	-	Capacity
CI	-	Capability Importance
COV	-	Coefficient of Variation
CS	-	Case Study
CSCC	-	Critical Supply Chain Capabilities
CSCV	-	Critical Supply Chain Vulnerabilities
CV	-	Vulnerability Component
DIS	-	Dispersion
EFF	-	Efficiency
EI	-	Expert Interviews
ESCV	-	Economic Supply Chain Vulnerabilities
FA	-	Factor Analysis
FIS	-	Financial Strength
FIV	-	Financial Vulnerabilities
FLE	-	Flexibility
FSE	-	Fuzzy Synthetic Evaluation
GIS	-	Geo Information Systems
HK	-	Hong Kong
IC	-	Industrialized Construction
IT	-	Information Technology
KMO	-	Kaiser-Meyer-Olkin test
LR	-	Literature Review
MF	-	Membership Function
MiC	-	Modular Integrated Construction
MS	-	Mean Score
OI	-	Overall Impact

OSCV	-	Organizational Supply Chain Vulnerabilities
PBSCV	-	Production-based Supply Chain Vulnerabilities
PLS-SEM	-	Partial Least Squares Structural Equation Modeling
POV	-	Project Organizational Vulnerabilities
PPVC	-	Pre-engineered Prefinished Volumetric Construction
PRV	-	Procedural Vulnerabilities
PSCV	-	Procedural Supply Chain Vulnerabilities
QS	-	Questionnaire Survey
RES	-	Resourcefulness
RM	-	Risk Management
S/CV	-	Supplier/Customer Vulnerabilities
SCC	-	Supply Chain Capabilities
SCM	-	Supply Chain Management
SCR	-	Supply Chain Resilience
SCV	-	Supply Chain Vulnerabilities
SDM	-	System Dynamics Modeling
SEM	-	Structural Equation Modeling
SNA	-	Social Network Analysis
TA	-	Thematic Analysis
TEV	-	Technological Vulnerabilities
TSCV	-	Technological Supply Chain Vulnerabilities
VIS	-	Visibility
WF	-	Weighting Function

Chapter 1 Introduction

1.1. Research Background

Organizations are presently experiencing and envisaging prolonged supply chain vulnerabilities, arising from COVID-19 (McKinsey Global Institute, 2020). The recent pandemic further reminds organizations of the need to rethink their plans and decision-making to survive these tumultuous vulnerabilities. Indeed, Supply Chain Vulnerabilities (SCV) can lead to major disruptions of normal supply chain operations (Zavala et al., 2019) and they can persist for prolonged periods while propagating to other supply chain tiers and links, in a ripple effect (Ivanov et al., 2018). Furthermore, due to extensive outsourcing, most supply chains are now vulnerable to weaknesses and complexities in their ancillary supply chains (McKinsey Global Institute, 2020). Therefore, the less the vertical integration of supply chains, the higher is the exposure to greater levels of disruptions, which are further fueled by social, economic and political disorders (Snyder & Shen, 2006).

In these circumstances, the attention of many leading economies worldwide, including in Hong Kong (HK) has been focused on strategies and methodologies to reduce the vulnerability levels of supply chains, while also safeguarding its supply chains from exploitation (Cedillo-Campos et al., 2014). The construction industry is one of the most significant drivers of the global economy (Ahmad et al., 2020). Also, this industry is well recognized for its significant contribution to the built-environment, generating massive employment opportunities and economic growth (Bao et al., 2020). Hence, the construction industry is reputed to be an engine of growth for economies in general, including of HK whose gross domestic product was of USD 366 billion in 2019 and a 4.5% contribution was from the construction sector (Trading Economics, 2020). The proportional contributions of the construction industry are usually even higher for developing countries and have been recognized for decades. Given the pivotal role of the construction industry, Governments have also periodically appointed high-powered Committees to recommend industry reforms to improve construction industry performance in many jurisdictions including for example, in the UK, Singapore and HK around the turn of this century (C21, 1999; CIRC, 2001; Egan, 1998). However, due to persisting poor safety performance, delays and cost overruns, the industry continues to seek innovative solutions to enhance industry performance in many jurisdictions including HK (CICID, 2011; Wang et al., 2019).

In one major response, Industrialized Construction (IC) proliferated worldwide (Goodier et al., 2019), enabling better quality, improved safety and reliability in the construction process (Wang et al., 2019). While shifting the emphasis to factory production of construction components, IC also covers the streamlining of processes and products from offsite fabrication (Gibb, 1999). The increased use of offsite manufacturing furthers the industrialization of the construction process (Rwamamara, 2007). Also, the intensity and nature of production activities are changing with industrialization since it facilitates more cost-effective methods and more efficient methods such as offsite prefabrication and onsite assembly. While IC with offsite fabrication may be traced back to mass multi-storey precast housing after World War II, its recent resurgence has emerged with an increase in the proportion and complexity of components that are prefabricated offsite (Luo et al., 2019) with recent demands for pre-engineered components, e.g. toilets with building services installed and more recent demands for more complete modules, e.g. for fitted out rooms.

Different countries, e.g., India (Arif et al., 2012); UK (Gibb & Isack, 2003); and Australia (Arif et al., 2009) provide evidence that justifies the above statements; as well as highlight the potential to achieve product consistency under a controlled factory environment as opposed to the uncertain conditions of a conventional construction site. Findings of Johnsson and Meiling

(2009) further demonstrate the benefit of improved quality in their study, whereas Jonsson and Rudberg (2014) explain the adaptability of improved quality control and higher quality finishes. Also, Wikberg et al. (2014) explain the possibility of proper design configuration in IC platforms, whereas Pan et al. (2007) highlights the reduction of maintenance cost as a significant benefit. Maintenance time and cost is reduced because of the possibility of easy upgrading, recycling (Ulrich, 2003) and replacement (Mikkola, 2006) since separated modules are used for subfunctions (Arnheiter & Harren, 2005). IC facilitates whole life benefits during the post-construction phase as well by providing innovative design solutions and flexibility in use and maintenance (Peltokorpi et al., 2018; Ulrich, 2003). The recent progression to Modular integrated Construction (MiC) enables off-site production and on-site assembly of volumetric units or modules with the advantages of reduced construction time, reduced labor usage, better quality, enhanced productivity and reduced exposure to external services with greater sustainability (Xu et al., 2020).

In this context, IC has been widely adopted in HK construction practice in general, targeting higher-quality, more productive, and safer construction process with less adverse impacts on the environment. Also, since HK is facing challenges such as an acute shortage of skilled labor, an ageing workforce, space constraints, and escalating costs, the government has encouraged IC (Zhai et al., 2019a). Space and logistics constraints are especially serious in HK being a particularly highly dense high-rise city. For instance, the HK Housing Authority has been using IC in their public housing projects for many decades, while the HK Housing Society has initiated using modular integrated construction in their subsidized sale flats to help address the housing problem more efficiently (Luo et al., 2019). Overall, IC is a game-changing and innovative approach that transforms cumbersome in-situ construction methods into a more integrated, value-driven production and assembly processes of mostly prefabricated components.

However, the potential benefits may not be fully exploited if its inherent weaknesses of fragmentation, discontinuity, and poor interoperability are not being mitigated. This would nurture a variety of risks that can adversely influence and compromise the performance of IC (Li et al., 2018a). Effective Supply Chain Management (SCM) is the key to the successful delivery of IC projects in this regard (Gann, 1996; Said, 2015). SCM facilitates control over the supply chain in the prefabrication and provides a sustainable competitive advantage (Chiang et al., 2006). However, SCM for prefabricated building projects is a complex task (Zhai et al., 2015). As defined by Xue et al. (2007), the construction supply chain is a network of many organizations and relationships connected by information flow, materials, services or product flow, and fund flow between stakeholders. In the IC supply chains, the client, the main contractor, designer, manufacturer, transporter, and assembly sub-contractors frequently interact in the multiple flows throughout the design, manufacturing, transportation, and assembly processes. Therefore, proper integration among stakeholders to ensure close coordination in maintaining labor, materials, and equipment is required (Čuš-Babič et al., 2014) and consequently add considerable difficulties to the supply chain. According to the findings of Koskela (2003), SCM in IC is complex since (i) a longer chain caused by two production environments, namely, factory and site; (ii) larger amounts of design work and earlier design for cast-in-situ construction because of the prefabrication lead time; (iii) longer error correction period; and (iv) higher requirements for dimensional accuracy.

There are three main phases in the IC supply chain, namely prefabrication factory, logistics and the final construction site (Zhai et al., 2015). Uncertainties of the construction arising from the processes involved in these supply chain phases include machine breakdown, material shortages in the production process, traffic jam and low efficiency of customs clearance in the shipping process, and prefabricated component damage in the assembling process. These uncertainties clear the path for time and cost overrun in construction projects (Zhai et al., 2015).

In fact, supply chains are complex networks that involve continual turbulence, creating a potential for unpredictable disruptions (Pettit et al., 2010). Therefore, supply chain disruptions can be identified as the major threats to the organizations. Effective management of those disruptions will be critical for ensuring timely project delivery in IC (Li et al., 2018a). Although the industry utilizes traditional risk management techniques to manage these inherent disruptions, they are lacking in their ability to assess the complexities of supply chains, evaluate the intricate interdependencies of threats, and prepare an enterprise to face future unknowns (Hertz & Thomas, 1983; Starr et al., 2003).

Under these circumstances many researchers tend to understand the value of the concept of resilience; "the capacity for an enterprise to survive, adapt, and grow in the face of turbulent change" (Fiksel, 2003, 2006). The concept of resilience utilizes strategies that do not require exact quantification, a complete enumeration of possibilities, or assumptions of a representative future compared to conventional risk analysis (Pettit et al., 2010). In addition, resilience imperatives call for supply chains to be less brittle and more adaptive to change through: (a) better supply chain design, (b) focus on business process management to enhance capabilities across the supply chain, (c) visibility of demand and supply throughout the supply chain, (d) supplier and customer relationship management and (e) infusing a culture of resilience (Murphy, 2006).

1.2. Problem Statement

IC, as a modern construction technology, surpasses and can eventually supersede conventional cast-in-situ concrete construction, and has attracted immense attention from many countries over the past two decades (Li et al., 2018a) due to the significant benefits gained from enhanced economies of scale (Han et al., 2017). The inherent superiority of technology can largely explain this widespread interest. For instance, HK also began to introduce prefabrication along with standard modular designs in public housing projects since IC is allied with benefits such as better onsite construction environment as a result of reduced dust, noise, and construction waste (Tam et al., 2015).

Despite the potential merits of adopting prefabrication, weaknesses such as fragmentation, discontinuity, and lack of interoperability are still obvious and exacerbated in the IC supply chains (Li et al., 2016). These weaknesses, in turn, arise from and foster numerous vulnerabilities that have been shown to adversely influence the performance of IC supply chains. Clearly, the vulnerabilities in IC supply chains would necessarily be more in number and deeper in impact than in traditional construction supply chains where more work is on-site. For instance, since the components for HK are manufactured far from the site, usually, in Mainland China, the risks of disruptions and/or damages in production and transport are necessarily higher than they had been produced onsite, or even closer to site and in the same jurisdiction. Such geographically (more) dispersed and complex IC supply chains may generate continual turbulence and trigger unpredictable disruptions, causing significant threats to project implementation. Hence, effective management of Supply Chain Vulnerabilities (SCV) is critical for ensuring timely project delivery in IC (Li et al., 2018a).

Many studies have investigated the risk-related issues, so as to address and better manage such problems in IC supply chains (Li et al., 2018a). However, conventional risk management approaches are designed to deal with disruptions or managing crises, where the predominant approach to risk management requires risk identification and quantification, which is not always possible in the absence of empirical data and; hence, demands Supply Chain Resilience (SCR) (Pettit et al., 2013). Further, available methods for mitigating disruptions in IC supply chains are inadequate to deal with some characteristics of the industry. For instance, prefabricated products are not common; hence often unique; they cannot be produced in advance, transshipped and dual sourced and the IC supply chain is relatively fixed and unchangeable once scheduled (Zhai et al., 2015). During the past few years, awareness has been raised among both academics and industry practitioners on the need to minimize the potentially devastating effects of disruptions by constructing more resilient supply chains (Tukamuhabwa et al., 2015) since the concept presupposes that it can quickly recover from a disruptive event, either returning to normality or progressing to an even better state of operational performance (Mandal, 2012).

Further, rapidly increasing expectations from IC in HK have highlighted risks from potential SCV, thereby opening a hitherto neglected research area of achieving resilient supply chains in IC. On the other hand, there is a lack of research in construction supply chain resilience (Zainal & Ingirige, 2018) in general. As an emerging research area, the research gap is highly significant in IC in particular, while it is essential to explore SCR in IC due to the following reasons; (a) IC supply chains are complex and associated with inherent disruptions (Zhai & Huang, 2017), (b) they are also vulnerable to many unforeseeable disruptions (Luo et al., 2019); (c) IC supply chains are relatively fixed and unchangeable once scheduled (Zhai et al., 2017) hence the disruptions may be amplified by the ensuing cascading impacts; and (d) although the industry practises traditional risk management approaches, they are unable to assess the supply chain complexities and prepare supply chains for future unknowns including black swan events. Such resilience targets become viable if deploying adequate, appropriate Supply Chain Capabilities (SCC) (Pettit et al., 2019). In addition, supply chain networks vary according to their geographical context in different ways that can shape their types and levels of vulnerability; hence there is a need for a specific and dedicated study to investigate IC supply chain behavior in HK. Also, it is important to clear pathways to enhance the resilience capability of IC supply chains to address the current performance conundrum faced by the industry in general. The preceding reasons underpin the rationale and imperative for this study.

Thus, the main thrust of this study is to rigorously develop, carefully formulate and propose strategies to enhance SCR in IC through developing a dynamic model to assess SCR in IC in HK so as to realize the potential benefits.

1.3. Aim & Objectives

The aim of the research is to develop and propose strategies to enhance supply chain resilience in IC through developing a dynamic model to assess SCR in IC in Hong Kong. The following objectives guided the pathway towards attaining the above-stated aim.

1. Identify the supply chain vulnerabilities and capabilities as critical measures of supply chain resilience in industrialized construction
2. Develop mathematical models to assess supply chain vulnerabilities, supply chain capabilities and their correlational impacts
3. Develop a dynamic SCR evaluation model for industrialized construction in Hong Kong via probing and assessing relevant supply chain vulnerabilities and capabilities
4. Propose strategies to enhance supply chain resilience in industrialized construction in Hong Kong

1.4. Research Focus

In a theoretical setting, this research focuses on developing and proposing strategies to enhance supply chain resilience in IC in HK through dynamic analysis of supply chain vulnerabilities and supply chain capabilities. Therefore, as explicated further in succeeding chapters, two systematic and comprehensive literature reviews through meta-analysis were conducted to identify supply chain vulnerabilities and capabilities as appropriate to the context of IC. Thereby, critical supply chain vulnerabilities which affect the normal supply chain process were determined, and highly influential capabilities were also identified within the context of IC practices in HK. By standing on these suppositions, two comparative case studies from HK were used to verify the developed dynamic SCR model. Hence, the research findings are specific to the jurisdiction of HK and the IC sector.

1.5. Research Design

Sound research design leads to a logical blueprint which can be explicit or implicit (Yin, 2017). Besides, it provides a plan for moving from the research problem to a conclusion (Tan, 2002). The plan should address the specific tasks to be conducted, who, how and when they can be completed in order to achieve success in the research process (Polonsky & Waller, 2018). Figure 1.1 depicts the research design and research framework of the study. The research framework consists of five phases; namely, preliminary study, primary phase, secondary phase, advanced phase and the closing phase, which establishes the research process, and each phase is further explained as follows. Besides, the research approach employed in this study is discussed in detail in Chapter 2.

1.5.1. Preliminary Study

At the beginning of this study, an exploratory, in-depth review of the literature on the knowledge domain was conducted to identify the existing knowledge base, research gap, and the trend of the research. This proceeded with developing research aim as well as the research objectives. Informal discussions were made with the academics, some industry experts and the peers to refine the research objectives in a more reasonable and achievable manner. Also, in this stage, the research methodology, which is to be adopted in the study, was drafted. The research outcome of this phase that is the research aim, objectives and the methodology were supportive in stepping to the next phase of the study.

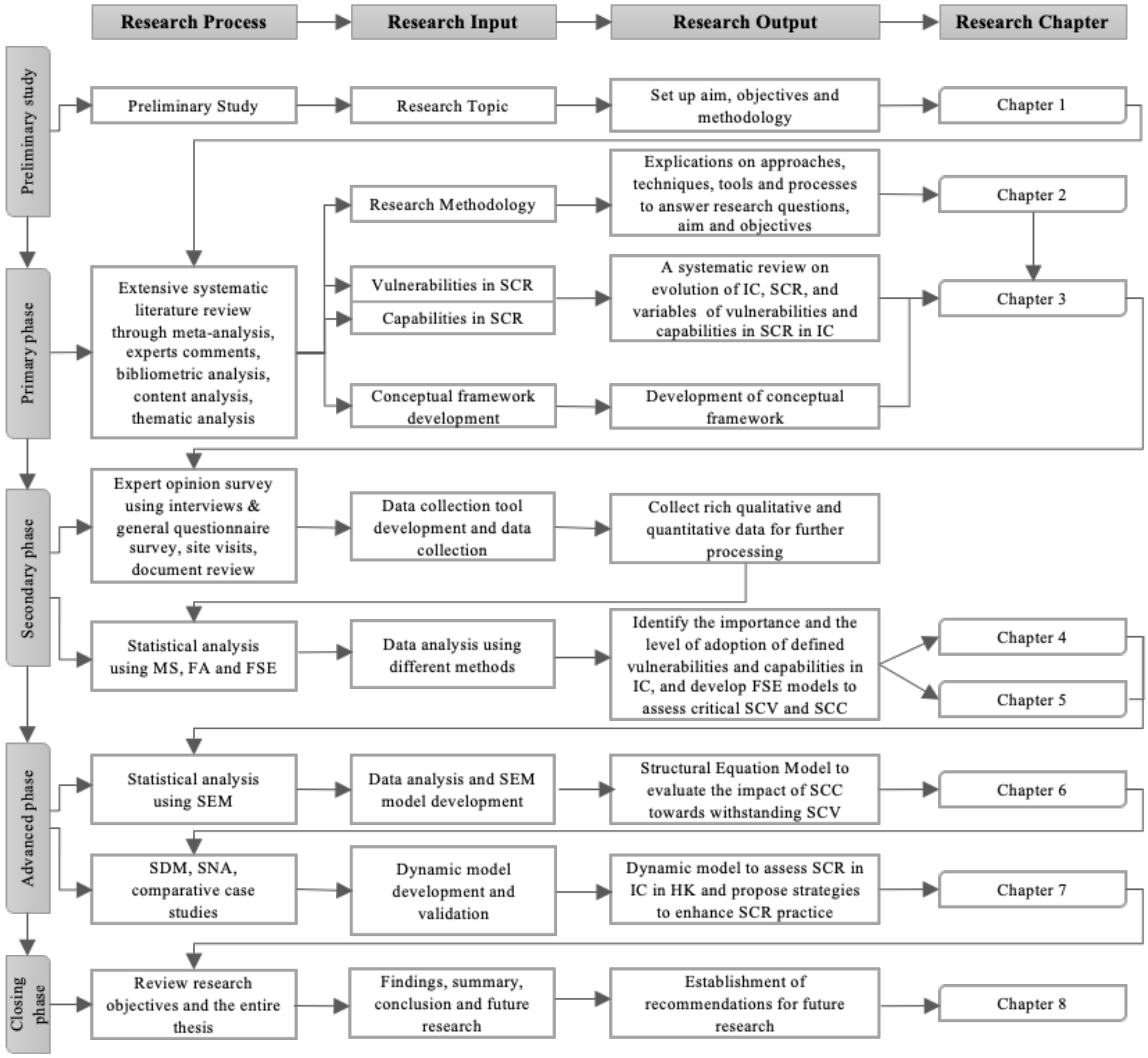


Figure 1.1: Research framework of the study

1.5.2. Primary Phase

During the primary phase, extensive systematic literature reviews through meta-analysis were conducted to identify SCV and SCC as the measures of SCR in IC. Further, content analysis and thematic analysis were applied throughout the literature reviews to develop the constructs of vulnerabilities and capabilities of SCR in IC. Past and current trends and evolutionary patterns of SCR in construction industry succeeding IC were examined further under this phase. Analytic considerations were included in relevant literature search from articles, academic journals, conference proceedings, review papers, and the book publications. Effective discussions with subject matter experts also strengthened the knowledge gained. In addition, an in-depth understanding of the research methodology was gained in this stage, and the research methods and techniques for data collection and analysis were identified.

1.5.3. Secondary Phase

With the research outcome generated in the primary phase, data collection tools were prepared in the secondary phase. Following the findings that were retrieved from the extensive literature reviews, a questionnaire was developed to solicit experts' opinions concerning the identified constructs of SCV and SCC. In addition, a semi-structured interview guideline was developed to capture the related information that cannot be collected through the questionnaire. Moreover, this phase included research data collection through an expert opinion survey using a questionnaire survey and interviews, site visits, and document review. Thereby, the adaptability, criticality and the importance of supply chain vulnerability and capability constructs were identified with related to the IC. Since the subject matter is an unexplored area within the IC, and only somewhat explored in the other fields, the subject matter expert opinion survey enabled rich data gathering. Further, the frequent site visits to the prefabricated construction sites and the extensive document reviews were useful to enrich the findings related to the HK context.

Collected data was then analyzed using mean score analysis and factor analysis techniques. The results facilitated the identification of the critical supply chain vulnerabilities and capabilities in IC and grouping the identified factors under appropriate vulnerability and capability constructs. Thereafter, fuzzy-synthetic evaluation so-called as a soft computing approach was employed to develop separate vulnerability and capability models which assess the impact of critical SCV, influence of critical SCC in achieving SCR and the current level of SCC adoption in IC.

1.5.4. Advanced Phase

This phase consists of advanced statistical analysis and the dynamic SCR model development. The pertinent and pragmatic variables obtained from the survey findings were further analyzed using Structural Equation Modeling (SEM), Social Network Analysis (SNA) and System Dynamics Modeling (SDM). The causal relationships between SCV and SCC were modelled using the SEM. Therefore, the impact of SCC in withstanding SCV targeting SCR in IC was determined. SNA of collected data enabled the identification of the most vulnerable supply chain phase in IC in HK with specific vulnerabilities. After that, SDM facilitated the development of a dynamic model to assess SCR in IC in HK in this advanced phase. The dynamic model developed in this study was validated by employing two comparative case studies in HK. Based on the findings and results derived from all these analyses, a set of strategies was finally proposed to enhance SCR in IC in HK.

1.5.5. Closing Phase

The closing phase started with a comprehensive review of the whole thesis to formulate the conclusions of this study. Recommendations for future research were also developed and articulated to assist in further knowledge development and dissemination. This closing phase also involved the review of the research outcomes *vis a vis* the research objectives and refining of the entire thesis.

1.6. Research Significance

Over the last few decades, interest in SCR grew due to the awareness gained on the substantial direct and indirect losses associated with the lack of resilience. However, insufficient attention has been still paid to the knowledge domain, and therefore SCR can be considered as an emerging research area which is yet to be explored. Despite the limited number of research studies devoted to supply chain resilience in the construction industry, there is also not much attention given to the sector in terms of supply chain resilience in the industrialized construction. Moreover, empirical research on SCR in IC itself was not found. Therefore, there is a substantial research gap in this respect, which this study bridges firstly by reviewing the concept of SCR very broadly. Given that, the study firstly unveils various forms of vulnerabilities which helps to assess the levels of uncertainty that the IC sector undergoes, thereby also contributing to a deep understanding of the vulnerabilities that retard the performance of supply chains. Identifying the capabilities of SCR also helped to measure the level of resilience that IC can achieve. Hence, this study secondly, identifies a set of SCC which is potentially useful in realizing resilient supply chains in IC.

Thereafter, this study developed the first known evaluation models of critical SCV and critical SCC as specific to the IC in HK which help to evaluate to what extent the IC supply chains are vulnerable to disruptions and how much these supply chains are capable of withstanding these disruptions. Also, the levels that the capability measures should reach was also assessed and proposed to the industry stakeholders.

In another important initiative, this study reveals the correlational impact of SCV and SCC by depicting and modeling the impact of SCC in defeating SCV, targeting SCR in IC in HK. Further, the most vulnerable supply chain phases were identified and pointed out for industry professionals to take necessary actions. Besides, the dynamic SCR model developed for IC in HK is the first known initiative to explore the potential use of system dynamics modeling to assess the dynamics of IC supply chains in the pursuit of resilience, contributing to theory and practice. This dynamic model evaluates SCR in IC by integrating the relevant vulnerabilities and the capabilities and hence should facilitate a revolutionary procedure to assess the level of resilience in IC. The findings strongly support enhancing SCR in IC by improving the capacity to survive, adapt, and grow in the face of turbulent change.

Moreover, this novel supply chain resilience model is expected to provide an alternative to the existing traditional risk management processes in IC, also unveiling and addressing the gaps and loopholes therein. Further, the model verification was assisted by an in-depth application of the suggested model in two comparative case studies. It enabled the identification of the existing level of SCR in IC in HK. Thereby, the study attempted to develop and propose strategies to enhance SCR in IC to boost the performance of IC supply chains.

Finally, the research contributes to both theory and practice by generating knowledge on vulnerabilities and capabilities as the measures of SCR in IC, by developing a dynamic model to evaluate SCR by integrating vulnerabilities and capabilities in IC, and by proposing strategies to enhance SCR in IC along with a validated model to realize the best performance of IC supply chains.

1.7. Structure of the Thesis

This thesis comprises eight chapters which are summarized as follows.

Chapter 1 introduces the rationale of this research study and the structure of the thesis. Hence, Chapter 1 includes the research background, the problem statement, the research aim, and objectives. Moreover, it presents the research focus encapsulating both the theoretical and practical focus, the research significance and knowledge creation, and the research design.

Chapter 2 presents the research methodology employed in this study to realize the research aim and objectives. This chapter discusses all the quantitative and qualitative research methods utilized in the entire research process. These methods include systematic literature reviews, content and thematic analysis, expert opinion survey, descriptive analysis, factor analysis, fuzzy-synthetic evaluation, partial least squares structural equation modeling, social network analysis, system dynamics modeling and comparative case studies. The rationale behind the adoption of these methods in realizing the research aim and objectives are explicated in this chapter.

Chapter 3 includes three sections. First, this chapter presents the outcomes generated from the comprehensive, systematic review of SCV related literature through meta-analysis. Second, Chapter 3 describes the results of the comprehensive, systematic review of SCC related literature through meta-analysis. Third, this chapter presents the details of the envisaged action framework developed in this study by including supply chain vulnerability and supply chain capability constructs.

Chapter 4 describes the results generated from the statistical analysis of SCV. Descriptive analysis and normalization of the gathered data enabled the identification of the most critical SCV which could have the greatest impact and the highest probability of occurrence. Thereby, factor analysis was employed to group the identified critical SCV into five underlying constructs. Finally, fuzzy-synthetic evaluation of these supply chain vulnerability constructs resulted in developing the first known mathematical model to assess SCV in IC.

Chapter 5 reports the results associated with the statistical analysis of SCC. SCC are the counteractors of SCV in realizing the resilient supply chains. Similarly, in Chapter 4, descriptive analysis and normalization of the gathered data helped determination of the most critical SCC which exert the greatest influence in achieving SCR. Thereafter, factor analysis was employed to group the identified critical SCC into nine underlying constructs. Finally, fuzzy-synthetic evaluation of these SCC constructs resulted in developing the first known mathematical models to assess the importance and the current level of practice of SCC, targeting SCR in IC in HK.

Chapter 6 proposes a Partial Least Squares – Structural Equation Model (PLS-SEM) to investigate the correlational impact of SCV and SCC. Accordingly, the model evaluates the impact of critical supply chain capability constructs in withstanding critical SCV, which is highly essential to realize SCR in IC in HK. Hence, this chapter informs the practitioners in HK, where and how to deploy critical SCC at appropriate levels, targeting critical SCV, to contain, if not extirpate them to develop resilient and sustainable construction supply chains.

Chapter 7 depicts the key research outputs of this study. First, the chapter presents a social network analysis model, highlighting the most vulnerable supply chain phases of IC. Thereafter, this chapter describes the first known dynamic model to assess SCR in IC. This model is appropriate to the IC practices in HK and therefore, validated through two comparative case studies from HK. Finally, Chapter 7 proposes strategies to boost SCR in IC in HK by satisfying the research aim derived in this study.

Chapter 8 is the final chapter which reviews and summarizes the entire research process, research findings and this thesis. Hence, the key research contributions and the implications of this research are highlighted in terms of both theoretical and practical contributions in Chapter 8. Further, limitations of this research, conclusions derived, and suggested future research directions are also described in Chapter 8.

1.8. Chapter Summary

Chapter 1-Introduction aimed to introduce the background of this research study which led to the modeling of SCR in IC in HK and describes the structure of this thesis. Therefore, this chapter highlights the theoretical and practical needs for this research, the ensuing research aim and objectives which were targeted. Further, this chapter briefly introduces the research design of this study by conveying the key research methods and techniques used at the different stages of the study. Also, this chapter highlighted both the practical and the theoretical significance of this research which would enable boosting the performance of IC in HK. Finally, the structure of the thesis is established in Chapter 1.

Chapter 2 Methodology

2.1 Introduction

Research is not just gathering and processing the information relevant to a topic, but also a quest for undiscovered knowledge (Goddard & Melville, 2004). It is about answering the unanswered question or implementing something new. Indeed, research includes enquiry and investigation (Amaratunga et al., 2002). In this regard, research methodology is the systematic approach used to answer the research question/problem or fill the research gap (Kothari, 2004) by creating new knowledge. Further, research is conducted within the procedural framework of research methodology (Remenyi et al., 1998).

This chapter primarily offers an overall picture of how this research exercise was designed and conducted. It presents in detail, the research methods employed in this research to achieve the aim and the objectives that were formulated to address the research gap. Hence, this chapter presents the details of the methods used to obtain the required data, tools for analyzing the collected data and the techniques utilized in developing the models proposed by this study.

2.2 Research Approach

A suitable research approach would enable organizing research activities in a way to satisfactorily achieve the research aim (Easterby-Smith et al., 2012). The basic research approach can be either based on positivism or interpretive science (Amaratunga et al., 2002). Accordingly, Yin (2017) offered two types of research approaches as Qualitative and Quantitative. In essence, the qualitative approach is subjective in nature, whereas the quantitative approach is objective. Both these types include strengths and weaknesses, and the selection of an appropriate method rests upon the nature of the research problem (Noor, 2008).

Amaratunga et al. (2002) highlighted the advantages allied with the quantitative approach as, comparison and replication are possible, the independence of the observer from the subject being observed is useful; hence reliability and validity may be determined more objectively than qualitative techniques, generally reducing the whole to the simplest possible elements to facilitate analysis. In contrast, Yin (2017) argued that the research approach may be limited by the inability to establish necessary research conditions, the difficulty of securing adequate sample respondents and obtaining a high response rate.

Although the qualitative approach requires detailed and in-depth information, qualitative research can provide distinct advantages (Yin, 2017). Qualitative methods enable focusing on a specific set of people and in-depth study of broad topics, offer greater latitude in selecting the topics, and representing the views and perspectives of people (Yin, 2017). In contrast, Amaratunga et al. (2002) stated the factors that hinder the use of qualitative approaches in practice as, the volume of data reachable and the complexity of analysis. Further, Amaratunga et al. (2002) recognized that purely quantitative research might neglect the social and cultural construction of the variables studied.

In this context, this research study followed a mixed-method approach which combines the positivism, and social constructionism approaches together by considering its advantage over adopting these two approaches as individual and separated approaches and by revisiting the need for this study. Besides, this mixed-method or the triangulation approach was justified as more powerful and advantageous than adopting either the qualitative or the quantitative approach as a single approach (Creswell, 2014). Hence, researchers adopted the quantitative approach to develop constructive theories and employed the qualitative approach to test the developed theories. Explicating further, a deductive research approach was primarily adopted in this study, basing the research approach primarily on the positivism philosophy. However, an element of interpretivism was found useful, indeed important, in seeking and providing industry-based justifications for the quantitative results, and therefore, used in describing and verifying the quantitative results.

The entire research approach employed in this study is clearly presented in Table 2.1, including systematic literature review, data collection methods and data analysis methods used. Each method used in this study is well explained with justifications in the subsequent sections.

2.3 Research Methods

The following research methods were employed to achieve the research aim and the objectives, as highlighted in the previous section.

2.3.1. Literature Review

A literature review is the thorough and systematic examination of previous research studies of a specific knowledge domain (Tsai et al., 2005; Yi & Wang, 2013). Literature reviews enable identification of current research trend and research gaps. Hence, this study commenced with a comprehensive review of relevant previous literature from professional and academic journals, doctoral theses, conference papers, research reports (both published and unpublished), textbooks and relevant information from the internet to retrieve all necessary information for the study and the background knowledge of SCR and IC.

Further, this study adopted a systematic review of literature through meta-analysis to explore the vulnerabilities and the capabilities associated with SCR in IC. Additionally, the literature review also formed the foundation for building a very firm theoretical base for the area of research aided and establishing of the groundwork for realizing the aim and objectives of the study as well as addressing the research gap. The findings of these reviews and the adopted methodology are further explained in the forthcoming chapter. Finally, the literature review was useful to formulate the envisaged action framework of the study to help structure and operationalize the findings from this study, based on the gaps in theory and practice.

2.3.2. Data Collection

Questionnaire development

This study developed a questionnaire as a data collection tool for the expert survey to solicit views from targeted respondents. Further, this instrument is deemed to be very useful for quantitative data analysis, with the higher probability of generalization of the results (Adabre & Chan, 2019; Oppenheim, 2000). Based on the thorough literature review, a very comprehensive questionnaire was developed to aid the solicitation of the required information. The questionnaire was structured in three sections. Section A entailed an explicit and easily understandable cover letter that introduces the survey. Also, Section A requested the personal data of the respondents. Section B encompassed closed-ended questions on the vulnerabilities in IC supply chains, and the respondents were asked to comment on the probability and the levels of vulnerability of the factors.

Further, section B contained 36 confirmed SCV following the preliminary study. Section C consisted of supply chain capabilities, and the respondents were asked to rank these capabilities based on their current levels of application and the importance. Indeed, 58 SCC measurement items, improving SCR in IC were included in the questionnaire following the preliminary study. All these questions in section B and C were needed to be rated using a five-point Likert scale, one representing low and five representing very high. This scale was used due to its relative brevity (Adabre & Chan, 2019), but suitability for the purpose. Finally, additional rows were provided for open-ended responses to add any known SCV and SCC that were not captured in the preliminary study. The sample questionnaire is attached as Annexure A to this report.

Table 2.1:Research design

RESEARCH OBJECTIVE	RESEARCH DESIGN											
	DATA COLLECTION				DATA ANALYSIS							
	LR	EI	QS	CS	CA	TA	MS	FA	PLS-SEM	FSE	SDM	SNA
Identify supply chain vulnerabilities and capabilities as critical measures of supply chain resilience in industrialized construction	√	√			√	√	√					
Develop mathematical models to assess supply chain vulnerabilities, supply chain capabilities and their correlational impacts	√	√	√				√	√	√	√		
Develop a dynamic SCR evaluation model for industrialized construction in Hong Kong via probing and assessing relevant supply chain vulnerabilities and capabilities	√	√	√	√					√		√	√
Propose strategies to enhance supply chain resilience in industrialized construction in Hong Kong		√	√	√							√	√

Glossary

LR – Literature review (to establish a theoretical underpinning for the research); EI – Expert Interviews (to verify study findings); QS – Questionnaire survey (to solicit experts' opinions on the subject matter and rank the factors); CS – Case Study (comparative case studies to verify findings); CA – Content Analysis (adopted to make valid and replicable inferences by coding and interpreting textual material through evaluating texts systematically); TA – Thematic Analysis (to identify, assess and record patterns in data); MS – Mean Score Analysis (to determine factor significance); FA – Factor Analysis (to express observed data as a function of possible causes and as a data reduction technique); PLS-SEM – Partial Least Squares-Structural Equation Modeling (to assess relationships that exist among capabilities and vulnerabilities); FSE – Fuzzy Synthetic Evaluation; SDM – System Dynamics Modeling (to model dynamic complex system of SCR in IC); SNA – Social Network Analysis (to model the impact of vulnerabilities in each supply chain phase).

Pilot study

After the initial development of the questionnaire, a pilot study was conducted to assess the entire comprehensiveness, relevance, and reliability before it was disseminated to the targeted respondents for their valuable responses. The data collection tool was further refined during 'pilot testing' with three academics and two industry practitioners with research and/or industry experience in IC. These respondents were considered as the experts on the subject matter because they had more than 20 years of experience and vast knowledge in handling IC projects. The academics were selected based on their expertise and experience in the subject matter, as revealed by their publications and their positions within various institutions as well as their availability and willingness to respond to the survey. Specifically, they were consulted to examine the questionnaire's appositeness with regards to the clarity of the questions, wordings, definitions, coherence, structure and length, relevance of the SCV and SCC measurement items, the level of complexity and the use of technical terms (Adabre & Chan, 2019; Ameyaw & Chan, 2015). As per the feedbacks of the experts, the questionnaire was reviewed and thoroughly revised to enhance its quality and appropriateness, thus making it more suitable for the questionnaire survey.

Sampling technique

Sampling is the act of taking a part of the entire population to represent that same population (Strydom & Venter, 2005). Polit and Hungler (1999) stated that if the whole population is smaller, the sample size should encompass of a relatively larger proportion of the population. In order to attain an accurate conclusion and a more concrete prediction, the researcher should consider using a larger sample than a relatively smaller sample (Polit & Hungler, 1999). Moreover, sampling is an essential and necessary aspect of any research study due to the constraints imposed by cost and time (Patton, 2005). Kothari (2004) emphasized that for a researcher to develop a suitable sample for the study, he must take into consideration the demographical pattern for the study, sampling unit, source list, sample size, parameters of interest, budgetary constraints and sampling procedure.

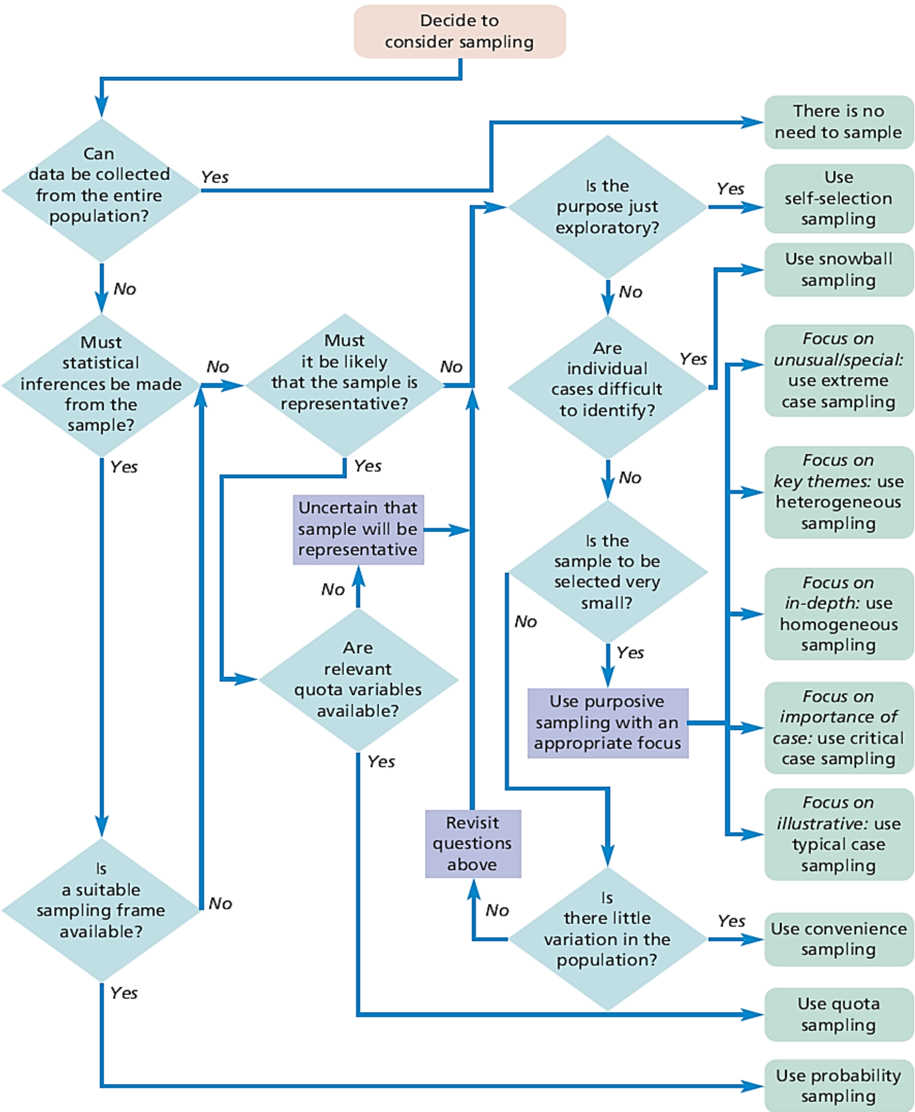


Figure 2.1:How to select a sampling technique

Source: (Saunders et al., 2009)

The sample selected for this study comprised of experts involved in IC. Specifically, they consisted of professionals from the construction industry in HK. When selecting a sample, a non-probability sampling technique was used since the study focuses on non-statistical data. Further, considering the flow chart developed by Saunders et al. (2009), as shown in Figure

2.1, this study necessitated the purposive sampling technique. Accordingly, a purposive sampling approach was first chosen to arrive at the selection of suitable respondents for this study (Owusu & Chan, 2019) and the respondents were identified by exploring their business profiles, attending seminars related to IC conducted by them, and through industry-based contacts. Thereafter, the snowball sampling technique was also used to expand the respondent 'catchment area' for this study. Adhering to the snowball sampling method enabled obtaining a valid and expanded sample size and rich information gathering through referral and social networks, as followed in previous construction management research (Chan et al., 2018; Owusu & Chan, 2019; Zhang et al., 2017).

Questionnaire Survey

After the pilot study, the researcher proceeded with a questionnaire survey as the primary data collection method of this study. A questionnaire survey offers a valid, reliable and quick source of information with a minimal resource requirement (Ameyaw et al., 2017). This data collection method was beneficial since, a) it enables rich and reliable information, b) this requires less time compared to the other methods, and c) this facilitates the expansion of respondent 'catchment area' through participants' suggestions and recommendations (Ameyaw et al., 2017). According to Table 2.2, the respondents selected for the primary data collection of this study comprised senior experts involved in the IC projects. All of them were managerial level or high-level staff experienced with the IC process. Apart from the foregoing essentials, these senior experts were also selected for the ability to convey the information in English. Many project engineers who were assigned to the manufacturing factory were involved in this study, and all the respondents were asked to provide their answers considering all the supply chain phases to maintain consistency of the data collected.

Table 2.2: Profile of Respondents

Category	Number of respondents	Relative frequency
Public Sector	23	30.3
Private Sector	42	55.3
Both	11	14.4
Total	76	100.0
1-5 Years' Experience	1	1.3
6-10 Years' Experience	18	23.7
11-20 Years' Experience	23	30.3
Above 20 Years' Experience	33	44.7
Total	76	100.0
Director	17	22.3
Senior Manager	27	35.5
Manager	16	21.1
Other Staff	16	21.1
Total	76	100.0

The total of 76 valid responses obtained was regarded as suitable for further analysis, contemplating the difficulty of soliciting respondents' opinions due to busy schedules and time concerns. Besides, 76 respondents are higher than the previous response rates obtained in some international survey-based studies (Adabre & Chan, 2019; Darko & Chan, 2018; Owusu & Chan, 2019), while this sample size is generally adequate to derive significant conclusions regarding a subject area of this nature (Owusu & Chan, 2019). According to Ott and Longnecker (2015), a sample size of 30 is deemed to be representative of any group. 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. Table 2.2 presents the background information of the respondents.

Expert opinion survey

In addition, subject matter expert opinion survey was conducted to enrich the data collected from questionnaire surveys. For that, semi-structured interviews with the subject matter experts were performed using an interview guideline as attached as Annexure B. The use of interviews as a data collection method has long been recognized in social science research (Bertrand and Bourdeau, 2010). Since interviews facilitate interactive, in-depth and clear explanations to the emerging research topics (Alshenqeeti, 2014), this study conducted a subject matter expert opinion survey using interviews. Further, semi-structured interviews were selected to confirm the natural flow of data and the richness of details received (Alshenqeeti, 2014). To warrant the consistency and quality of interviews, the researcher adopted the purposive and snowball approaches to select interviewees. Polit and Hungler (1999) also delineate the purposive sampling technique to be a type of non-probability sampling technique which involves the mindful selection of certain respondents to be included in the study.

According to Bernard (2017), most types of research design compel the researcher to make decisions concerning the individual participants who would stand in a position to give the appropriate and needed data, in terms of both depth and relevance. Given this background, purposive and snowball sampling techniques were adopted considering the research design, purpose, and practical implications of the study. All the respondents were contacted face-to-face or through online (Skype) interviews. Online interviews were significantly useful given the benefits of easy, faster, cheap and flexible data collection (Bertrand and Bourdeau, 2010) during the early Covid-19 pandemic. A brief description of the survey was conveyed at the beginning of the interviews, including the requirements of this data collection. Then, they were asked to complete the questionnaire. Thereafter, the respondents were interviewed using the semi-structured interview guideline. All these interviews lasted for 45 to 150 minutes.

Frequent site visits and document reviews

Site visits (Nagapan et al., 2013) and document reviews (Bowen, 2009) are useful qualitative data collection methods used to collect real-life project information in construction management. Therefore, frequent site visits to the prefabricated construction sites in HK were conducted to gather actual and observational data on the vulnerabilities they face and the capabilities the firms contain. It enabled justifications to the findings of the questionnaire survey. Further, document reviews of the IC projects facilitated underpinnings to the survey findings by justifying the real-life problems and practices. Hence, the researcher conducted frequent site visits and document reviews during the study period to strengthen the study findings.

Case study

The case study method is suitable for new research areas or research areas where existing theories are found to be inadequate (Eisenhardt, 1989). Further, case studies are more useful in the early stages of new research and the latter stages of theory development. Case studies support a more detailed and more profound investigation of a subject matter and offer insights that cannot be received through other methods (Rowley, 2002). This method moves beyond the questionnaire survey and interviews and facilitates justifications considering the evidence from documents, observation and artefacts (Rowley, 2002). Thus, a case study is a valuable method to analyze real-life contexts using mixed research approaches, including both qualitative and quantitative tools (Eisenhardt, 1989). Moreover, this method is highly applicable to understanding the dynamic systems and hypothesis testing research (Eisenhardt, 1989). Given these merits, this method is widely adopted in construction management research field and used explicitly for model validations (Mok et al., 2017).

Case studies can be either single-case research or multiple-case research (Yin, 2017). In the construction management research domain, single case studies (Luo et al., 2019; Mok et al., 2017) and two comparative case studies are commonly observable (Iyer et al., 2020; Yang & Zou, 2014). Multiple case studies enable the higher generalization of results, bring additional validity of the results and enhance confidence of the findings (Eisenhardt, 1989). Given this background, this study used two comparative case studies of IC projects in HK as the inputs of system dynamics model simulation and validation. The rationale behind the selection of these two case studies and further details of the selected cases are illustrated in Chapter 7.

2.3.3. Data Analysis

Data analysis is a challenging and exciting stage of the entire research process. Analysis, on the other hand, refers to the computation or calculations or simulations of some measures together with searching for relational or correlational patterns that exist among the groups of gathered data. It relates to the ways by which answers are found through interpreting the collected data (Strydom & Venter, 2005). Since explaining all the raw data is either impossible or difficult, data description and analysis must be done at first, and then the analysis results should be interpreted (Strydom & Venter, 2005). There are several different types of research analysis techniques (Tesch, 2013). Some of them are outdated; hence ways to develop these are still being explored. As appropriate to this research study, several data analysis techniques were utilized for effective data analysis and research results and the conclusions were derived. The following paragraphs further explicate the analysis techniques used by relating them to this study.

Mean Score (MS) Ranking Technique

The mean score ranking technique has been recognized as one of the most important and critical tools employed by many researchers to determine the significance or the relative importance of individual factors, enabling the easy identification of critical factors (Owusu & Chan, 2019). Therefore, this study used the mean score ranking technique to determine critical supply chain vulnerability and critical supply chain capability components together with their allied measurement items.

Reliability Test

Reliability tests measure the consistency of the data collected (Tavakol & Dennick, 2011). They are used to determine the average internal consistency or the interrelations of variables in survey instruments to measure the reliability thereof (Brown, 2002). In this study, a reliability test was conducted using Cronbach's alpha test tool in the Statistical Package for Social Sciences (SPSS), because Cronbach's alpha test tool is more flexible, commonly used, provides sound estimates and enables calculating reliability using a single test (Brown, 2002). Cronbach's alpha values range from 0 to 1, where 0 represents no reliability (Tavakol & Dennick, 2011). Acceptable values of alpha, ranging from 0.70 to 0.95, whereas the effective limit is between 0.70-0.90 (Tavakol & Dennick, 2011).

Factor Analysis

Factor analysis is considered as a data reduction technique (Lederer et al., 2000). It is the statistical technique, commonly used to determine the relatively fewer 'parent' or 'root' categories underlying a set of correlated variables (Mooi et al., 2018). This method facilitates categorizing a large number of variables into a lesser amount of more significant constructs by factor points of responses (Pallant, 2020). There are two types of factor analysis: exploratory and confirmatory (Borkenau & Ostendorf, 1990). Exploratory factor analysis attempts to discover the nature of the constructs influencing a set of responses while confirmatory factor analysis tests whether a specified set of constructs is influencing responses in a predicted way (Borkenau & Ostendorf, 1990). Therefore, exploratory factor analysis was conducted in this study to appropriately categorize and group the identified critical supply chain vulnerabilities and critical supply chain capabilities. This factor analysis facilitated a systematic approach for factor extraction and categorization compared to the manual categorization. The Kaiser-Meyer-Olkin test (KMO) and Bartlett's test of sphericity were conducted to verify data for the factor analysis (Adabre & Chan, 2019; Le et al., 2014). KMO measures the sampling adequacy using the size of the partial correlation coefficients that describe the ratio of the squared interrelationship among the composing variables to the corresponding squared partial correlations (Dziuban & Shirkey, 1974).

Further, a KMO of 0 indicates that the data set is inappropriate for factor analysis, whereas 1 shows an appropriate data set for further analysis. Bartlett's test of sphericity checks for the variance homogeneity (Owusu & Chan, 2019). The factor model is considered appropriate, and the population correlation matrix is not an identity matrix if the sphericity test statistic is relatively large, with a corresponding lower significance level (Pallant, 2020). Moreover, as stipulated in the literature, if the KMO value is above 0.5 and Bartlett's test of sphericity statistic is significant ($p<0.05$), the data can be considered as appropriate for factor analysis (Kaiser, 1974). Therefore, KMO test and Bartlett's test of sphericity were conducted prior to the factor analysis during this research.

Fuzzy Set Theory (Fuzzy Synthetic Evaluation)

Fuzzy set theory has been vastly applied in data analysis since 1965 (Zadeh, 1965). This theory supplements the interpretation of linguistic uncertainties basing real-world phenomena (Chang et al., 2001). Jamshidi (1997) defined a fuzzy set as a collection of elements in a universe of information where the boundary of the set contained in the universe is ambiguous. The fuzzy weighted average is a combination of extended algebraic operations. It usually has been utilized in design evaluation to calculate the overall desirability of a design alternative when the importance (weight) of criteria and single desirability levels are represented by fuzzy numbers

(Jamshidi, 1997). Fuzzy Synthetic Evaluation (FSE) is one of the frequently used techniques comes under the fuzzy set theory (Chang et al., 2001).

Further, FSE, which is the fuzzy logic approach, has been used in several research disciplines for evaluation in multi-criteria decision making (Xu et al., 2010), demarcating its ease of application and practicality (Lo, 1999). Evaluation of risk levels is always fuzzy and shrouded in vagueness; hence FSE can be used as a powerful tool to transform such imprecise data (Ameyaw et al., 2015). Therefore, FSE, as a soft computing approach, was employed in this study to evaluate the impact of critical supply chain vulnerabilities and critical supply chain capabilities to achieve resilient supply chains in IC in HK. Also, this evaluation process included developing the evaluation indices, determining the membership functions, estimating weighting functions, developing multi-stage-multi-criteria FSE models and evaluating the overall indices of vulnerability and capability. All these steps of fuzzy synthetic evaluation are explicated in Chapter 4 and Chapter 5, respectively as appropriate to SCV and SCC.

Partial Least Squares-Structural Equation Modeling (PLS-SEM)

Structural Equation Modeling (SEM), being a useful multivariate statistical analysis tool, was applied to test the postulated hypotheses of this study. This method goes beyond the conventional multiple regression analysis, variance and factor analysis (Darko et al., 2018) and enables both path analysis and confirmatory factor analysis together within a single model (Xiong et al., 2015). In SEM analysis, there are two approaches, namely covariance-based (CB-SEM) and variance-based (PLS-SEM) (Hair et al., 2014). However, this study used PLS-SEM since PLS-SEM can handle small sample sizes and non-normal data (Hair et al., 2014). Given this advantage, construction management research studies have also adopted PLS-SEM techniques widely to date (Darko et al., 2018; Owusu, Chan, & Hosseini, 2020; Zhao & Singhaputtangkul, 2016). This justified the PLS-SEM analysis using SmartPLS 3.3.2 software in the current study to test the research hypotheses and validate the developed hypothetical models.

PLS-SEM analysis included three stages, namely, model specification, outer model evaluation, and reflective indicators (Hair et al., 2014). The SCV and SCC factors were the observable variables, and the constructs were the latent variables that cannot be directly measured. The PLS-SEM algorithm was run during the outer model evaluation (Henseler et al., 2012), and the reliability and the validity of the outer model constructs were evaluated.

Cronbach's alpha and composite reliability scores were used to assess the internal consistency reliability of the measurement items. The postulated model is considered to be reliable when Cronbach's alpha > 0.70 (Nunnally, 1978) and composite reliability scores > 0.70 (Hair et al., 2014). The validity was assessed using the construct's convergent validity and discriminant validity. Convergent validity is supported when each item's outer loading > 0.70 and each construct's average variance extracted (AVE) ≥ 0.50 (Hair et al., 2014). AVE presents the grand mean value of the squared loadings of a construct, equivalently to the construct's commonality (Hair et al., 2014). Discriminant validity was verified using the Fornell and Larcker (1981) criterion and by studying the cross-loadings of the indicators. The first criterion is satisfied if the construct variance (AVE) with its measurement items is greater than what it shares with any other construct. The second criterion is supported if each measurement item's loading on its respective construct is higher than the cross-loadings on different constructs.

Finally, the significant weight of each path (path coefficient) was computed using the bootstrapping technique in PLS-SEM. As suggested by Hair et al. (2011), the number of bootstrap samples used was 5000, ensuring the stability of the findings. Further, the critical t-values of two-tailed tests are 1.65, 1.96, and 2.56, with the significance levels of 10%, 5%, and

1%, respectively (Hair et al., 2011). Chapter 6 further elaborates on the results generated in PLS-SEM analysis.

Social Network Analysis (SNA)

Social Network Analysis (SNA) is a comprehensive paradigmatic method that considers social structures as systems by direct examination of resource allocation patterns in the social systems (Scott & Carrington, 2011). SNA, which is specific to network theory, has emerged as a key research technique in sociology and has become a popular topic of speculation and study (Yang et al., 2016). Besides, this method facilitates easy access to the data, simplicity of design, the use of 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 (Chinowsky et al., 2008, 2010; Yang et al., 2016), 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 SNA 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 SNA to analyze the vulnerability levels of the principal supply chain phases of IC, namely factory-prefabrication, logistics, and on-site assembly. The details of the SNA deployed in this research are clearly stated in this thesis Chapter 7.

System Dynamics Modeling (SDM)

System Dynamics Modeling (SDM) was introduced by Professor Jay Forrester in 1958, using a computer simulation technology and feedback control theory as means of quantitative analysis of multifaceted real-world systems (Ajayi, 2016; Li et al., 2014). SDM is a multidisciplinary research tool that has been widely used in project management, decision sciences, and construction management domains, among others. Dynamic modeling of construction activities enabled identifying solutions for several complex problems where non-linear relationships and multiple interdependent connections existed (Sterman, 1992). Further, SDM can correlate several factors and allow experiments within a controlled environment (Love et al., 2000). As an advanced research tool, SDM facilitates managing complex processes, relying upon its feedback loops and connections.

Thus, the modeling process is highly dependent upon the captured interactions among the variables. Also, SDM enables the examination of the behavior of a complex system over time with changes in the variables. Hence, the construction industry has employed SDM 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 SCR in construction practices, using SDM principles. Given the importance as mentioned above of such a research study and in response to the research lacuna identified, SDM 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. The details of the SDM are clearly stated in Chapter 7 of this thesis.

2.3.4 The Rationale Behind Using the Multiple Data Analysis Methods

First, this study needed a scientific approach for supply chain capability and supply chain vulnerability measurement item extraction and categorization under appropriate vulnerability and capability components to achieve the first Objective. Since factor analysis is proven as an effective method for factor extraction and categorization, it was decided to employ factor analysis for the purpose. To fulfil the second Objective, the research necessitated developing evaluation models for SCV, SCC and their co-relational impacts. As described in the above sections, evaluation of vulnerability and associated capability levels are always fuzzy and shrouded in vagueness; whereas FSE (Fuzzy Synthetic Evaluation), is a powerful tool that helps transform such imprecise data. Given that, the FSE method was used to develop supply chain vulnerability and capability evaluation models.

However, FSE was not supportive of analyzing the co-relational impact of SCV and SCC. Indeed, it required both path analysis and confirmatory factor analysis within a single model to develop an effective SCV and SCC co-relationship evaluation model, in order to identify the appropriate SCC that can effectively withstand appropriate and critical SCV. Therefore, the PLS-SEM (Partial Least Squares-Structural Equation Modeling) research technique was selected for this purpose since the method facilitated all these functions. Moreover, it worked well with relatively small sample sizes and non-normal data.

Furthermore, to achieve the third research Objective, this study needed to test the dynamic impact of SCV ad SCC to achieve SCR in IC in HK. Therefore, it was required to consider the whole supply chain as a system and simulate the impact of SCV and SCC. For that, another research data analysis technique was needed since the already used techniques were inadequate to fulfil this requirement. Given the merits of SDM (System Dynamics Modeling) as explained in the above sections, this study employed SDM for dynamic SCV and SCC analysis. On the other hand, the literature was silent on vulnerability impact analysis of each IC supply chain phase, although it is essential for the effective supply chain management. Therefore, the researcher needed to conduct a two-mode network analysis by considering supply chain phases and SCV as the key nodes. Since SNA (Social Network Analysis) enabled effective two-mode network analysis, which was not possible with the previously used techniques, the researcher employed SNA to evaluate the vulnerability levels of each supply chain phase.

Accordingly, this research employed FSE, PLS-SEM, SDM and SNA as advanced data analysis techniques, apart from the initial factor analysis, in order to achieve each of the research objectives stepwise, because it was not possible to adequately fulfil all the research objectives by utilizing just one or two data analysis techniques, as explicated and clarified in this section.

2.4 Chapter Summary

The chapter was written based on the research process which was carried out to achieve the ultimate research aim. Research methodology is the systematic framework for achieving the research aim. Hence, this chapter described the research methodology employed in this piece of research work which included a mixed method research approach in attaining the research objectives and the aim. Further, it highlighted the research design, the entire research process, data collection methods, and data analysis techniques used in this study. Moreover, it reasoned out the whys and wherefores for selecting each research method and technique in the entire research process, in this chapter.

Chapter 3 Literature Review[1]

3.1 Introduction

This chapter presents the results generated from the state-of-the-art review of supply chain resilience and industrialized construction knowledge domains targeting supply chain resilience in industrialized construction. Hence, this chapter begins by initiating the concept of SCR in IC followed by describing supply chain vulnerabilities and supply chain capabilities as the two fundamental measures of SCR as appropriate to IC. Further, this chapter presents the details of the systematic review of literature conducted through meta-analysis to support supply chain vulnerabilities and supply chain capabilities associated with IC projects. Finally, Chapter 3 explains the theoretical framework developed in this study by incorporating supply chain vulnerability and capability measures and constructs to enhance SCR in IC.

3.2 Supply Chain Resilience in Industrialized Construction

Global supply chains are susceptible to a wide array of disruptions (Zavala et al., 2019) not only due to the external environmental forces but also due to the strategic and managerial decisions made by the organizations (Vecchi & Vallisi, 2016). This highlights the need for

---

[1] The core research and findings in this chapter have been peer-reviewed before publication in:

Ekanayake, E.M.A.C., Shen, G. and Kumaraswamy, M.M., 2021. Identifying supply chain capabilities of construction firms in industrialized construction. *Production Planning & Control*, 32(4), 303-321, DOI: 10.1080/09537287.2020.1732494.

Ekanayake, E.M.A.C., Shen, G.Q., Kumaraswamy, M.M. and Owusu, E.K., 2020. Identifying supply chain vulnerabilities in industrialized construction: an overview. *International Journal of Construction Management*, DOI:10.1080/15623599.2020.1728487.

Ekanayake, E.M.A.C., Shen, G. and Kumaraswamy, M.M. 2021. Supply Chain Resilience: Mapping the Knowledge Domains through a Bibliometric Approach. *Built Environment Project and Asset Management Journal*, DOI 10.1108/BEPAM-03-2020-0040.

Ekanayake, E. M. A. C., Shen, G. Q. P. and Kumaraswamy, M. 2019. Managing Vulnerabilities and Capabilities for Supply Chain Resilience in Industrialized Construction. In proceedings of the *ARCOM2019* Conference. 02-04 September 2019 at Leeds Beckett University, Leeds, United Kingdom. pp.811-820.

strategies and practices which mitigate the effects of diverse disruptions that adversely affect global supply chains and calls for supply chain resilience (Zavala et al., 2019). The concept of resilience typically refers to the ability to deal with shocks, which may include global economic crises, natural disasters, extreme weather events, and environmental threats (Tan et al., 2017). According to Cutter et al. (2010), it is an outcome measure with an end goal of limiting damage (resistance), mitigating the consequences (absorption), and recovery to the pre-event state (restoration). Without focusing on the predictive events, resilience needs to be improved to respond adequately to any uncertainty (Comes & Van de Walle, 2014). Further, resilience is a "horizontal concept" since it straddles diverse disciplines, including ecology, psychology, metallurgy, and management, due to the wider adoption of the context around different knowledge domains (A. Ali et al., 2017). Each of these knowledge domains is a research cluster itself, in which resilience is demanded (Bevilacqua et al., 2018), and Supply Chain Resilience (SCR) is also one of the clusters researched in the management and engineering research fields.

There has been a growing interest in SCR over previous decades, due to the increasing awareness of huge direct and indirect losses arising from a lack of resilience (Ponis & Koronis, 2012). SCR indicates the ability of a company to withstand the disruptions and ensure the continuity of the operations (Ponomarov & Holcomb, 2009) or, at least, to ensure a quick restoration (Vecchi & Vallisi, 2016). According to Christopher and Peck (2004), SCR is 'the ability of a supply chain to return to its original state or move to a new, more desirable state after being disturbed.' Explicating the concept further, Ponomarov and Holcomb (2009) comprehensively defined SCR as 'the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function.' Supply chain resilience and supply chain sustainability have several intersections (Seuring, 2013), including the ripple effect in supply chain, and resilient supply chains contributes to supply chain sustainability (Ivanov, 2018). Initiating resilient supply chains should abide by the principles of practicability, integrity, safety, and standardization of logistics information (Cui, 2018). Adhering to these principles facilitates optimized supply chain (SC) performance and helps withstand SCV. According to the empirical study findings of Pettit et al. (2013), SCR increases as capabilities increase and vulnerabilities decrease. Ponis and Koronis (2012) also studied how supply chain capabilities could mitigate the presence of disruptions and how it affects SCR.

The construction industry is not exempt from being affected by the interconnected risks associated with global supply chains (Zainal & Ingirige, 2018b). Indeed, the supply chain of a construction project is clearly vulnerable to the aforementioned disruptions, which lead to significant cost impacts and subsequent losses due to the downtime (Wedawatta et al., 2010). New initiatives in construction supply chain management have been launched from 1980 (Dulaimi et al., 2007; Eriksson & Laan, 2007; Vrijhoef & Koskela, 2000). These initiatives targeted improving the supply chain efficiency, waste reduction and supply chain value additions by discarding the adversarial supply chain relationships and fragmented business processes (Gadde & Dubois, 2010; Saad et al., 2002). Further, members of the construction supply chain, especially the main contractor and the sub-contractors should appropriately deal with organizational, managerial, technological and relational supply chain issues in order to apply supply chain initiatives effectively (Palaneeswaran et al., 2003). However, supply chain management practices in the construction industry are ad-hoc and scattered (Gadde & Dubois, 2010).

Under these circumstances, Industrialized Construction (IC) as an increasingly attractive construction approach has been emerged in the construction industry to improve the efficiency, flow and the quality of construction supply chains (Gibb, 1999; Lawson et al., 2012).

Manufactured construction, offsite manufacturing, offsite production, offsite construction, modern methods of construction, prefabricated construction and the industrialized construction are used interchangeably in the literature to describe a similar phenomenon (Goulding et al., 2015) and all these terms share a common standpoint in production methods and prefabrication (Lessing et al., 2015). Primarily, the focus of IC is associated with manufacturing or factory-based production which creates a controlled environment in the onsite assembly phase (Arif & Egbu, 2010). The IC process consists of three phases: prefabrication; logistics; and on-site assembly (Zhai & Huang, 2017), each of which is serviced by its supply chain. The foregoing researchers found that each phase of IC supply chains is vulnerable to the disruptions such as traffic jams, machine breakdowns, issues related to the customs clearance and damages to critical equipment. Therefore, it is essential to minimize and/or manage these potential disruptions effectively to elicit the potential benefits of IC. In such circumstances, the first attempt should be preventive risk management, that make the supply chain robust and risk resilient (Cui, 2018). According to the findings of Vecchi and Vallisi (2016), being resilient is the answer to countering the negative impacts and subsequent losses associated with the supply chain disruptions.

3.3 SCR vs. Supply Chain Risk Management

Organizations adopt numerous Risk Management (RM) strategies to reduce the level of vulnerability to supply chain disruptions (Zavala et al., 2019). RM is regarded as the traditional way of dealing with disruptions, and it employs empirical data, mathematical modeling and probability distributions in identifying risks and making future predictions (Van Der Vegt et al., 2015). A typical RM process involves hazard identification, risk assessment, controls implementation and review (Pettit et al., 2010). However, it is very difficult to identify all potential risks to conduct adequate risk assessments (Van Der Vegt et al., 2015). Indeed, it would be onerous to apply traditional RM approaches to every possible supply chain disruptive cause (Pettit et al., 2010) and these RM practices are inadequate to facilitate the required protection against potential disruptions since these uncertainties trigger potential disruptions whose root causes are difficult to be understood (Van Der Vegt et al., 2015). These researchers also found that most of the disruptions emerged as a set of joint events with generated cascading impacts which are hard to anticipate and predict. Besides, traditional RM is unable to respond to the low-probability, high impact disruptive events adequately, as it cannot deal well with the unpredictable events (Pettit et al., 2010). To cope with these circumstances, the attention of academic researchers and the industry practitioners has increasingly shifted towards resilience (Van Der Vegt et al., 2015), which goes beyond mitigating risk and enables organizations to deal with disruptions more effectively (Fiksel, 2015).

SCR also goes beyond the traditional supply chain RM approaches (Zavala et al., 2019) and enable handling the disruptions, which cannot be handled within the RM framework. Hence, resilient supply chains develop adaptive capabilities in supply chains to deal with vulnerabilities and enhance recoverability in the presence of a disruption. Moreover, resilience is defined as 'the ability to react proactively to disturbances and to return to its original state or a more desirable one after being disturbed' (Christopher & Peck, 2004). Adding further to the concept of resilience, Sheffi and Rice (2005) defined SCR as the ability of an organization to recover from a large disruption or a supply chain's ability to react to unexpected disruptions and restore quickly to normal supply network operations. Therefore, Ponomarov and Holcomb (2009) viewed SCR as the adjustment capacity of a supply chain to balance changing circumstances and restore operations to normality or to a steady state after facing a disruption.

3.4 Supply Chain Vulnerabilities (SCV): A Systematic Review

In the last few decades, vulnerability levels of many supply chains have been increased (Vecchi & Vallisi, 2016) as stated above and most of the industrial supply chains are now characterized by complexity and extensive outsourcing. Additionally, the supply chains are less vertically integrated compared to the past and are exposed to increased levels of disruptions/ vulnerabilities such as stemming from political, social and economic disorders (Snyder & Shen, 2006) which are unanticipated and unplanned events affect/disturb the normal flow (Zavala et al., 2019). In the previous literature the aforementioned vulnerabilities are referred as 'disruptions' (Ponomarov & Holcomb, 2009), 'risks' (Chopra & Sodhi, 2004), 'errors,' 'uncertainties' and 'crises.' Vulnerability is the status or the degree of fragility of a system (Elleuch et al., 2016). In terms of SCR, vulnerabilities are the key disruptions that disturb the normal supply chain process.

3.4.1. Risk Vs. Vulnerability

It is also important to differentiate risk and vulnerability. Findings of Heckmann et al. (2015) identified risk as "the fear of losing investment" or "the probability of events that result in loss", while it is characterized by the probability of happening and the impact (Elleuch et al., 2016). Referring to the supply chain, risk is the "variation in the distribution of possible supply chain outcomes, their likelihood, and their subjective values" (March & Shapira, 1987). On the other hand, 'vulnerability is an exogenous variable that determines the risk through the intensity of the impact generated or caused damage' (Elleuch et al., 2016). It is the status or the level of fragility of a system (Bonnefous et al., 1997), and hence, it is the readiness to handle risk, which includes the system capacity and the system preparation to face the risk or anticipated consequences (Birkmann, 2007; Elleuch et al., 2016). Vulnerability is characterized by the predisposition to risk, strength-building, and elasticity to withstand shock (Gondard-

Delcroix & Rousseau, 2004). Besides, supply chain vulnerability is exposure to the serious disturbance of the supply chain (Christopher & Peck, 2004).

Risk is the function of hazard and vulnerability (Wisner et al., 2004). Vulnerability is a factor that explains why different buildings with the same level of exposure to natural disasters can be at different levels of risk. For instance, if a building is highly vulnerable to natural disasters due to less careful design or construction, or even over-loading, it could be at a high risk of collapsing or incurring other damages. However, the risk of experiencing natural disasters for each building in the same small area is equal, so better designed, constructed, and maintained buildings may be less vulnerable. Similarly, a supply chain of construction type A can be highly vulnerable to the transportation disruptions whereas a supply chain of construction type B is less vulnerable although both construction types may experience the same risk of facing the transport disruptions. Hence, construction type A will be affected more and incur a higher number of losses. Therefore, under the same risk events, different supply chains/systems can be more or less vulnerable due to their adaptive and coping capacities that withstand the risk event.

However, all these vulnerabilities can lead to significant cost impact and subsequent losses due to the downtime (Wedawatta et al., 2010). Therefore, organizations must adopt appropriate methods to identify the risks with their vulnerabilities to realize enhanced resilience in the supply chains (Christopher & Peck, 2004; Surjan et al., 2016). In these circumstances, dealing with the vulnerabilities has engaged many researchers' attention by establishing its vital significance (Wang & Li, 2016). Hence, the first and foremost problem was of preventive risk management, where the contractor should identify and/or develop various mechanisms to make the supply chain robust and risk resilient (Cui, 2018) as a new initiative in construction supply chain management.

3.4.2. Supply Chain Vulnerabilities (SCV) in IC

The interdependencies of the supply chain in the construction industry is unique. It differs from other industries such as manufacturing, being project-based with overlapping risks, which are wider than the immediate contractual responsibilities of the supply chain members (Loosemore, 2000). A typical construction supply chain includes both upstream linkages and downstream linkages, where upstream linkages include construction client and the design team conducting activities leading to the preparation for the production on-site, and the downstream linkages include the main contractor, sub-contractors and the suppliers commencing the tasks and the activities in the delivery of construction projects (Akintoye et al., 2000).

In the context of temporary multiple organization (Cheng & Zhu, 2010); as consequences arising from the difficulties arising in managing networks of a large number of different companies, supplying materials, components and multiple services (Briscoe & Dainty, 2005; Dainty et al., 2001), and with adversarial relationships (Saad et al., 2002), supply chain management processes in the construction industry face numerous obstacles (Ekanayake et al., 2019). Further, the fragmentation of design and construction processes often results in reduced visibility to detect vulnerabilities along with the supply chain network (Zainal & Ingirige, 2018a). Therefore, it is critical to swiftly identify the vulnerabilities associated with the supply chain process in order to manage the supply network efficiently and effectively (Aloini et al., 2012).

As explained above, the need for uplifting building performance, the flexibility of the product, the involvement of many specialists and the higher market uncertainty, all make construction projects more complex (Bataglin et al., 2017). In this context, the advantages of Industrialized Construction (IC – the adoption of prefabricated building components and systems), have been perceived to improve the efficiency of the flow and the quality of the construction (Gibb, 1999;

Lawson et al., 2012). However, the disruptions such as machine breakdown, traffic jams, low efficiency of customs clearance, and damages to the modular units all appeared in each phase of the IC supply chain. If these situations are not managed effectively and efficiently, the time and the cost savings realized from adopting IC will undoubtedly wither away. Any disturbance at any point of the IC supply chain will impact the entire process since once scheduled, it is relatively unchangeable and fixed (Zhai & Huang, 2017). Being resilient is also fundamental to avoid exceptionally high costs caused by the vulnerabilities when there are no precautionary measures (Vecchi & Vallisi, 2016). Therefore, the researchers Christopher and Peck (2004) presented several approaches to overcome SCV, including dual sourcing, transshipping and improved supply chain visibility (Zainal & Ingirige, 2018a).

It is critical to take vulnerabilities into account during the design of supply chain networks, so that, the supply chain networks will perform well even after a disruption (Snyder & Shen, 2006). Therefore, it is vital to properly determine the SCV relating to supply chains. Indeed, "supply chains in the face of vulnerabilities" has become a subject that has motivated the interest of numerous researchers and practitioners over recent years (Zainal & Ingirige, 2018a). For instance, Elleuch et al. (2016) also conducted a review to determine SCR and SCV. However, insufficient attention has been paid to identify the effect of vulnerabilities in SCR. Hence, this is an emerging area of research. Moreover, this research gap is highly significant in IC supply chains where there is no known focused research on this subject matter. This study, therefore, aims to fill this research gap and contribute to the existing body of literature by presenting a thorough review of the vulnerabilities in IC supply chains, from the perspective of the increasingly critical imperative for greater resilience.

3.4.3. Structured Search for Articles on SCV

This study followed a methodical approach suggested by Yi and Chan (2014), Owusu et al. (2019) and Wuni et al. (2019) which is the systematic review of literature in a domain, namely through meta-analysis to identify, retrieve and examine the extensive output in Vulnerabilities in IC Supply Chains. The approach consisted of three phases, including desktop search, targeted publications search, and examining the selected publications. Besides, the approach is clearly illustrated in the following Figure 3.1.

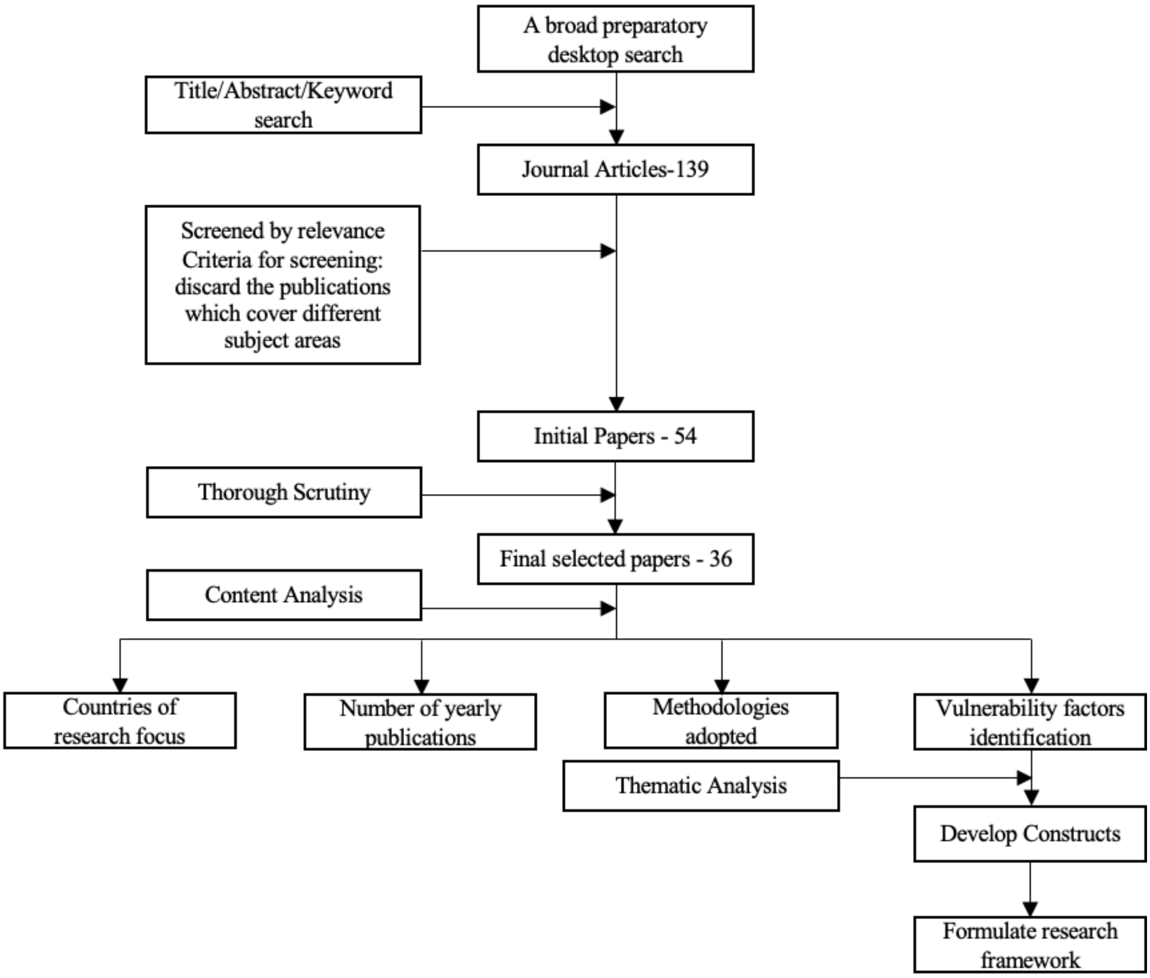


Figure 3.1:Research Methodology of SCV review

Phase 1: Desktop Search

Phase 1 involved a broad preparatory desktop search using Scopus, Web of Science, Google Scholar, ASCE library, Taylor and Francis, and Emerald Insight. The desktop search was carried out to identify publications related to vulnerabilities in SCR. However, the study used the database of Scopus first since Scopus is one of the most substantial abstracts and citation databases of peer-reviewed literature: scientific journals, books and conference proceedings (Hong & Chan, 2014; Osei-Kyei & Chan, 2015) and thereby expanded the search into other databases. Further, the study retrieved the publications from these three categories (scientific journals, books, and conference proceedings), through a title/abstract/keyword search using the keywords; 'supply chain resilience,' 'vulnerabilities,' 'risks' and 'disruptions' to retrieve the initial publications. The search was not limited to the publications belonging to a specific period since the objective was to retrieve as much of the literature as possible to date. However, the language was set to English, and the document type was limited to journal articles, books, reviews, and conference proceedings. This led to 139 publications being retrieved from this search.

A preliminary screening was then conducted for all the retrieved 139 publications to discard the publications which cover different subject areas outside the main scope of this study. Therefore, a deep scanning of the title/abstracts/keywords, as well as a document scan, was carried out to aid selecting the publications that appeared relevant and valid for the literature review. In choosing the journal articles for further processing, this study adopted a method suggested in the studies of Osei-Kyei and Chan (2015) and Owusu and Chan (2019), as explained and followed further in this study. The publications were selected after a deep scanning of the title/abstracts/keywords, as well as a document scan, of the top-ranked journals in different fields. Further, the initial study identified 54 publications, including two book publications and ten conference papers based on their relevance for this literature review (with a high number of citations) for the next phase of analysis.

Phase 2: Targeted paper search

During phase 2 of this study, a more comprehensive visual examination was conducted of the selected publications to identify the highly relevant publications on vulnerabilities in IC supply chains. This study excluded the publication categories of 'editorial,' 'letter to the editor,' 'briefing sheet,' 'introduction,' and 'forward' from the analysis. Also, the publications which did not fully express or explicate the vulnerabilities that can be related to IC supply chains were discarded in this phase. Therefore, 36 publications out of 54 publications were selected for examining in the next phase of this structured literature review. The final selection included 2 books, 7 conference papers, and 27 journal articles. An exhaustive summary of the targeted publications that were finally selected for the SCV review analysis is presented in Table 3.1.

Table 3.1:Targeted publications in the review of SCV

Paper No	Year	Citation count	Authors	Methods used	Source	Country
1	2013	102	Pettit, T.J., Croxton, K.L., Fiksel, J.	Empirical Study and focus group interviews	Journal of Business Logistics	United States
2	2004	760	Christopher, M., Peck, H.	Empirical Study	The International Journal of Logistics Management	United Kingdom
3	2012	25	Aloini, D., Dulmin, R., Mininno, V., Ponticelli, S.	Literature review	Business Process Management Journal	Italy
4	2018	-	Wang, J., Su, K., Wu, Y.	Literature Review and mathematical experiment	Wireless Personal Communications	China
5	2018	-	Truong, H.Q., Hara, Y.	Empirical Study, structural equations modeling and multiple-group analysis	Journal of Manufacturing Technology Management	Japan
6	2007	10	Berry, A.J., Collier, P.M	Exploratory case study	International Journal of Risk Assessment and Management	United Kingdom
7	2018	-	Bevilacqua, M., Ciarapica,	Modular analysis	IFAC-Papers On-Line	Italy

			F.E., Marcucci, G.			
8	2017	3	Meinel, U., Abegg, B.	Case study	Global Environmental Change	Austria
9	2010	20	Wedawatta, G., Ingirige, B., Amaratunga, D.	Literature literature review and synthesis of a doctoral research study	International Journal of Strategic Property Management	United Kingdom
10	2017	1	Ali, I., Nagalingam, S., Gurd, B.	Semi-structured interviews	Production Planning and Control	Australia
11	2015	23	Fiksel, J., Polyviou, M., Croxton, K.L., Pettit, T.J.	A research study based on literature and case study findings	MIT Sloan Management Review	United States
12	2005	274	Peck, H.	In-depth exploratory case study	International Journal of Physical Distribution & Logistics Management	United Kingdom
13	1998	48	Einarsson, S., Rausand, M.	Discussion based on case studies	Risk Analysis	Norway
14	2018	-	Zavala, A., Nowicki, D., Ramirez-Marquez, J.E.	Literature Review and mathematical modeling	Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability	United States
15	2018	-	Chaghooshi, A.J., Momeni, M., Abdollahi, B., Safari, H., Kamalabadi, I.N.	Literature review, Questionnare survey, Interpretative Structural Modeling (ISM) and Fuzzy MICMAC	Uncertain Supply Chain Management	Iran
16	2005	499	Sheffi, Y., Rice Jr., J.B.	Literature review and case study	MIT Sloan Management Review	United States
17	2007	21	Kumar, V., Viswanadham, N.	Case study	Proceedings of the 3rd IEEE International Conference on Automation Science and Engineering, IEEE CASE 2007	India
18	2011	150	Tummala, R., Schoenherr, T.	Conceptual framework	Supply Chain Management	United States

19	2004	860	Chopra, S., Sodhi, M.S.	A review	MIT Sloan Management Review	United States
20	2002	665	Handfield, R. B., Handfield, R. & Nichols Jr, E. L	A book	Book	United States
21	2016	5	Tran, T.T.H., Childerhouse, P., Deakins, E.	Case Studies	Journal of Manufacturing Technology Management	Viet Nam
22	2006	112	Cucchiella, F., Gastaldi, M.	Real options theory	Journal of Manufacturing Technology Management	Italy
23	2012	2	Chowdhury, Md.M.H., Dewan, M.N.A., Quaddus, M.A.	Analytical Hierarchy Process (AHP) integrated Quality Function Deployment (QFD)	Proceedings - Pacific Asia Conference on Information Systems, PACIS 2012	Australia
24	2011	1	Xiao, W., Liu, Z., Zhong, W.	A two-level fuzzy synthesis evaluation	Proceedings of the 2011 Chinese Control and Decision Conference, CCDC 2011	China
25	2018	-	Zainal Abidin, N.A., Ingirige, B.	A comprehensiv e questionnaire survey	Construction Innovation	United Kingdom
26	2018	-	Kochan, C.G., Nowicki, D.R.	A systematic literature review	International Journal of Physical Distribution and Logistics Management	United States
27	2008	58	Pettit, T. J.	Conceptual framework	Ohio State University	United States
28	2016	38	Annarelli, A., Nonino, F.	A review	Omega	Italy
29	2006	880	Tang, C. S.	A review	International Journal of Logistics: Research and Applications	United States
30	2014	27	Bueno-Solano, A., Cedillo-Campos, M.G.	System dynamics model	Transportation Research Part E: Logistics and Transportation Review	Chile
31	2010	48	Boin, A., Kelle, P., Clay Whybark, D.	A review	International Journal of Production Economics	Netherlands

32	2015	5	Mensah, P., Merkuryev, Y., Manak, S.	A simulation model	Procedia Computer Science	Latvia
33	2015	5	Bruno, M., & Clegg, R.	A review	Lloyd's Register Foundation	United Kingdom
34	2008	20	Stolker, R. J. M., Karydas, D. M., & Rouvroye, J. L.	Multi-Attribute Utility Theory	Third resilience engineering symposium	France
35	2015	6	Green, P. E.	A book	A book	United Kingdom
36	2014	75	Scholten, K., Scott, P.S., Fynes, B.	Case study	Supply Chain Management	Netherlands

However, this review study was limited to the selected publications on vulnerabilities for impeding SCR, rather than adopting an exhaustive and comprehensive search of vulnerabilities related publications due to the limited time and resources. While emphasizing that the analysis is based on the data obtained from the above approach, it is considered to serve the purpose well, for the current study. Further, this study first limited the search to SCR in IC, but no publications emerged. Then the search was expanded to the construction industry. The fact that only 4 relevant articles were found for analysis highlights the research gap in this important area in construction and IC, hence reinforcing the need for this study. In order to learn lessons from, and build on, relevant approaches and findings in previous studies that could benefit this study, the search was then expanded without limiting the vulnerabilities to a specific field to gather a higher number of vulnerabilities. This enabled cross-references to draw on and adapt relevant findings to the IC supply chains, as discussed in the findings and discussion section. Hence, 139 publications were first retrieved, and, finally, 36 publications were screened out after thorough scrutiny, inclusive of 4 papers based on the construction industry, as mentioned above for this structured literature review.

This study followed a systematic review approach to comprehensively identify and trace the background of all the literature (Eysenck, 1994) on SCV using a meta-analysis. Systematic review enabled collecting and reviewing all related literature, whereas meta-analysis helped in obtaining and combining these data to generate a summary of results including statistical analysis (Gopalakrishnan & Ganeshkumar, 2013). Then, the study followed a deductive research approach (Mayring, 2004) using directed content analysis without adhering to conventional or summative content analysis techniques (Hsieh & Shannon, 2005) since this method facilitates the extension of SCV related theories towards IC considering the existing theories of SCV and SCR. Further, directed content analysis is guided by a more structured process compared to other content analysis methods and it enables theory validation and extension (Hsieh & Shannon, 2005). Determining the appropriate SCV using such directed content analysis and the analysis of annual publication trends were completed at this stage. This study then continued with the thematic analysis of the identified SCV through the three phases of; coding of text, development of descriptive themes; and the generation of analytical themes (Thomas & Harden, 2008). The qualitative content analysis just provided clarification of the content of data through a systematic classification process of coding and identifying themes, whereas thematic analysis enabled generating new interpretive constructs and explanations based on the underlying themes of variables (Vaismoradi et al., 2013). Hence, following the thematic analysis, supply chain vulnerability constructs were developed in this study, by taking their underlying themes into account, formulating the framework, and explicating the developed constructs.

3.4.4. Findings and the Discussion on State-of-the-Art review of SCV

This study sets out to review the body of literature connected to the identification of vulnerabilities in IC supply chains, by targeting resilience, through the thematic categorization and eventually addressing of such vulnerabilities. In order to achieve this objective of the study, 36 selected targeted publications were examined as explained in more detail in the preceding section, and 37 vulnerabilities were identified. The researcher found identical relationships between some of the vulnerabilities and hence, categorized the vulnerabilities under six newly formulated constructs, which form the basis for the developed envisaged action framework of achieving SCR in IC.

Although there was no restriction as to the year of publication in the literature search, all the screened publications were from 1998-2018. Because the concept of SCR is relatively new, and this has been broadly studied during the last decades by demarcating the importance of this concept (Bevilacqua et al., 2018). This concept is evident basically in the management sector (A. Ali et al., 2017) and recently emerges in the construction sector (Cui, 2018). Figure 3.2 plots numbers of research papers on vulnerabilities in SCR related publications for the 20 years up to 2018.

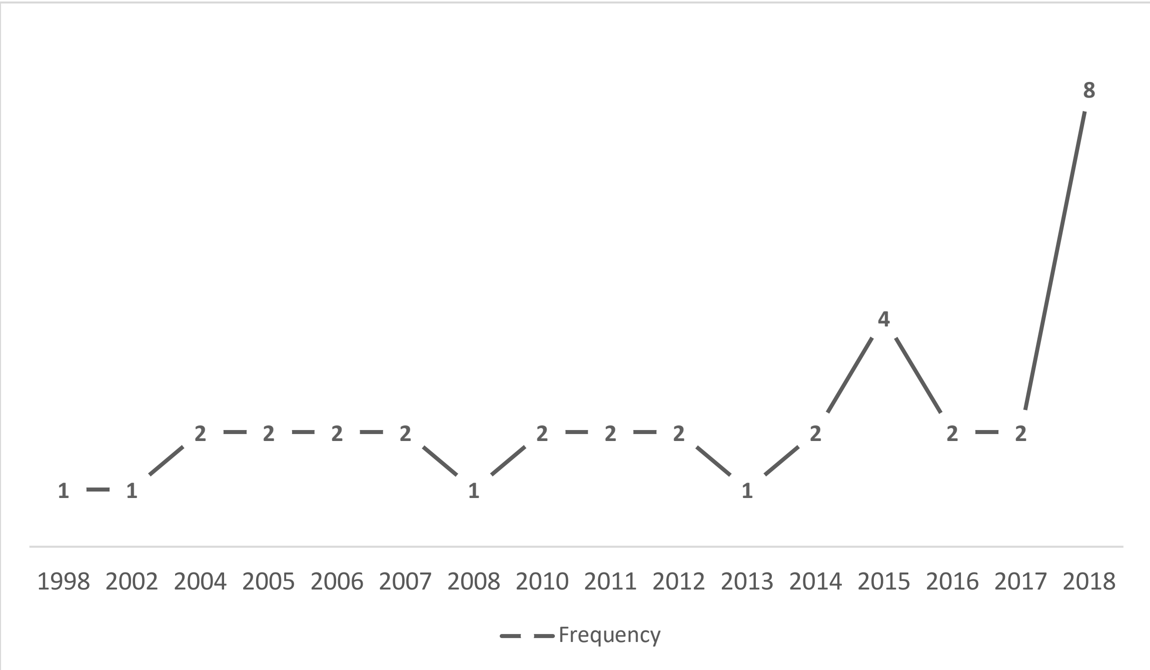


Figure 3.2: Research Papers on vulnerabilities in SCR related publications

As shown in Figure 3.2, the total number of publications from 1998 to 2014 remained steady, although a little sporadic, whereas an increment in the numbers of publications was seen in 2015. Further, the trend seems briefly steady again in 2016-2017, whereas a rapid increase in publications is evident in 2018. Before 2015, most of the papers were based on empirical studies and case studies in different industries. From 2018, the research interests have broadened towards mathematical experiments, modular analysis, and modeling such as Fuzzy-Micmac. Indeed, this pattern indicates the emerging interest in exploring better approaches to achieving SCR in project delivery. Also, this indicates that the domain of vulnerability has become more critical in SCR research.

It is also not surprising that SCR attracted more attention after four reviews published by Christopher and Peck (2004); Chopra and Sodhi (2004); Sheffi and Rice (2005) and Tang (2006) which received 760; 860; 499 and 880 citations, respectively. From 1998-2008 the SCR concept was still at an infancy stage, and publications were only from a few countries such as the United States (USA) and United Kingdom (UK). After 2010, SCR publications originated from a broader base, also indicating the growing and maturing trend of SCR. Figure 3.3 denotes the vulnerabilities in SCR related research by country.

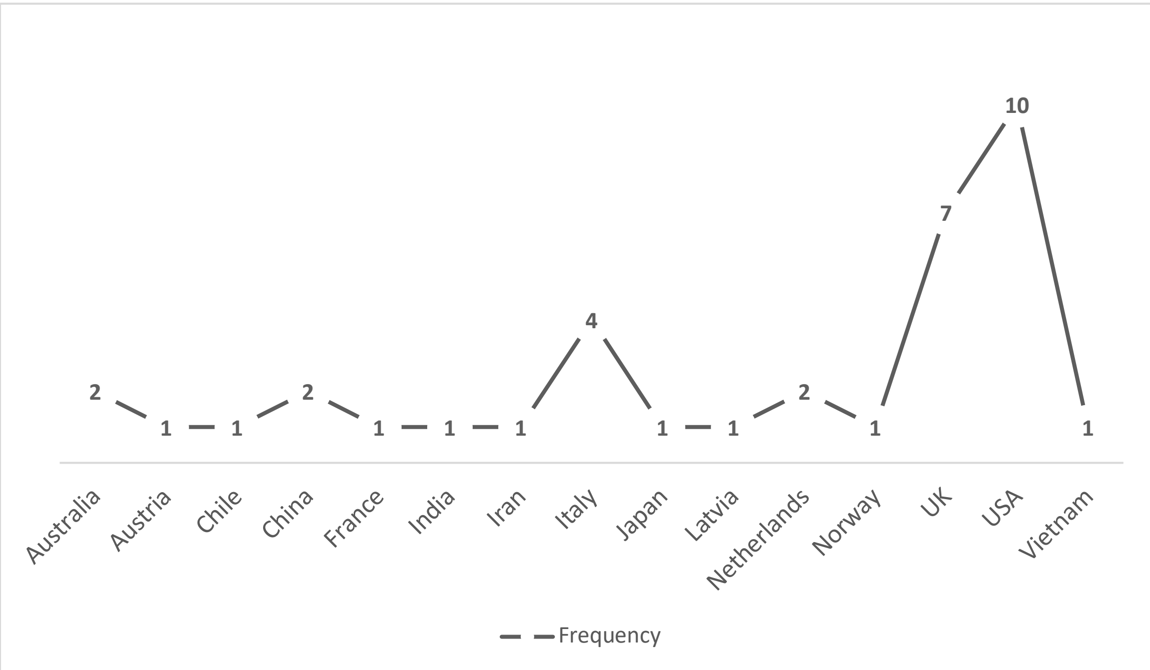


Figure 3.3: Research Papers on vulnerabilities in SCR related publications

As depicted in Figure 3.3, UK, USA, and Italy have the highest numbers of publications on the vulnerabilities in SCR within the selected publications. All three are developed countries and have contributed greatly to the knowledge domain of this study by identifying the vulnerabilities associated with supply chains. This may indicate that more developed construction industries may have already made some preliminary attempts towards SCR by identifying and addressing relevant vulnerabilities since they value the need for SCR.

The previous focus was mainly on natural and human-induced disasters, whereas research attention has now shifted to SCV such as transport disruptions, system failure, and financial disruptions. Moreover, the number of SCR studies worldwide is increasing and hence would obviously foster more research studies on vulnerabilities in supply chains and on overcoming them to uplift SCR.

Until 2018, there was no published research on SCR related to the construction industry, but the publication of Zainal and Ingirige (2018a) has triggered research interest in this too. However, most of the vulnerabilities identified in all these 36 publications have plagued the construction industry over time, specifically in IC, so much so, that diverse forms of supply chain vulnerabilities permeate the industry, hence should have received attention even earlier, thereby illustrating a long-neglected research gap.

There are different forms of IC, and these are also differently named in different countries. For example, Hong Kong (HK) uses the term Modular integrated Construction (MiC). In Australia, they call it off-site construction, and in Singapore, it is termed prefabricated construction and, more recently, Pre-engineered Prefinished Volumetric Construction (PPVC) for the 'bigger' pre-engineered volumetric units (Hwang et al., 2018). A different module assembly process is used in Japan (Barlow et al., 2003). Furthermore, the types and levels of vulnerabilities in their supply chains could differ.

According to the findings of Hwang et al. (2018) in PPVC, more attention is needed on supply chain logistics to boost project performance. Similarly, in MiC, logistics plays a critical role since the prefab components are produced in Pearl River Delta in Guangdong and then moved by trucks to the assembly sites in HK. In the Australian context, production facility logistics and stock management are difficult; crane use is vulnerable to stoppages; transport curfews affect deliveries; low tolerances cause problems in assembly; financial and political vulnerabilities can be expected, and limited supply capacities can be identified (Arif et al., 2009). Australian regulatory fragmentation appears to pose similar challenges to those in the UK and USA, while the Australian supply chain appears to have more constraints due to the relatively small market and the wide physical dispersion of production centers (Arif et al., 2009). Therefore, supply chain disruptions vary with the geographical locations and the level of vulnerabilities are also disparate. Thus, the literature review may not be exhaustive enough to provide an explicit overview of each vulnerability, given substantial differences in industry maturity levels in different countries and wide geographical spread. Therefore, for a complete picture, empirical studies on each vulnerability are needed in each country or region.

Following the trend revealed in this review, it is expedient that research into vulnerabilities in IC supply chains should be encouraged due to the following reasons; (a) IC supply chains are complex networks subjected to continual turbulence, creating a potential for unpredictable disruptions/vulnerabilities; (b) effective management of those disruptions will be critical for ensuring timely project delivery in IC; and; (c) although the industry utilizes traditional risk management techniques to manage these inherent disruptions (Luo et al., 2019), they cannot assess the complexities of supply chains, evaluate the intricate interdependencies of threats, and prepare the industry for future unknowns. These reasons lay the foundations for exploring and addressing the vulnerabilities associated with IC supply chains, so as to enhance resilience and improve performance.

Overview of the Methodological Approaches

Each research publication that was analyzed had adopted methodological approaches that were best fitted to that study in deriving the specific findings. These methods were found to be literature reviews, experts' interviews/questionnaire surveys, case studies, and mathematical modeling/simulation. Since the studies needed to ensure adequate and reliable data collection, subject matter expert surveys and case studies were predominantly used. Case studies emphasized a detailed contextual analysis of a limited number of events or conditions and their relationships in these studies. Mathematical models are usually useful when it is required to analyze a system to be controlled or optimized. Since project optimization has become vital in SCR, most of the related studies have considered mathematical modeling and analysis, such as the Fuzzy Logic and Quality Function Deployment approaches. Notwithstanding these publications, the rest of the publications were literature reviews, including systematic review methods which analyzed the existing knowledge domain, as in the case of this study.

Analysis of Vulnerabilities in IC Supply Chains

All the vulnerabilities identified following the comprehensive analysis of 36 publications are presented in Table 3.2. Thirty-seven vulnerabilities were identified in total. During the process of screening, the researcher attempted to sort out the vulnerabilities which are relevant to the IC supply chains and avoided some of the vulnerabilities such as turbulence, sensitivity, and connectivity that are specifically relevant to some other industries.

On the other hand, Table 3.2 denotes the relationship between the vulnerabilities and the cited frequency with relevant citations in previous publications. For instance, the vulnerability to 'natural disasters' was the most cited in the literature that include 18 citation counts ([1];[2];[4];[7];[11];[13];[15];[17];[23];[24];[25];[26];[30];[31];[32];[33];[34];[35]).

Table 3.2: Citation frequency analysis of general vulnerabilities for SCR

No	Supply chain vulnerability	References	Frequency	Mean	COV	Rank
	Category POV		**46**	**6.57**	**0.45**	
1	Labor strikes and related disputes	[1] [4] [5] [7] [11] [13] [23] [25] [27] [36]	10			5
2	Communication breakdowns	[3] [11] [18] [19] [20] [21] [22] [23] [25]	9			6
3	Loss of skilled workforce	[1] [7] [8] [10] [13] [25] [27] [29] [31]	9			6
4	Closing/selling off the organisations	[4] [5] [6] [8] [9] [23] [25]	7			8
5	Loss of trust/fraud	[3] [11] [13] [23] [24] [25]	6			9
6	Disruptions due to outsourcing	[1] [2] [11] [25]	4			11
7	Poor project definition	[3]	1			13
	Category PRV		**45**	**5.63**	**0.35**	
8	Transport disruptions including port stoppages	[5] [7] [11] [13] [14] [10] [23] [25] [35]	9			6
9	Quality loss	[1] [3] [5] [7] [23] [24] [25] [35]	8			7
10	Variations and/or rework	[1] [3] [6] [7] [8] [11] [27]	7			8
11	Utility disruptions i.e. electricity, water	[7] [8] [13] [25] [26]	5			10
12	Systems/machines breakdown	[1] [6] [11] [23] [25]	5			10
13	Safety hazards	[1] [11] [13] [25]	4			11
14	Site inventory losses/theft	[1] [11] [24] [26]	4			11
15	Energy scarcity	[7] [12] [35]	3			12
	Category S/CV		**12**	**4.00**	**0.74**	
16	Supply-demand mismatch/shortages	[1] [8] [10] [11] [23] [24] [25] [26]	8			7
17	Inappropriate supplier selection	[1] [3] [9]	3			12
18	Forced take over by the client	[6]	1			13
	Category TEV		**41**	**8.20**	**0.25**	
19	Information loss	[3] [7] [13] [18] [19] [20] [21] [22] [24] [25] [35]	11			4
20	Technology failure	[1] [3] [18] [19] [20] [21] [22] [24] [35]	9			6
21	Information misuse	[1] [3] [18] [19] [20] [21] [22] [24] [35]	9			6
22	Inadequate IT systems	[1] [3] [7] [8] [10] [11] [24]	7			8
23	IT system failure	[1] [3] [7] [11] [24]	5			10
	Category EEV		**75**	**8.33**	**0.65**	
24	Natural disasters	[1] [2] [4] [7] [11] [13] [15] [17] [23] [24] [25] [26] [30] [31] [32] [33] [34] [35]	18			1
25	Terrorism/war	[1] [2] [4] [7] [9] [11] [16] [23] [25] [26] [27] [28] [29] [30] [31]	15			2
26	Political Instability	[1] [2] [7] [9] [11] [23] [24] [25] [26] [27] [30] [31]	12			3
27	Adverse weather	[1] [7] [9] [10] [11] [13] [15] [17] [25]	9			6
28	Implication of new laws/regulation	[7] [11] [26] [27] [35]	5			10
29	Industry/market pressures	[2] [7] [11] [25] [31]	5			10
30	Epidemics/viruses/bacteria	[11] [12] [13] [25]	4			11

31	Physical damage to the buildings/accidents (eg: fire, boiler explosion)	[8] [16] [23] [25]	4			11
32	Nuclear radiation attack	[11] [13] [25]	3			12
	Category FIV		**18**	**3.60**	**0.50**	
33	Cash flow issues	[5] [7] [10] [23] [25] [26]	6			9
34	Price fluctuations	[1] [5] [11] [26]	4			11
35	Exchange rate fluctuations	[1] [7] [11] [26]	4			11
36	Liability claims	[11] [13] [25]	3			12
37	Economic crises	[7]	1			13

1=(Pettit et al., 2013); 2=(Christopher & Peck, 2004); 3=(Aloini et al., 2012); 4=(J. Wang et al., 2018); 5=(Truong & Hara, 2018); 6=(Berry & Collier, 2007); 7=(Bevilacqua et al., 2018); 8=(Meinel & Abegg, 2017); 9=(Wedawatta et al., 2010); 10=(A. Ali et al., 2017); 11=(Fiksel, 2015); 12=(Peck, 2005); 13=(Einarsson & Rausand, 1998); 14=(Zavala et al., 2019); 15=(Chaghooshi et al., 2018); 16=(Sheffi & Rice, 2005); 17=(Kumar & Viswanadham, 2007); 18=(Tummala & Schoenherr, 2011); 19=(Chopra & Sodhi, 2004); 20=(Handfield et al., 2002); 21=(Tran et al., 2016); 22=(Ketikidis et al., 2006); 23=(Chowdhury et al., 2012); 24=(Xiao et al., 2011); 25=(Zainal & Ingirige, 2018a); 26=(Kochan & Nowicki, 2018); 27=(Pettit, 2008); 28=(Annarelli & Nonino, 2016); 29=(Tang, 2006); 30=(Cedillo-Campos et al., 2014); 31=(Boin et al., 2010); 32=(Mensah et al., 2015); 33=(Bruno & Clegg, 2015); 34=(Stolker et al., 2008); 35=(Green, 2015); 36=(Scholten et al., 2014)

Similarly, all the citations are highlighted for each supply chain vulnerability resulting from the publications. Frequencies of the relevant citation counts are presented in Table 3.2. All the vulnerabilities were categorized into six constructs namely, Project Organizational Vulnerabilities (POV); Procedural Vulnerabilities (PRV); Supplier/customer Vulnerabilities (S/CV); Technological Vulnerabilities (TEV); External Environmental Vulnerabilities (EEV); and Financial Vulnerabilities (FIV) following a thematic analysis process.

Categorization and Explanation of the SCV

Adhering to the studies of Pettit et al. (2013), Pettit (2008), Zainal and Ingirige (2018b), and the thematic analysis research method, the identified 37 variables were categorized under the six constructs mentioned above. Pettit et al. (2013) identified seven categories of vulnerabilities, namely, turbulence, deliberate threats, external pressures, resource limits, sensitivity, connectivity, and supplier/customer disruptions following the data collection from seven global manufacturing and service firms. Therefore, those vulnerability constructs mostly cover the disruptions related to the manufacturing and the service sector.

Zainal and Ingirige (2018a) developed 11 constructs including strategic, management, personal, process, supplier/customer, technology, political/legal, environmental, physical damage, market pressures, and liquidity or credit vulnerabilities following a questionnaire survey in Malaysian public projects. These authors' focus was mainly on distinguishing the effects of interdependent supply chains within the public and private sector construction organizations in Malaysia. The study also recognized how critical vulnerabilities could generate direct cascading impacts across the supply chain through a layered framework. Also, the framework offered to understand the dynamics of the cascading effects of vulnerabilities when observed through several supply chain layers. However, it was not based on an in-depth exploration of each supply chain vulnerability and evaluation of the effects of these vulnerabilities towards construction projects. Besides, the authors suggested taking their research forward by considering the dynamics and interdependencies in evaluating vulnerabilities across the supply chains in other similar industries as well.

Both the above studies have considered the attributes of supplier/ customer vulnerabilities and the external disruptions, which highlight the vitality of these vulnerability constructs to the subject matter and hence, are also considered as vulnerability constructs in this study. However, targeting the IC supply chains, the study expanded the search limits and gathered 37 vulnerabilities causing the new categorization using a thematic analysis approach. A thorough analysis of each supply chain vulnerability helped draw out the main themes of categorization. Therefore, the newly developed constructs resemble the main vulnerability categories in the IC projects compared to the findings of Pettit et al. (2013); Pettit (2008) and Zainal and Ingirige (2018a). Further, these categories serve to extend the body of knowledge devoted to SCV in IC.

Each construct: project organizational, procedural, technological, supplier/customer, external environmental, and financial vulnerabilities consist of its inherent subfactors. Since these constructs are not independent of each other, they can arise together and interchangeably, and also contribute to one another even if arising individually or in a sequence. For instance, external environmental vulnerabilities may tend to trigger supplier/customer vulnerabilities, and the level of disruption may be cumulative. However, all these constructs may directly or indirectly cause supply chain disruptions even in IC.

The intensity of occurrence of these vulnerabilities, as based on the number of appearances in the literature was determined using citation frequency analysis to indicate the relative importance and the severity of each construct. Therefore, the total cited frequency, Mean Score (MS) and the Coefficient of Variation (COV) in each construct was calculated and stated in

Table 3.2. In calculating the MS of each construct, the total of the frequencies of all the vulnerabilities within the construct was summed up and divided by the corresponding number of variables - n. For instance, the MS of the TEV construct was calculated as follows.

$$MS\ of\ TEV = \sum_{i=1}^{n} (fTEVi)\ /n \qquad \text{Eq (3.1)}$$

i=1,2,3,4,5

Therefore, MS of TEV = (11+9+9+7+5)/5=8.20

The highest frequency construct was ranked as the most frequent vulnerability construct, as cited by the previous literature.

External Environmental Vulnerabilities-(EEV)

EEV is the construct of vulnerabilities that can cause disruptions, themselves arising from the external environment, which is beyond the SC's control. These disruptions can be either human-induced disruptive events or 'Act-of-God' (*Force Majeure*) situations. For instance, natural disasters are mostly Act-of-God situations since no person can control such events or be held responsible. On the other hand, war or terrorism are human-induced disaster events. However, this construct includes both Act-of-God and human-induced types and received 75 citation counts with 8.33 MS and the 0.65 COV. Therefore, this became the highest frequency construct. The construct included 09 vulnerabilities; natural disasters; terrorism/war; political economy changes; adverse weather; the implication of new laws/regulation; industry/market pressures; epidemics/viruses/bacteria; physical damage to the buildings/accidents (e.g., fire, boiler explosion); and nuclear radiation attack. It is not surprising that the construct received a higher MS since the first four SCV in the construct are within the top six highly cited SCV. Also, the first ranked variable 'natural disasters' is with 18 citation counts. Although the COV is the highest among the constructs, the MS is also the highest, which signifies the construct as the most important construct according to the reviewed literature.

The second-ranked supply chain vulnerability terrorism/war is also a subjective phenomenon that is ranked so high since many countries are susceptible to terrorist attacks. According to the findings of Masood and Choudhry (2010), terrorism/war, political instability are significant external risks that tend to stop or delay construction activities. This may cause disturbances to the smooth flow of supply chain activities, including supply chain logistics. Considering the IC supply chains, most prefabricated units are fabricated in a manufacturing yard away from the construction site, and transportation (and the related logistics issues) plays a significant role in the timely delivery of the units produced by the factory. Also, these risks are very volatile and also often more difficult to observe, so they may go unnoticed and affect the offshore outsourcing process (Chauhan et al., 2015).

Besides, extreme wind levels could compromise the use of cranes on-site and may delay the installation process (Gibb & Neale, 1997). Hence, these disaster events significantly affect the performance of the IC supply chains, which suggests the need for more resilient supply chains to deal with these disruptive situations.

As the third highly cited supply chain vulnerability, 'political instability' also significantly affects the performance of supply chains. Findings of Zainal and Ingirige (2018a) highlighted 'political instability' as the first ranked vulnerability in the supply chain of Malaysian public construction projects. The reason behind the finding is that public projects depend on federal money following a set of rules and regulations hence rendering the process more susceptible to political and regulatory changes. Further, regardless of the procurement type chosen, this vulnerability has shown a significant impact on supply chain performance. Political instability in offshore destinations is one of the significant risks related to IC due to the offshore outsourcing (Chauhan et al., 2015) and hence becomes more critical compared to the traditional construction projects. Adoption of novel technologies such as IC is highly dependent on the government rules and regulations (Ekanayake et al., 2019). For instance, countries and jurisdictions, including Hong Kong, Singapore, China, Australia, and the United Kingdom have benefited from their own government initiatives to encourage implementation of IC (Arif et al., 2009; Jiang et al., 2018; Tam et al., 2015). The absence of these motivational policies or application of other disruptive government regulations would retard the adoption of IC.

Industry/market pressures were ranked as the second-highest vulnerability in the study by Zainal and Ingirige (2018a). According to this review, this vulnerability was cited in five publications. The main target of any construction project is to achieve cost, time, quality, and safety targets, and it hence remains vulnerable to the industry/market pressures considering competitiveness.

Supply chains are associated with various sorts of disruptions (Snyder et al., 2006), including natural disasters, terrorism (Christopher & Peck, 2004), war, and political instability that result in serious SCV (Wedawatta et al., 2010). Also, fuel protests in the UK or France, foot and mouth disease spread in 2001 (Peck, 2005); hurricane Katrina and Rita (Snyder et al., 2006); terrorist attack in Sep 2011 in the USA (Sheffi & Rice, 2005) are some of the examples of EEV that have created critical supply chain disruptions. Further, as declared by Snyder et al. (2006), these disruptions can generate significant cost impacts due to the facility/ inventory/ network/ infrastructure breakdowns and subsequent downtime losses. Also, stock-outs, inventory costs due to obsolescence (Christopher & Peck, 2004), declines in shareholder wealth, sales growth, customer goodwill, and stock returns (Snyder & Shen, 2006) are the possible important connected issues.

Since the construction supply chains are allied with the supply chains of various other industries, economies, and regions, they are also profoundly affected by climate change or adverse weather conditions (Wedawatta et al., 2010). According to these researchers, it is vital to be well prepared to withstand the extreme weather, not only to reduce the direct influence but also the indirect adverse influence on their supply chains, which in turn might affect the organizational performance too. Hence, adverse weather has become a noteworthy vulnerability in traditional construction project supply chains (Wedawatta et al., 2010), and this supply chain vulnerability also significantly affects the logistics and on-site assembly processes when considering the supply chain of IC (Wang et al., 2018b). In addition, Meinel and Abegg (2017) have highlighted physical damage to the buildings/collapsing as another vulnerability. Though this vulnerability severely impacts IC, industry practitioners argue that after a disruption, the reusability of the prefabricated units are higher in the IC context compared to the traditional construction (Ekanayake et al., 2019).

In this EEV construct, the mostly cited publication in each supply chain vulnerability is Fiksel (2015). According to the study findings, though the industries utilize different risk management strategies to cope with supply chain disruptions, the complex, dynamic nature of supply chains invite exceptional agility and flexibility when disruptions occur.

Project Organizational Vulnerabilities-(POV)

Project organizational vulnerabilities (frequency = 46) is the second-ranked construct derived by the frequency analysis consisting of seven vulnerabilities namely, labor strikes and related disputes; communication breakdowns; loss of skilled workforce; closing/selling off the organizations; loss of trust/fraud; disruptions due to outsourcing and poor project definition. MS of the construct is 6.57, and the COV 0.45 signifies the high citation mean and the widespread within the construct.

This construct refers to the disruptions arising from the inadequate strategic business decisions undertaken, poor management decisions in project execution, and the vulnerabilities arising from the staff within the organization, and human resources availability. The most cited supply chain vulnerability within the construct was labor strikes/disputes, which was ranked as the 5th cited supply chain vulnerability. Wang et al. (2018a) divided SCV into two different classes, namely, random and non-random disruptions. ‘Labor strikes, industrial disputes and similar’ come under the non-random disputes and have a significant impact on the construction supply chain performance. Since the construction industry is a labor-intensive industry, rather than automated, labor disruptions have a considerable negative impact. Even in the IC, labor strikes, disputes are frequent, and significant (Wang et al. 2018b) since contributions from different parties’ involvement are needed to achieve one single aim, despite their own separate goals and targets.

Communication breakdown within the project team may lengthen the decision-making process (Abdul-Karim, 2008); hence, unexpected project delays may be expected. In IC, if the manufacturer is unable to respond quickly to the design changes, it may result in late delivery of the precast components to the site (Luo et al., 2019). Sudden master program changes from the main contractor result in inconsistencies between the downstream demand and the upstream production of precast components. Further, these communication breakdowns result in industrial disputes and supply chain inefficiencies in IC as well and exert strong direct influences on other IC vulnerabilities such as design changes/variations (Luo et al., 2019). Owing to the poor incorporation and management of the IC supply chain, vulnerabilities have an adverse impact on the reliability of the supply chain (Ekanayake et al., 2019). Delays in the delivery of prefabricated components to the assembly site could generate schedule delays and additional cost as a result of project organizational inefficiencies (Li et al., 2018b).

Loss of talent and unavailability of the skilled workforce also affects supply chain performance and is more critical in the IC. This is because beginning from the prefabrication factory process, skilled labor is essential up to the project delivery in IC since handling the prefabricated units are not easy but require skilled labor. Chan (2001) also agreed that skilled labor is less plentiful and could slow processes. Loss of trust/fraud also need to be critically considered since the construction supply chain is an integrated team process and loss of trust/fraud can stop the entire project process (Owusu, Chan, & Shan, 2019).

Inadequate design brief or poor project definition causes schedule variations and delays to project delivery (Abdul-Karim, 2008). This can be in the form of planning and scheduling errors that include master planning errors and sub-optimal production scheduling in the IC (J. Wang et al., 2018). Closing/selling off some supply chain organizations can generate cascading impacts on supply chain performance (Zainal & Ingirige, 2018a) by stopping the real-time delivery of finished prefabricated units in IC supply chains. Disruptions due to the outsourcing are also significant vulnerabilities under the POV, with 4 citations. Although this strategic initiative facilitates opportunities in collaboration, organizations face risks allied with this effort (Zainal & Ingirige, 2018a). Sheffi and Rice (2005) pointed out that managing these outsourcing parties and having deep relationships with these multiple outsourced suppliers often become too costly to maintain, hence reducing control over the supply chain and resulting in more disruptions. IC supply chains need outsourcing since modules are manufactured in a factory environment and pose significant challenges such as demand uncertainty, assembly problems (J. Wang et al., 2018), and poor visibility of the supply chain (Zainal & Ingirige, 2018a).

Procedural Vulnerabilities-(PRV)

PRV refer to the vulnerabilities arising from the operation at any node of the supply-production-distribution chain and can be considered as process-based disruptions. This is the construct with the third highest frequency of vulnerabilities, namely, transport disruptions;

quality loss; variations/rework; utility disruptions, such as electricity, water; systems/machines breakdown; safety hazards; site inventory losses/theft; and energy scarcity. This construct yields a 5.63 MS with a very low 0.35 COV; hence, depicts a higher level of popularity in the literature.

Transport network disruptions are highly susceptible in the supply chains of IC since most the uncertainties happen in the logistics processes. These can be due to traffic jams, the efficiency of customs clearance, damages to the units in transporting (Zhai & Huang, 2017), technical problems with vehicles, too late or too early delivery, and insufficient transportation capacity (J. Wang et al., 2018). According to these researchers, time and money savings in IC will quickly decline due to these logistics disruptions; hence, this has become a significant area of concern. Also, there is a need for adopting supply chain visibility, transshipping, dual sourcing, and holding buffer or safety stocks to improve the ability to withstand these disruptions (Christopher & Peck, 2004).

Furthermore, machine breakdowns, inventory losses, workforce unavailability, safety hazards, including damages and accidents, are also common areas of disruptions that can be expected in the assembly process of the IC supply chain (Zhai & Huang, 2017). Considering the safety hazards, the most common type of danger in IC is 'fracture' whereas 'fall' is the most common cause of accidents. The underlying root cause is 'unstable structure' where special attention is required (Fard et al., 2017). Machine breakdown is likely with negligent maintenance (J. Wang et al., 2018), and the system can fail, for instance, with the failure occurring in the manufacturing plant (Li et al., 2018b). Variations/rework is the most cost significant issue in the IC supply chain (identified as the 8th ranked vulnerability in the literature analysis). The reason behind that is, the IC supply chain is relatively fixed and unchangeable once it is scheduled (Zhai & Huang, 2017).

As explained earlier in this chapter, variations/rework appear in the form of design changes due to the poor communication between the main contractor and the manufacturer. As a result, the manufacturer will not be able to respond quickly to design changes and continues producing of precast components according to outdated design drawings, thereby incurring increased costs and delayed delivery of prefabricated components for assembly (Luo et al., 2019). In fact, the information gap between the upstream and the downstream of the IC supply chain regarding the latest delivery schedule may disrupt the production rhythm of the factory, increasing operation costs, lead to poor layout management of components, and delayed project completion.

In addition to the results generated from the meta-analysis, Wang et al. (2018b) highlighted assembly equipment problems, including periodic maintenance of assembly equipment as a disruption to the IC supply chain. Also, Li et al. (2018b) indicated mechanical failures and malfunctions of cranes and misplacement of modules on storage sites as a highly disruptive event related to the IC supply chain. Hence, this study considered this supply chain vulnerability and included it in the envisaged action framework developed in the study under the POV construct by considering its relevance to the construct.

More so, the impact of risks on IC can be 'violent' considering the shorter schedules, difficulty in rectifying errors, inability to make design changes during installation, and the prohibitive cost of reworks. There is zero-tolerance on defects in IC projects since the production schedule becomes fixed once initiated (Hsu et al., 2017). However, given that a defect only arises when a component exceeds a specified allowed tolerance, issues may materialize between design, manufacture, and assembly in IC and increase the cost of rectification and rework (Ekanayake et al., 2019). Therefore, this construct includes highly significant disruptions related to the IC supply chains.

Technological Vulnerabilities-(TEV)

TEV construct is the second-highest MS construct with the value of 8.20 with 0.25 COV and indicates that all the SCV within the construct are similarly significant. It represents the disruptions arising from the technology changes or failures in supply chains. Five vulnerabilities were categorized in this construct, namely, information loss, technology failure, information misuse, inadequate IT systems, and IT system failure by adhering to the thematic analysis technique. These SCV have received very high-frequency scores compared to most of the other SCV.

Considering the construction industry and focusing especially on IC, fragmentation of the sequential design-construction process (Zainal and Ingirige, 2018a) often results in information loss/misuse in the industry. According to their findings, technological vulnerabilities are the 6th ranked category of vulnerabilities and showed the significance of the construct. Information sharing with the supply chain members are quite complicated and implementing the information systems is costly (Tran et al., 2016). Although the contemporary information systems facilitate real-time data capturing, transmitting the data, and sophisticated analysis of supply chain data (Li & Lin, 2006), inadequate information sharing tends to aggravate operational problems in supply chains (Tran et al., 2016). These create costly consequences for every supply chain member (Madenas et al., 2015), thus highlighting needs for more effective collaboration in supply chains that requires greater attention on technical and social aspects of information sharing in equal measure (Wu et al., 2014). IC supply chains are also susceptible to technological problems (J. Wang et al., 2018). Building Information Modeling (BIM) and Radio Frequency Identification (RFID) enabled IT platforms have therefore been developed to achieve real-time visibility and traceability of IT in IC (Zhong et al., 2017).

Financial Vulnerabilities-(FIV)

FIV is the fifth cited construct in the literature consisting of 3.17 MS with 0.50 COV, also relating to less citation popularity in the literature due to the limited research in the area. However, the construct consists of influential and significant SCV, including liquidity or credit issues relating to money and poor management of monitory assets and insolvency. Hence, the construct includes cash flow issues, price fluctuations, exchange rate fluctuations, liability claims, cost overrun, and economic crises. Due to the FIV, there can be detrimental effects of late payment to the parties involved in the construction supply chains, hence resulting in frequent inefficiencies in acquiring materials/prefabricated units and the loss of trust between the project team (Kadir et al., 2005). Despite the good financial strength, it is difficult to expect excellent performance or even survival of the supply chains. Therefore, it is essential to maintain the financial consistency in the construction supply chains to address the risk associated with them (Zainal and Ingirige, 2018a).

Supplier/Customer Vulnerabilities-(S/CV)

The S/CV construct is attributed to the susceptibility factors allied with suppliers and customers of the supply chain. This is ranked as the last with the least citation frequency, due to the availability of fewer SCV in the construct. MS of the construct is low because it includes a supply chain vulnerability with one citation frequency; hence, the COV is very high.

Suppliers and the customers are the primary nodes of a supply chain, and the other activities link these two parties. According to the previous categorizations made by Pettit et al. (2013); Pettit (2008); Zainal and Ingirige (2018a), a similar construct can be found referring to the vitality of the available vulnerabilities. Disruptions of the supply chain begin with the supply resource scarcity/ shortages and it is similar in IC supply chains (Zhai & Huang, 2017). These will accumulate with the supply-demand mismatch and lead to unmet customer/client needs in any of the construction-related supply chains. Especially in the IC, insufficient material quantity, poor quality of materials, scarcity of raw parts, and inadequate production resources such as molds cause supply-demand mismatch or uncertainty (J. Wang et al., 2018).

Construction supply chains are vulnerable to single supplier dependency because it is challenging to find sub-contractor or supplier backups in one contract. The forced takeover by the client is also a significant vulnerability there. The project team must be talented in effectively managing these vulnerabilities and their downstream impacts to overcome the probable susceptibilities (Keane et al., 2010). However, it is difficult to address these vulnerabilities in IC supply chains since the project process is somewhat fixed. Therefore, it is essential to develop strategies to withstand these uncertainties targeting holistic SCR.

3.5 Supply Chain Capabilities (SCC): A Systematic Review

3.5.1. Supply Chain Capabilities

Supply chain capabilities can be considered as a source for firms' success and as the building blocks for supply chain strategy that includes operational excellence and customer closeness (Morash, 2001). However, relating to SCR, Pettit et al. (2013) identified SCR as derived from an appropriate balance between the associated vulnerabilities and capabilities in the supply chains. As previously explained, vulnerabilities are the key disruptions that disturb the normal construction process and are unanticipated and unplanned (Zavala et al., 2019). These vulnerabilities can be counterbalanced by implementing appropriate managerial controls through Supply Chain Capabilities (Pettit et al., 2013). Therefore, these SCR capabilities are distinguished from the general SCC and, these are the 'attributes that enable an enterprise to anticipate and overcome supply chain disruptions' (Pettit, 2008). Therefore, some researchers conducted studies on SCR capabilities and suggested several approaches that could be followed.

Accordingly, Christopher and Peck (2004), suggested several supply chain capability approaches, including transshipping, dual sourcing and improved visibility of the supply chains. Tomlin (2006) proposed flexibility as a supply chain capability to deal with supply chain disruptions. Purvis et al. (2016) highlighted robustness, agility, leanness and flexibility as relevant management capacities for resilient supply chains. Based on the empirical findings, Pettit et al. (2013) developed a 13-factor capability assessment tool. Also, Chowdhury and Quaddus (2015) proposed resilient SCC based on three case studies of Bangladesh garment industry. Considering the dynamics of supply chain vulnerabilities and capabilities, Zainal and Ingirige (2018a) proposed 12 capability components to improve SCR in Malaysian public construction projects. Therefore, research findings indicate that it is essential to consider the SCC in designing the supply chain networks since it denotes the resilience capability which mitigates the vulnerabilities and contributes to sustainable supply chain management (Chowdhury et al., 2012).

'Supply chain capabilities' has become a topic which has motivated research over recent years (Cui, 2018). However, insufficient attention has been paid to researching SCC in the construction industry (Zainal & Ingirige, 2018a). Therefore, it is noteworthy to consider SCC as an emerging research area in the construction industry. Indeed, the research gap is highly significant in IC. This study, therefore, attempts to fill the existing knowledge gap and contribute to the existing body of literature by conducting a systematic analysis of literature of the SCC in IC. This could underpin a robust platform to generate greater resilience in IC supply chains and lays a strong foundation for the next phases of this reseasrch.

3.5.2. Structured Search for Articles on SCC

In-depth and systematic analysis of published literature is required to conduct a comprehensive literature review and deep analysis on a particular topic (Bellisario & Pavlov, 2018; Durach et al., 2017; Thomé et al., 2016; Tsai & Lydia Wen, 2005). Therefore, this study adopted a methodical approach on the lines of that successfully used by Osei-Kyei and Chan (2015); Owusu et al. (2019) and Batista et al. (2018) to identify, retrieve and examine the extensive literature on capabilities in IC supply chains. This approach is the systematic review of literature through meta-analysis and consists of two phases, namely: searching for and identifying the targeted papers and examining and analyzing the selected papers.

Phase 1: Searching for and identifying the targeted papers

In phase 1, a broad preparatory desktop search was conducted across Scopus, Web of Science, Google Scholar, ASCE library, Taylor and Francis, and Emerald Insight, to identify the research papers on the subject of capabilities in SCR. This phase of the study initially identified that the majority of the retrieved articles are published in all these databases and libraries. Therefore, to reduce upfront overlaps, the Scopus search engine was first used in this study since this database covers most of the publications in different related research fields such as management, engineering, business, and accounting (Hong & Chan, 2014) and it is recognized for its wide coverage and accuracy (Falagas et al., 2008). In addition, the same methodology was followed and accepted by similar review studies in the construction management and engineering field (Hong & Chan, 2014; Osei-Kyei & Chan, 2015; Owusu, Chan, & Shan, 2019; Yi & Wang, 2013). Further, a comprehensive Scopus search was carried out to retrieve the research papers using the title/abstract /keyword search option with the keywords; 'supply chain capabilities,' 'supply chain capacities,' 'supply chain competencies', 'supply chain abilities', and 'resilience.' Papers with these specific terms in their title, abstract or the keywords were considered as appropriate and relevant for further consideration in this study. The search was not restricted to any specific year of publication since the study aimed to retrieve as much of the research publications as possible to date. However, the language was set to English, and document type was limited to articles. With these limits applied to the search, 167 articles were retrieved as the preliminary data set. Following the initial selection and use of Scopus, the search was next expanded to also cover the other databases and the libraries. Thereby, 184 articles were considered to be appropriate (avoiding the repetitions in the databases and the libraries) for further analysis.

After retrieving the 184 articles, a preliminary screening was conducted to identify publications specifically related to supply chain capabilities for SCR, this being the scope covered in this study. Therefore, an in-depth scanning of title/abstract/keywords was carried out to aid the appropriate retrieval of the articles. Thereby, 50 articles were retrieved. The details of these publications are listed in Table 3.3. Further, by identifying the importance of including highly cited highly relevant publications within the scope of the study, albeit not highlighting the term SCC, 5 more papers were also selected for the next phase of this study. These added up to 55 articles. Furthermore, most of these articles were published in the journals which are ranked as the top journals in their respective fields.

After the above secondary screening and adjustment process, a more comprehensive visual examination of the articles was conducted to identify highly relevant articles on capabilities in IC supply chains. Therefore, the articles were thoroughly studied to identify their relevance to the subject matter. In particular, the articles which include SCC that can be incorporated to achieve resilient supply chains in IC were selected for the further content analysis in this screening out process. Although the publications were not directly addressing IC, they were selected by considering their potential/apparent relevancy in determining SCC for IC. The publications belong to the broad categories of 'articles in press,' 'editorial,' 'letter to the editor,' 'discussions and closures,' and 'briefing sheet' in the selected journals were also excluded from the analysis. The results of the selection are presented in Table 3.3. Therefore, 44 out of 55 articles were selected for examining in the next phase of this study.

Table 3.3: Search results of papers on capabilities in SCR in selected journals

Name of the journal	Number of papers retrieved in final search	Number of papers retrieved in initial search
Construction Innovation	1	1
Journal of Business Logistics	1	1
Procedia-Social and behavioral sciences	1	1
Computers and Industrial Engineering	1	2
International Journal of Logistics: Research and Applications	1	1
Transportation Research Part E: Logistics and Transportation Review	1	2
International Journal of Logistics Management	2	4
Supply Chain Management an International Journal	5	10
Human Resource Management Review	1	1
Expert systems with applications	1	1
Production Planning and Control	4	4
International Journal of Production Research	2	2
International Journal of Production Economics	2	4
Journal of Construction Engineering and Management	1	1
Towards a Vision for Information Technology in Civil Engineering	1	1
MIT Sloan Management Review	1	1
International Journal of Physical Distribution & Logistics Management	4	4
Management Science	3	3
Manufacturing and Service Operations Management	1	1
Industrial Management and Data Systems	1	1
International Journal of Strategic Property Management	1	1
Journal of Risk and Reliability	1	1
Uncertain Supply Chain Management	1	1
Journal of Operations Management	1	1
Omega	1	1
Benchmarking: An International Journal	1	1
Civil Engineering Journal	1	1
Sustainable Production and Consumption	1	1
International Journal of Disaster Resilience in the Built Environment	1	1
Total	**44**	**55**

However, the review study is limited to the selected articles on capabilities in SCR related to IC arena rather than conducting an exhaustive and all-inclusive search in the area of study such as SCR and supply chain vulnerabilities. Therefore, it should be emphasized that the analysis is solely based on the specific data collection method adopted in this study, which is shown in Figure 3.4 and serves the study purpose as well, while ensuring its rigor. Indeed, this study does not intend to examine the entire population of the SCR related papers but to review the research trend on capabilities in SCR specially to identify the capabilities in IC supply chains for future research and development. In addition, the study first limited the search to SCR in IC, but no publications were found. After expanding the search to the construction industry, 3 articles were found. This also highlighted the research gap in this important area in construction and IC, which reinforced the need for the current study. Therefore, the search was expanded without limiting the capabilities to a specific field in order to gather a higher number of potential capabilities. This enabled learning lessons from and building on, as well as drawing on cross-references to adopt and/or adapt relevant findings that can be applied to IC supply chains.

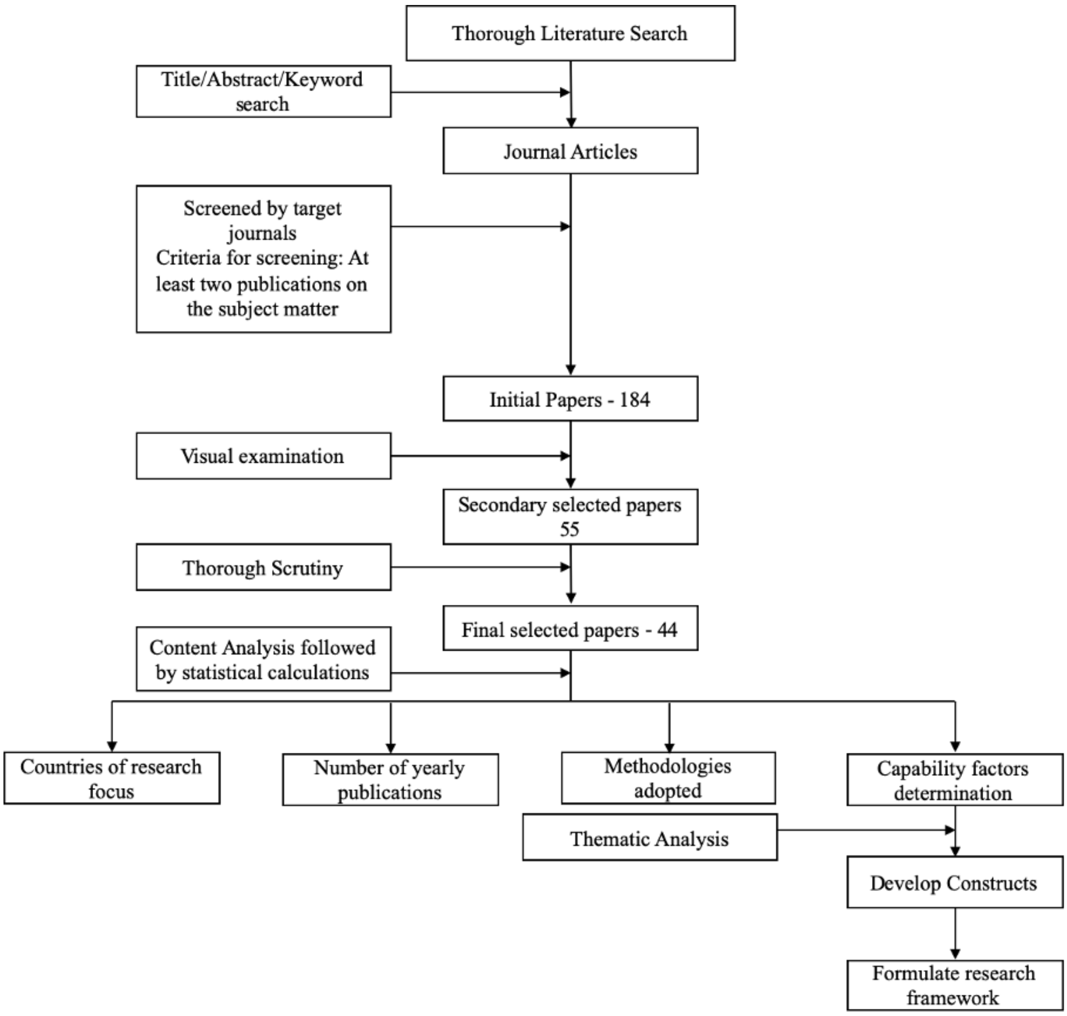


Figure 3.4: Research Methodology of SCC review

Adapted from Osei-Kyei and Chan (2015), Owusu et al. (2019)

Phase 2: Examining and analyzing the targeted papers

In phase 2, the articles retrieved after the screening process were subjected to content analysis to examine and analyze the capabilities in SCR related publications based on countries of research focus, number of yearly publications, methodologies adopted and explaining the factors identified as capability measurement items. An exhaustive summary of the selected articles is presented in Table 3.4. Following from that exercise, a thematic analysis was employed in this study to develop the constructs and to formulate the envisaged action framework of SCR.

Table 3.4: Targeted publications in the review of SCC

Paper No	Year	Citation count	Authors	Principal Research Methods used	Source	Country
1	2018	-	Zainal Abidin, N.A., Ingirige, B.	A comprehensive questionnaire survey	Construction Innovation	United Kingdom
2	2013	102	Pettit, T.J., Croxton, K.L., Fiksel, J.	Empirical Study and focus group interviews	Journal of Business Logistics	United States
3	2014	44	Mensah, P. & Merkuryev, Y.	A review	Procedia-Social and behavioral sciences	Latvia, Italy
4	2014	67	Soni, U., Jain, V. & Kumar, S.	Interpretive Structural Modeling approach, Graph Theory	Computers and Industrial Engineering	India, United Arab Emirates, United States
5	2006	880	Tang, C. S.	A review	International Journal of Logistics: Research and Applications	United States
6	2014	27	Bueno-Solano, A., Cedillo-Campos, M.G.	System dynamics model	Transportation Research Part E: Logistics and Transportation Review	Chile
7	2004	760	Christopher, M., Peck, H.	Empirical Study	The International Journal of Logistics Management	United Kingdom
8	2011	194	Jüttner, U. & Maklan, S.	Empirical Study	Supply Chain Management an International Journal	United Kingdom

9	2014	75	Scholten, K., Scott, P.S., Fynes, B.	Case study	Supply Chain Management an International Journal	Netherlands Irelands
10	2013	60	Johnson, N., Elliott, D. & Drake	Social constructionist approach	Supply Chain Management an International Journal	United Kingdom
11	2011	165	Lengnick-Hall, C. A., Beck, T. E. & Lengnick-Hall, M. L.	Review based study	Human Resource Management Review	United States
12	2014	48	Kristianto, Y., Gunasekaran, A., Helo, P. & Hao, Y	Fuzzy analysis	Expert systems with applications	Finland, United States
13	2015	54	Scholten, K. & Schilder, S.	Case study	Supply Chain Management an International Journal	Netherlands
14	2017	1	Ali, I., Nagalingam, S., Gurd, B.	Semi-structured interviews	Production Planning and Control	Australia
15	2017	36	Ivanov, D., Dolgui, A., Sokolov, B. & Ivanova, M.	Literature review	Journal of Production Research	France, Russia, Germany
16	2017	14	Brusset, X. & Teller, C.	Variance-based structural equation modeling	International Journal of Production Economics	France, United Kingdom
17	2011	35	Lim, B. T. H., Ling, F. Y. Y., Ibbs, C. W., Raphael, B. & Ofori, G.	Empirical study	Journal of Construction Engineering and Management	Singapore, United States
18	2003	6	Vaidyanathan, K. & O'brien, W.	A review	Towards a Vision for Information Technology in Civil Engineering	United States
19	2005	499	Sheffi, Y., Rice Jr., J.B.	Literature review and case study	MIT Sloan Management Review	United States
20	2005	274	Peck, H.	In-depth exploratory case study	International Journal of Physical Distribution & Logistics Management	United Kingdom
21	2006	726	Tomlin, B.	Mathematical modeling	Management Science	United States
22	2012	62	Dong, L. & Tomlin, B.	Mathematical modeling	Management Science	United States
23	2010	127	Wang, Y., Gilland, W. & Tomlin, B.	Mathematical modeling	Manufacturing and Service Operations Management	United States

24	2013	31	Kim, S.-H. & Tomlin, B.	Mathematical modeling	Management Science	United States
25	2018	1	Panova, Y. & Hilletofth, P	Simulation and modeling	Industrial Management and Data Systems	China, Russia, Sweden
26	2010	20	Wedawatta, G., Ingirige, B., Amaratunga, D.	Literature review and synthesis of a doctoral research study	International Journal of Strategic Property Management	United Kingdom
27	2018	-	Zavala, A., Nowicki, D., Ramirez-Marquez, J.E.	Literature Review and mathematical modeling	Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability	United States Mexico
28	2018	-	Chaghooshi, A.J., Momeni, M., Abdollahi, B., Safari, H., Kamalabadi, I.N.	Literature review, Questionnare survey, Interpretative Structural Modeling (ISM) and Fuzzy MICMAC	Uncertain Supply Chain Management	Iran
29	2017	22	Chowdhury, M. H., and Quaddus, M	Empirical Study	International Journal of Production Economics	Australia
30	2016	12	Chowdhury, M. H., and Quaddus, M	Field Study Questionnaire Survey and Structural Equation Modeling	Supply Chain Management: An International Journal	Australia
31	2015	112	Ambulkar S., blackhurst, J., and Grawe, S.	Empirical Study	Journal of Operations Management	United States
32	2015	27	Chowdhury, M. H., and Quaddus, M	QFD Methodology	Omega	Australia
33	2013	158	Wieland, A., and Wallenburg, C. M.	Empirical Study with Structural Equation Modeling	International Journal of Physical Distribution and Logistics Management	Germany
34	2010	149	Colicchia, C., Dallari, F. And Melacini, M.	Simulation based framework	Production planning & control	Italy
35	2016	22	Purvis, L., Spall, S., Naim, M. and Spiegler, V.	Case Study	Production planning & control	United Kingdom

36	2019	-	Singh, N.P. and Singh, S.	Survey based study	Benchmarking: An International Journal	United States
37	2019	1	Shahbaz, M.S., Soomro, M.A., Bhatti, N.U.K., Soomro, Z. and Jamali, M.Z.	Questionnaire Survey	Civil Engineering Journal	Malaysia
38	2019	4	Rajesh, R.	Fuzzy approach	Sustainable Production and Consumption	India
39	2013	47	Gosling, J., Naim, M. and Towill, D.	Empirical research based on a case study	Production Planning & Control	United Kingdom
40	2018	37	Namdar, J., Li, X., Sawhney, R. and Pradhan, N.	Numerical Study	International Journal of Production Research	United States
41	2016	37	Riley, J.M., Klein, R., Miller, J. and Sridharan, V	Questionnaire Survey	International Journal of Physical Distribution & Logistics Management	United States
42	2016	19	Mandal, S., Sarathy, R., Korasiga, V.R., Bhattacharya, S. and Dastidar, S.G.	Questionnaire Survey	International Journal of Disaster Resilience in the Built Environment	India
43	2018	10	Machado, S.M., Paiva, E.L. and Da Silva, E.M.,	Interviews based study	International Journal of Physical Distribution & Logistics Management	Brazil
44	2018	7	Treiblmaier, H	Contingency Theory and Grounded Theory approach	The International Journal of Logistics Management	Austria

3.5.3. Findings and the Discussion on State-of-the-art Review of SCC

As explained in the previous section of this chapter, 44 articles were finally selected as relevant for deeper examination after a two-phase systematic selection process. Thereafter, the selected articles were examined for research findings. Results generated from the content analysis process assisted to identify 58 capabilities for achieving SCR in IC. During the thematic analysis of the SCC, the researcher categorized these capabilities measurement items under 12 identified constructs. These constructs include the capability measurement items which have identical relationships with the constructs by being part of common themes. This laid the basis for developing the envisaged action framework for achieving SCR in IC. The articles were further analyzed to determine the annual number of publications on the subject, publications based on countries of research focus, methodologies adopted and explications to the developed constructs including their constituent measurement items as explicated below.

Trend of Publications on SCC Targeting Resilience

Figure 3.5 denotes the number of yearly publications on SCC for resilient supply chains from 2003 to 2019. Although the number of yearly publications remained steady from 2005-2010, the figures indicate a somewhat sporadic publication trend ranging from 1 (minimum) to 5 (maximum) after 2010. Therefore, it is noteworthy to state that less attention has been paid to the SCC related research studies over the past two decades, hence, these low numbers call for critical attention, research and development on SCC as well as highlight the need for more innovative research frameworks to achieve SCR.

The maximum number of publications (7) were reported in 2018. Also, moving from the literature review and empirical studies, the research interests have broadened towards structural modeling, graph theory, system dynamics modeling, QFD modeling and fuzzy analysis. This may be because of the awareness gained by the academic researchers with the set of SCR related publications made by Pettit (2008); Pettit et al. (2010) and Pettit et al. (2013). After 2014, the researchers have focused more on mathematical modeling and simulation in SCC research by maintaining a similar research pattern. In fact, this pattern depicts the growing interest in exploring better approaches to deliver SCR related research for further knowledge development.

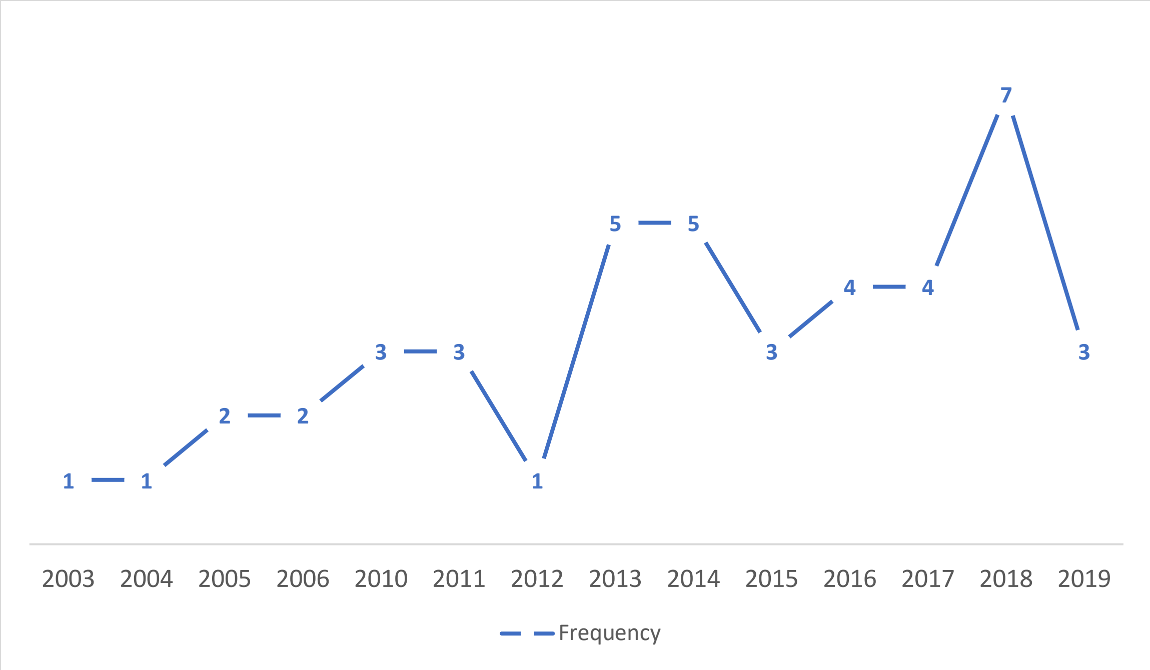


Figure 3.5: Yearly research publications on capabilities in SCR from 2003 to 2019

However, there was a sudden drop in publications in 2015, and thereafter again the figures show a gradual increment in the number of publications. Hence, the results agree with the research findings of Bevilacqua et al. (2018), that is that the concept of SCR was broadly studied during the last few decades evidencing its importance towards the organisational performance. This is clearly evident in the management research (A. Ali et al., 2017), while the trend has been explored in the construction industry recently as well (Cui, 2018). However, only three articles which discuss SCC in the construction industry were found within the selected list of publications Shahbaz et al. (2019); Zainal Abidin and Ingirige (2018a) and Lim et al. (2011). Therefore, the construction industry appears to be still lacking innovative practices in dealing with supply chain vulnerabilities despite a few ground-breaking advancements. Besides, there was no publication found on SCC in IC, hence spotlighting the long-neglected research gap that this study aims to fill. Although it appears that a specific research interest has not been previously triggered in IC itself that is until the present study that addresses this identified lacuna, all these 58 capabilities are more or less important in IC supply chains over time and are therefore 'ripe' for appropriate application to improve SCR in IC.

Each selected paper in this study has explained the different research methodologies that the researchers followed in their respective studies when deriving the findings. These methods comprised empirical studies (19), literature reviews (6), case studies (4), and mathematical modeling and simulation (14). Empirical studies and the case studies were predominantly used in research studies targeting adequate and reliable data collection. Further, case studies have facilitated detailed contextual analysis of SCC by being specific to the special cases studied. Mathematical modeling and simulation were used in the studies to analyse these systems in a controlled environment to optimise their performance by means of SCR. Notwithstanding these published papers, the other papers were the literature reviews that have analysed the existing knowledge base of SCR.

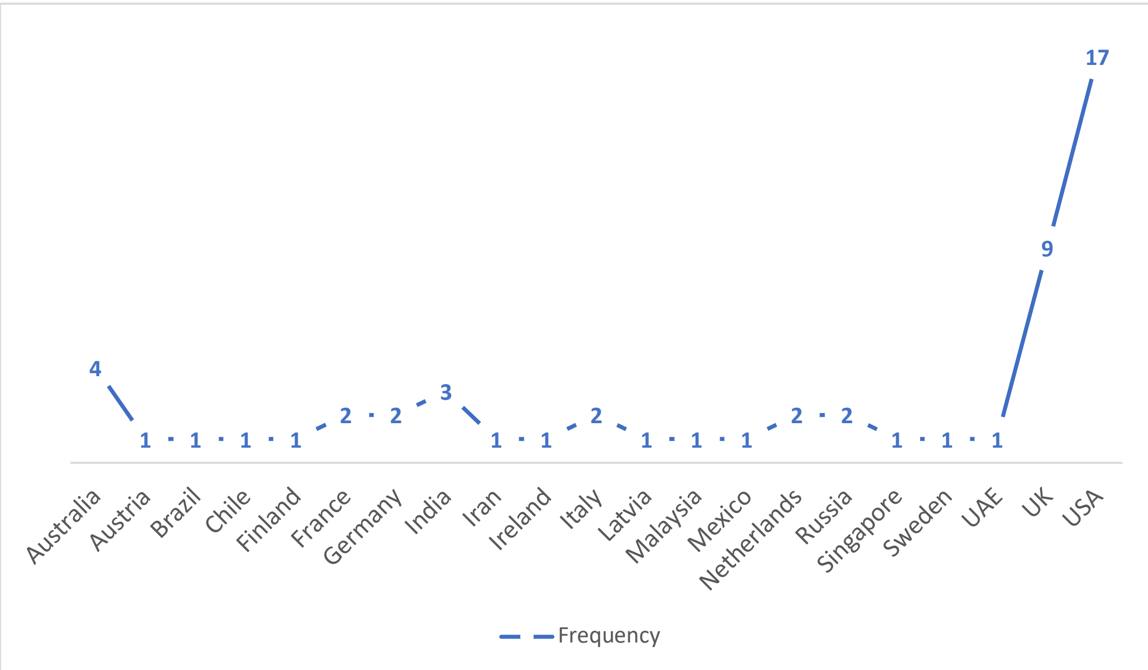


Figure 3.6: 'Capabilities in SCR' related research publications by country from 2003 to 2019

From 2003-2010, the supply chain capability concept was at its 'infancy' stage, and only two countries viz., the United States (USA) and United Kingdom (UK) paid attention to researching

SCC. After 2010, the concept broadened its horizons and was applied in research studies conducted in many developed countries such as UAE, Singapore, Australia and many more as shown in Figure 3.6.

However, USA (17) and the UK (9) accounted for the highest number of publications in the SCC knowledge domain within the selected publications. This may indicate that developed countries have already launched some exercises if not initiatives, to develop SCC targeting resilience since these countries apparently value SCR and its associated benefits. Moreover, the emerging attention paid to SCC worldwide can be identified in Figure 3.6. This, obviously fosters more research studies on SCC and strengthens them in uplifting SCR. The primary lesson to draw from this analysis is that more research studies on SCC should be encouraged with the objective of developing pragmatic and innovative SCC to successfully deal with the alarming rate of supply chain vulnerabilities.

Identifying the research trend revealed in this study, it is expedient and encouraging to research on SCC in IC due to the following reasons; (a) IC supply chains are complex and vulnerable to a number of unforeseeable disruptions (Luo et al., 2019); (b) the IC supply chain is relatively fixed and unchangeable once setup (Zhai et al., 2015) hence the disruptions may generate the cascading impacts; (c) although the industry practises traditional RM approaches, they are unable to assess the supply chain complexities, and prepare the supply chain for future unknowns including black swan events and (d) there is, therefore, a need to determine the appropriate SCC to successfully withstand all these supply chain disruptions in IC. These reasons provide the basis for exploring the SCC associated with IC for enhanced SCR in a value-added supply chain.

Analysis of the SCC associated with IC

All the SCC identified from the 33 publications following the systematic analysis of the literature are presented in Table 3.5. After a comprehensive screening out process, the researcher identified 58 SCC which are relevant to the IC in total and excluded some of the capabilities such as part commonality, asset utilization, product variability reduction, deviation, near-miss analysis, and layered defences that are specifically relevant to the manufacturing industry.

Table 3.5: Citation frequency analysis of general capability measurement items for SCR

Nr	Capabilities	References	Frequency	Mean	COV	Rank
1	**Flexibility: Ability to quickly mobilise resources when required**		**85**	**9.44**	**0.68**	
	Multiple sources	[1] [2] [4] [7] [8] [10] [11] [14] [15] [19] [20] [21] [22] [23] [29] [30] [35] [37] [38] [39] [40] [42]	22			1
	Supplier contract flexibility	[1] [2] [5] [17] [19] [20] [28] [29] [30] [32] [35] [37] [39] [40] [42] [43]	16			2
	Alternate distribution channels/multimodal transportation	[1] [2] [5] [20] [28] [29] [30] [35] [37] [38] [39] [42]	12			5
	Risk pooling/sharing	[1] [2] [4] [7] [8] [10] [16] [20] [28] [30]	10			7
	Integrating inventory management with SCM tools	[1] [2] [16] [18] [27] [28] [33] [35] [37]	9			8
	Vertical integration	[14] [28] [33] [39] [41]	5			12
	Multiple uses	[1] [2] [5] [19]	4			13
	Production postponement	[1] [2] [28] [38]	4			13
	Modular product design	[1] [2] [37]	3			14
2	**Capacity: Availability of resources to enable continuous production**		**44**	**11.00**	**0.43**	
	Reserves capacity/inventory buffers	[1] [2] [7] [15] [23] [20] [21] [28] [29] [30] [32] [34] [35] [37] [38] [43]	16			2
	Backup facilities	[1] [2] [5] [15] [16] [19] [24] [27] [30] [32] [35] [40] [43]	13			4
	Redundancy	[1] [2] [7] [9] [14] [19] [20] [21] [35] [43]	10			7
	Backup energy sources	[1] [2] [29] [30] [32]	5			12
3	**Efficiency: Capability to produce outputs with minimum resources**		**22**	**5.50**	**0.79**	

	Waste elimination	[1] [2] [3] [4] [19] [25] [26] [28] [29] [32] [38]	11			6
	Labor productivity	[1] [2] [5] [19] [28] [29] [32]	7			10
	Product variability reduction	[1] [2]	2			15
	Failure prevention	[1] [2]	2			15
4	**Visibility: Knowledge of the status of current operating resources and the environment**		**28**	**7.00**	**0.76**	
	Products, assets, people visibility	[1] [2] [4] [7] [8] [9] [10] [30] [33] [38] [40] [42] [43]	13			4
	Efficient IT system & information exchange	[1] [2] [29] [30] [32] [33] [36] [38] [41] [43]	10			7
	Business intelligence gathering	[1] [2] [38]	3			14
	Finite capacity scheduling tools with procurement visibility/e-procurement	[18] [38]	2			15
5	**Adaptability: Ability to modify operations in response to disruptions or opportunities**		**35**	**4.38**	**0.52**	
	Fast rerouting of requirements	[1] [2] [5] [20] [29] [30] [33] [44]	8			9
	Learning from experience	[1] [2] [5] [12] [19] [20]	6			11
	Alternative technology development	[1] [2] [13] [16] [29] [43]	6			11
	Deploying IT based reporting tools	[16] [29] [30] [32] [33]	5			12
	Conducting parallel processes instead of series processes	[7] [19] [28] [38]	4			13
	Lead time reduction	[1] [2]	2			15
	Strategic gaming and simulation	[1] [2]	2			15
	Maintaining buffer time	[27] [34]	2			
6	**Anticipation: Ability to detect potential future disruptive events**		**43**	**6.14**	**0.51**	
	Risk management	[1] [2] [4] [5] [6] [7] [9] [30] [31] [34] [38] [43]	12			5
	Monitoring early warning signals	[1] [2] [19] [20] [29] [30] [43]	7			10
	Forecasting/predictive analysis	[1] [2] [19] [20] [29] [32] [37] [43]	8			9
	Quality control and checking defection	[1] [2] [29] [32]	4			13
	Cross training/intensive training	[14] [29] [30] [41] [43]	5			12
	Deploying tracking and tracing tools	[16] [30] [32] [43]	4			13
	Business intelligence and disruption management research	[10] [19] [30]	3			14

7	**Recovery: Ability to return to normal operational state promptly**		**18**	**6.00**	**0.17**	
	Consequence mitigation	[1] [2] [29] [30] [34] [43] [44]	7			10
	Communications strategy	[1] [2] [28] [29] [30] [43]	6			11
	Crisis management	[1] [2] [29] [30] [43]	5			12
8	**Dispersion: Decentralization of resources and clients**		**10**	**3.33**	**0.17**	
	Distributed decision making	[1] [2] [33] [44]	4			13
	Distributed capacity and assets	[1] [2] [44]	3			14
	Decentralization of key resources	[1] [2] [44]	3			14
9	**Collaboration: Ability to work effectively with other parties for mutual benefit**		**24**	**4.80**	**1.23**	
	Collaborative information exchange & decision making	[1] [2] [13] [18] [20] [28] [29] [30] [32] [33] [37] [38] [40] [42] [43]	15			2
	Collaborative forecasting	[1] [2] [30] [38] [43]	5			12
	Public–private collaboration	[14] [43]	2			15
	Obtain more competitive price from suppliers and subcontractors	[17]	1			16
	Procure materials globally	[17]	1			16
10	**Market position: Status of an organization or its services/ products in specific markets**		**32**	**6.40**	**0.45**	
	Close and healthy client-contractor relationships	[1] [2] [6] [14] [17] [28] [29] [32] [33] [37]	10			7
	Improve the quality of SC process	[5] [14] [17] [19] [20] [22] [23] [28]	8			9
	Improve delivery speed	[5] [17] [19] [20] [22] [23] [28]	7			10
	Brand equity of the organizations	[1] [2] [14] [29]	4			13
	Market share of the organizations	[1] [2] [5]	3			14
11	**Security: Defense against deliberate intrusions**		**8**	**4.00**	**0.00**	
	Cyber-security	[1] [2] [29] [32]	4			13
	Personnel security	[1] [2] [29] [32]	4			13
12	**Financial strength: Capacity to absorb fluctuations in cash flow**		**23**	**5.75**	**0.09**	
	Insurance	[1] [2] [22] [23] [29] [32]	6			11
	Financial reserves and funds	[1] [2] [17] [29] [30] [32]	6			11
	Price margin	[1] [2] [29] [32] [38] [43]	6			11
	Portfolio diversification	[1] [2] [28] [29] [32]	5			12

1=(Zainal & Ingirige, 2018a); 2=(Pettit et al., 2013); 3=(Mensah & Merkuryev, 2014); 4=(Soni et al., 2014); 5=(Tang, 2006); 6=(Cedillo-Campos et al., 2014); 7=(Christopher & Peck, 2004);

8=(Jüttner & Maklan, 2011); 9=(Scholten et al., 2014); 10=(Johnson et al., 2013); 11=(Lengnick-Hall et al., 2011); 12=(Kristianto et al., 2014); 13=(Scholten & Schilder, 2015); 14=(A. Ali et al., 2017); 15=(Ivanov et al., 2017); 16=(Brusset & Teller, 2017); 17=(Lim et al., 2011); 18=(Vaidyanathan & O'Brien, 2004); 19=(Sheffi & Rice, 2005); 20=(Peck, 2005); 21=(Tomlin, 2006); 22=(Dong & Tomlin, 2012); 23=(Wang et al., 2010); 24=(Kim & Tomlin, 2013); 25=(Panova & Hilletofth, 2018); 26=(Wedawatta et al., 2010); 27=(Zavala et al., 2019); 28=(Chaghooshi et al., 2018); 29=(Chowdhury & Quaddus, 2017); 30=(Chowdhury & Quaddus, 2016); 31=(Ambulkar et al., 2015); 32=(Chowdhury & Quaddus, 2015); 33=(Wieland & Wallenburg, 2013); 34=(Colicchia et al., 2010); 35=(Purvis et al., 2016); 36=(Singh & Singh, 2019); 37=(Shahbaz et al., 2019); 38=(Rajesh, 2019); 39=(Gosling et al., 2013); 40=(Namdar et al., 2018); 41=(Riley et al., 2016); 42=(Mandal et al., 2016); 43=(Machado et al., 2018); 44=(Treiblmaier, 2018)

In addition, Table 3.5 presents the relationship between SCC and the cited frequency of relevant citations in the selected papers. For instance, 'Multiple Sources' was the first ranking supply chain capability measurement item as cited by the papers which includes 22 citation counts ([1] [2] [4] [7] [8] [10] [11] [14] [15] [19] [20] [21] [22] [23] [29] [30] [35] [37] [38] [39] [40] [42]). Similarly, all the relevant citations are stated in front of each capability in Table 3.5. The researcher conducted thematic analysis as demonstrated by Owusu et al. (2019); Chan and Owusu (2017) and Owusu, Chan, and Shan (2019) to categorize all the identified SCC into 12 constructs namely, Flexibility, Capacity, Efficiency, Visibility, Adaptability, Anticipation, Recovery, Dispersion, Collaboration, Market Position, Security and Financial Strength. The results generated from the thematic analysis are further elaborated as follows.

Categorization and Explanation of the SCC

The researcher categorized all the 58 SCC into the aforementioned 12 constructs based on the study protocols and developments by Pettit et al. (2013); Pettit (2008) and Zainal and Ingirige (2018a) during their thematic analysis process. Pettit et al. (2010) identified 14 categories of SCC related to the limited brands in the manufacturing industry. Zainal and Ingirige (2018a) developed 12 constructs by making the categorization more specific to the construction industry, which also laid the basis for this current study. Pettit et al. (2010) and then, Zainal and Ingirige (2018a) have used the following capability constructs in their studies namely

Flexibility, Capacity, Efficiency, Visibility, Adaptability, Anticipation, Recovery, Dispersion, Collaboration, Market Position, Security and Financial Strength in their studies. This highlights the vitality of each construct considered in this study as the capability constructs. However, the study expanded the search limits targeting the IC supply chains and gathered 58 SCC for the new categorization using a thematic analysis approach. Therefore, these SCC will now be addressing the SCR in industrialized construction, which is not explored in the previous studies. Therefore, this study specifically facilitates a significant contribution to the IC knowledge domain. A thorough analysis of each SCC was triggered, developing the main constructs, and these specifically formulated constructs along with supply chain capability measurement items, serve as an extension to the body of knowledge specific to the SCC in IC.

Citation frequency analysis was conducted to indicate the relative importance of each construct (Chan & Owusu, 2017; Owusu et al., 2019). Hence, the total cited Frequency (F), Mean Score (MS), and Coefficient of Variation (COV) of each construct were calculated and presented in Table 3.5. The total of the frequencies of all the SCC within each construct was added together and divided by the corresponding number of variables – n, in deriving the MS of each construct. For instance, the MS of the 'security' construct was calculated as follows. Further, the construct which received the highest total frequency was considered as the most frequently cited SCC in the previous literature.

$$MS\ of\ 'Security' = \sum_{i=1}^{n}(fSecurityi)\ /n \qquad \text{Eq (3.2)}$$

i=1,2

Therefore, MS = (2+2)/2=2.00

Flexibility

Flexibility is the construct that denotes the ability to quickly mobilize resources when required. This construct was the most highly cited construct in the literature with 85 citation counts and

9.44 MS. Although this belongs to the highest total frequency, the construct reserves the second highest MS value due to the citation counts spread (from 22 to 3 with 0.68 COV) within the construct. According to Pettit et al. (2010), flexibility can be in sourcing or order fulfilment. Multiple sources, multiple uses, and supplier flexibility belong to the first category, whereas the other SCC in the constructs belong to the flexibility in the order fulfilment. According to the study findings of Badir et al. (2002), the delays in IC supply chains are due to the supply delays and shortage of raw materials. Having alternative suppliers/sources may be effective in dealing with such issues in IC. Most of the materials in IC systems in Malaysia are imported from developed countries and cause increased construction costs (Thanoon et al., 2003) hence calls for multiple sources of supply. Flexible risk sharing, and pooling is also vital in IC supply chains as it is cited as the second highest ranking capability measurement item in this analysis. It is evident that some of the project teams used to share inventory holding costs (Zhai et al., 2018) as a result of risk impact sharing in IC. Lim et al. (2011) also highlighted some of the SCC relating to the flexibility that should be adopted in construction firms to realize the benefits.

Supplier contract flexibility is also vital in construction projects (Zainal and Ingirige, 2018a) since there are many uncertainties associated with the supply and demand. This will avoid the unnecessary cost and time implications with the availability of easy modifications to specifications, quantities, and terms. However, decision parameters of supplier selection and employment of multi-supplier configurations are still needed to be formulated and analytically solved in the context of IC (Arashpour et al., 2017). Integrating inventory management with supply chain management was also considered as a supply chain capability in the studies of Zainal and Ingirige (2018a); Brusset and Teller (2017); Zavala et al. (2018) and Chaghooshi et al. (2018). Identifying the benefits allied with Zhong et al. (2017) suggested the possible integration of BIM and RFID in IC projects to manage IC supply chains effectively and efficiently. As vertical transportation has been identified as an issue in IC due to the transportation of heavy and bulky prefabricated units, the need for having alternative/multi-modal transportation is urged.

Further, since the IC supply chains are highly vulnerable to transportation disruptions (Z.Wang et al., 2018), this capability measurement item may be in high demand in IC. Having multiple capabilities at each location also adds flexibility to the supply chains (Sheffi & Rice, 2005). Postponement of the production is also essential for a flexible supply chain (Chaghooshi et al., 2018) and it is even vital in the IC supply chains since on-site disruptions such as tower crane breakdowns (Arif et al., 2009) may lead to postpone the delivery of prefabricated units to the site to mitigate the potential associated costs. In addition, modular product design with appropriate production plans and with the optimum outsourcing quantities is value added in IC (Hsu et al., 2017). Also, it is worth proposing vertical integration of supply chain configuration between logistics, on-site assembly, and outsourcing manufacturer under such circumstances (Hsu et al., 2017).

Capacity

Capacity is the availability of resources in the supply chain to enable continuous output in IC. This construct includes 4 SCC such as redundancy, backup facilities, reserves capacity/inventory buffers, and backup energy sources. This is the second highest frequency construct with an MS of 11.00, and 0.43 COV indicating the higher internal consistency of citation counts within the construct. One of the measurement items within the construct is ranked as the second in the overall analysis, which justifies the emerging attention of the researchers towards this construct. An organization's ability to quickly recover from a disruption can be enhanced by achieving redundancy (Sheffi & Rice, 2005). According to the authors, it is important to maintain additional resources in reserve to be used during a disruption

(Shahbaz et al., 2019). However, it is extremely important to determine the correct level of redundancy to avoid unnecessary cost implications. Since IC supply chains are commonly vulnerable to tower crane breakdowns, transportation disruptions, low tolerance-linked problems in assembly and limited supply capacities (Arif et al., 2009), it is vital to maintain back-up facilities, safety stocks, and reserves. Besides, it has been evident that labor force on site spends considerable time waiting for prefabricated units, and the allied benefits of IC will wither away as a result (Zhai et al., 2018). If it can maintain adequate inventory buffers to hedge against supply chain uncertainty, profitable supply chains can be realized by mitigating rearrangement cost and the tardiness penalty (Zhai et al., 2018). Further, standard operational research methods such as linear programming have been widely employed to optimize the size of the inventory buffers in IC since it is essential to avoid maintaining wasteful stocks (Arashpour et al., 2017). Maintaining adequate energy source backups is also suggested as a supply chain capability in the studies of Zainal and Ingirige (2018a) and Pettit et al. (2013).

Efficiency

Efficiency depicts the supply chain capability to produce more outputs with less resources. Therefore, the construct includes the SCC of waste elimination, labor productivity, product variable reduction, and failure prevention. This construct belongs to 22-citation frequency with 5.50 MS, and 0.79 COV. It also signifies the less frequent appearance of these capabilities in the literature and highlights the relative importance of conducting the research studies on these capabilities in future. According to the findings of Wong et al. (2003), IC enables lesser waste generation at the site. Also, the rate of reusability and the recyclability of wastage is higher in the IC (Begum et al., 2010). However, targeting these benefits in IC, it is vital to reduce the waste in IC supply chains. Just-in-time management, adhering to lean construction principles, and the planning of industrial plants play a major role in such circumstances (Li et al., 2011).

Improving labor productivity helps to improve the supply chain efficiency (Tang, 2006). This is evident in Japanese and Swedish IC projects (Thanoon et al., 2003). However, low labor productivity and associated high costs have negatively impacted industrialized building production in Malaysia (Thanoon et al., 2003); hence, there is a need for efficiency in resilient IC supply chains. Product variability reduction and failure prevention are another two important SCC, come under the main construct of efficiency as cited by Zainal and Ingirige (2018a) and Pettit et al. (2013).

Visibility

Visibility is referred to as having knowledge of the status of current operating resources in the supply chain and the supply chain environment. The construct consists of 4 measurement items with 28 citations frequency. By stressing the need for visibility in IC supply chains, Zhong et al. (2017) proposed BIM and RFID enabled platform to achieve traceability and real-time visibility in IC. Besides, business intelligence gathering is another important parameter that improves the visibility of supply chains (Pettit et al., 2010). Further, it is vital to have an efficient IT system in IC supply chains to bridge the existing gap between these IT systems used in design, prefabrication and on-site assembly processes (Čuš-Babič et al., 2014). Further, the integration of information flows and information mapping is possible with BIM-based construction (Čuš-Babič et al., 2014). In addition, paper-based documentation at the site is usually ineffective and difficult in terms of receiving quick responses, therefore, integrating promising IT namely bar code scanning, personal digital assistants (PDA), and data entry mechanisms are critical in improving the convenience and the effectiveness of construction supply chain visibility (Tserng et al., 2005).

RFID and bar code reading facilitate promising visibility, via increased speed and accuracy of data entry in IC (Li et al., 2011). Hence, supply chains of construction projects attempt to achieve efficient real-time data and information sharing by adhering to these techniques (Wang et al., 2007). Indeed, adapting BIM-based tools is extremely useful in achieving procurement visibility in construction projects whereas integrating BIM with Geo-Information Systems (GIS) is useful for logistical purposes in IC supply chains (Irizarry et al., 2013). Also, Singh and Singh (2019) suggested big data analytics as a technique for building SCR. Therefore, this 'visibility' construct provides numerous advantages for improved resilience in dealing with disruptions.

Adaptability

Adaptability is the ability to modify operations in response to disruptions or opportunities. The construct received 35 total citations count with 4.38 MS, and 0.52 COV. This shows that less attention is paid on the supply chain adaptability in the literature. As the SCC can be for any kind of a project and/or organization, it is beneficial to deploy lessons learnt to manage SCR (Peck, 2005), develop alternative strategies/innovations to enhance the capability of dealing with supply chain vulnerabilities (Brusset & Teller, 2017; Scholten & Schilder, 2015), employ fast rerouting of requirements (Peck, 2005), conduct parallel processes instead of series processes as much as possible (Chaghooshi et al., 2018), and reduce the lead time of the activities and the processes (Zainal and Ingirige, 2018a).

On the other hand, in IC, transportation and installation of the prefabricated units are risky. Unavailability of clear instructions for transportation and installation may cause supply chain disruptions, and therefore, the trials or simulation need to be conducted in a virtual environment prior to commencing the activities, so as to save costs and time (Li et al., 2011). These researchers also suggested that virtual prototyping helps mitigate the rework cost and time delays under these circumstances. In addition, to effectively dealing with disruptions, optimization of precast production scheduling is extremely important. Therefore, the industry utilizes advanced programming techniques such as constraint programming-based production scheduling and genetic algorithm-based production scheduling (Chan & Hu, 2002). Deploying IT-based reporting tools also enables efficient information sharing between the supply chain members (Tserng et al., 2005) and can be a precursor to the resilient supply chains in IC.

Maintaining adequate buffer time between prefabrication and on-site assembly are beneficial in enhancing the adaptability of IC supply chains (Arashpour et al., 2017). To reduce delays in delivery to the site, the contractor would request the order at an earlier due date from the prefabrication factory in IC (Zhai et al., 2018). Production lead time hedging, and operational lead time hedging (keeping safety lead-time) were considered as effective ways to improve supply chain adaptability (Zhai & Huang, 2017; Zhai et al., 2018). Also, transportation lead-time hedging is particularly required in IC supply chains to mitigate the impact of transportation disruptions while contributing to win-win benefits from better coordination between supply chain members (Zhai et al., 2018).

Anticipation

Anticipation is the ability to detect potential future disruptive events in the supply chains, and it is vital to enhance the preparedness to the enforceable disruptions. This construct consisted of 7 SCC with 43 total frequency and 6.14 MS. Industries including IC follow various RM practices in order to identify and contain supply chain disruptions since IC supply chains are vulnerable to the numerous risks throughout the prefabrication supply chain, from design, manufacturing, and logistics, to on-site assembly (Li et al., 2016).

Further, IC supply chain risks are closely associated with the stakeholders involved in the supply chain. Therefore, it is necessary to identify the risks based on stakeholders in order to address these risks successfully (Luo et al., 2019). By identifying the importance of predictive analysis, many studies, including Hsu et al. (2017) attempted to predict the best production quantity and the schedule before the construction under demand uncertainty of IC. Further, Ambulkar et al. (2015) highlighted the importance of establishing a risk management structure that manage both high and low impact supply chain disruptions. In addition, there is a tremendous need for intensive training of the supply chain members of IC to prepare for potential uncertainties, since a disruption at one point can trigger the failure of the entire supply chain. Besides, quality control and checking for defects also play a major role in anticipating the disruptions for SCR (Zainal and Ingirige, 2018a).

However, very little attention has been paid in the construction industry to gather business intelligence via disruption management research to achieve SCR (Zainal and Ingirige, 2018a), whereas this is an imperative in IC, hence addressed in this study. RFID, as an automated data collection technology is a promising technology to efficiently track and trace the components in prefabricated construction supply chains (Demiralp et al., 2012). However, it is vital to apply a proper cost-sharing ratio that can be calculated based on the benefits received prior to enabling the RFID on-site (Demiralp et al., 2012). Moving ahead of the RFID technology, Irizarry et al. (2013) suggested integrated BIM and GIS tool, which tracks the status of the supply chain and provides warning signals to ensure the adequate delivery of materials.

Recovery

Recovery is another supply chain capability which can be considered as the ability to promptly return to a normal operational state. This construct includes 3 SCC, namely, communications strategy, consequence mitigation, and crisis management. Comparatively low citations frequency (18) in this category depicts the need for future research and development of the knowledge concerned. Maintaining a proper communication strategy during a disruption is highly significant to respond promptly to the situation, and it will assist in the prompt recovery from the disruption and the possible reduction of the impact (Zainal and Ingirige, 2018a). As a technique for 'consequence mitigation', the IC supply chains currently follow the traditional RM strategies, which enables risk reduction based on the likelihood and impact (Li et al., 2016). This evokes and highlights the need for a proper consequence mitigation strategy specifically targeting resilience in IC that is based on the particular context, constraints and priorities in IC. As a suggestion for crisis and emergency response management in IC supply chains, Irizarry et al. (2013) suggests employing IT technologies such as GIS and digital building information technologies.

Dispersion

Dispersion is the supply chain capability which enables decentralization of resources and clients. This construct has received the least attention among the academic researchers in focusing SCR and hence received the least citation count of 10 with 3.33 MS and 0.17 COV. However, Arashpour et al. (2017) asserted robust decision making to be critical in the advanced manufacturing of prefabricated products. Therefore, distributed decision making is essential in making optimized and timely purchasing decisions in IC supply chains (Arashpour et al., 2017). Dispersion of the facilities at various locations is also significant in dealing with disruptions since they enable prompt availability of the facilities right after the disruption. Performance of a decentralized resources system is also needed in IC since the supply chain is usually hampered by supply chain uncertainties (Zhai et al., 2018) and the system could be further improved through coordinating the logistics processes which are operated by separated entities in the supply chain (Vrijhoef & Koskela, 2000).

Collaboration

Collaboration is the ability to work effectively with the other parties for mutual benefit and considered as one of the important supply chain capabilities in SCR (Pettit et al., 2013; Shahbaz et al., 2019). The total citation frequency of 24 along with the MS of 4.80 depicts the low attention paid towards the construct within the literature, although the construct is vital. Multi-party collaboration is vital in the supply chain of IC (Thanoon et al., 2003) during design, production, logistics, and the assembly and its absence may cause design errors and construction problems as usual disruptions (Arashpour et al., 2017). Therefore, Li et al. (2011) proposed virtual prototyping as effective and efficient collaboration and communication platform in IC supply chains. Indeed, Zhong et al. (2017) presented an internet of things enabled BIM platform in their research to improve the collaborative data interoperability in the IC supply chains. Therefore, these developments can be considered as the precursors to SCR. Apart from these considerations collaborative forecasting of the supply chain uncertainties (Pettit et al., 2013) and obtaining more competitive prices from suppliers and subcontractors (Li et al., 2011) are also the SCC where the focus should be placed. Although globalized broader-based material procurement may be helpful in dealing with supply shortages in construction (Zainal and Ingirige, 2018a), it can generate additional cost implications as materialized in Malaysian IC (Thanoon et al., 2003). Therefore, the supply chain members should be careful in implementing this supply chain capability measurement item in the projects. As the last supply chain capability measurement item in this construct, public–private collaboration is essential for sharing disruption risks effectively in withstanding risk impacts as witnessed in HK prefabricated housing project developments (Li et al., 2018; Luo et al., 2015).

Market Position

Market position is the status of an organization or its products/services in specific markets. The construct consisted of 5 SCC, and the total citation count of the construct was 32 with 6.40 MS and 0.45 COV. This signifies the relatively higher importance assigned to these SCC in the previous literature. Improving the quality of supply chain processes ranked as the 9th highly cited capability measurement item with 8 citation counts ([5] [14] [17] [19] [20] [22] [23] [28]) and highlighted the relative importance of the measurement item. Improving the quality of supply chain facilitates positive outcomes during uncertainties, and it is quite evident in the prefabricated homes constructed in Japan (Noguchi, 2003). Maintaining close and healthy client-contractor, sub-contractor, supplier relationship is very important in avoiding the supply chain stakeholder associated risks (Lim et al., 2011) and hence, Wang et al. (2005) proposed an agent-based multi-attribute negotiation system to coordinate contractors in construction supply chains.

In addition, the brand-equity of an organization resembles its reputation among the stakeholders. Having good brand equity helps to resist any market pressures and market competition. Therefore, A. Ali et al. (2017) identified brand equity of the organization as a supply chain capability towards resilience. As the market share increases, a higher level of profits is achievable in IC and facilitate adequate competency to resist market competition and withstand supply chain risks (Han et al., 2017). Therefore, achieving a good market position by an organization in the construction industry should contribute to the capacity to successfully withstand market pressure, economic vulnerabilities and market competition.

Security

Security is the supply chain ability to defend against deliberate intrusions. The category includes 2 relevant capability measurement items such as cybersecurity and personnel security, with the least citation frequency of 8 and highlights the long-neglected gap of research in the knowledge area. Although BIM is suggested to be used as a method to enhance information sharing, visibility and traceability of the IC as SCC, one of the main challenges faced here is enabling the cybersecurity (Ghaffarianhoseini et al., 2017). In order to avoid the risks of unauthorized access to the data and copyright infringement, it is extremely important to apply appropriate cybersecurity to the supply chain information, data sharing and use. Taken as a safe construction method, IC facilitates improved safety (Wong et al., 2003). However, IC supply chains become vulnerable to personal safety hazards when installing prefabricated components (Li et al., 2011).

Since most of the precast members are heavy and bulky, special attention is required during the installation. The workers cannot fully understand the process if the installation programme is not clear, and hence, accidents such as collisions are likely to occur. Further to the findings of Li et al. (2011), the most common type of injury in IC is a fracture, and the most common cause of hazard is fall due to the unstable structure. Therefore, providing adequate personal security such as securing fall protection systems during on-site assembly of components, and developing training programmes and standards focused on IC will be extremely important in mitigating safety-related risks and withstanding related disruptive situations (Fard et al., 2017).

Financial Strength

Financial strength is also another required supply chain capability to withstand supply chain vulnerabilities. It represents the capacity to absorb fluctuations in the cash flow. This construct includes 4 SCC with a total of 23 citations count. This supply chain capability area is also another less explored area in research where greater attention is required. Insurance and contingencies (price margin) are the assurance while other techniques used to recover and absorb losses after any disruption are also considered as the SCC (Dong & Tomlin, 2012; Wang et al., 2010). Furthermore, these aspects are considered in the sustainability decision making criteria of construction projects as well (Sharafi et al., 2018). Indeed, standard protocols in contracts require insurance coverage of items in storage on and offsite including during the transit journeys to the site in IC supply chains as a mechanism for timely and assured delivery of construction outputs while minimizing and containing disturbances (Fateh & Mohammad, 2017). As further explained by these researchers, 'all the unfixed material offsite should be insured against loss or damages to their full value starting from the fabrication process, storing period, and until delivering it to the site' according to the JCT 2011. On the other hand, maintaining a healthy cash flow by keeping financial reserves and funds is important to improve the maturity of the IC market (Hong et al., 2018) and will result in improved supply chain performance despite uncertainties (Zhai et al., 2018). In addition, implementing strategic partnerships can support portfolio diversification in construction supply chains (Said, 2015), and it will lead to the SCR (Chaghooshi et al., 2018).

3.6 Envisaged Action Framework for Achieving SCR in IC

The results derived from the systematic analysis of literature on SCC were drawn upon to develop the proposed framework in Figure 3.7. As identified in the previous sections, there are numerous vulnerabilities namely Project Organizational; Procedural; Supplier/customer; Technological; External Environmental; and Financial Vulnerabilities that retard the performance of IC supply chains. In order to successfully withstand these vulnerabilities, there is a dire need for 'counteractive' capabilities (Kurniawan & Zailani, 2010).

These capabilities can prevent, mitigate or 'adapt' disruptions and include flexibility, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, market position, security and financial strength that can be successfully applied in construction projects (Zainal and Ingirige, 2018a). The literature review presented in the current chapter identifies a suite of SCV and SCC as specific to IC.

However, it is proposed as timely to investigate the dynamics of SCC that can address the vulnerabilities in IC supply chains through a suite of counteractive capabilities as proactive initiatives to reduce any negative impacts from the corresponding vulnerabilities as illustrated in Figure 3.7. In this respect, the envisaged action framework to achieve SCR in IC was carefully developed by consolidating and generalizing the current literature findings accordingly.

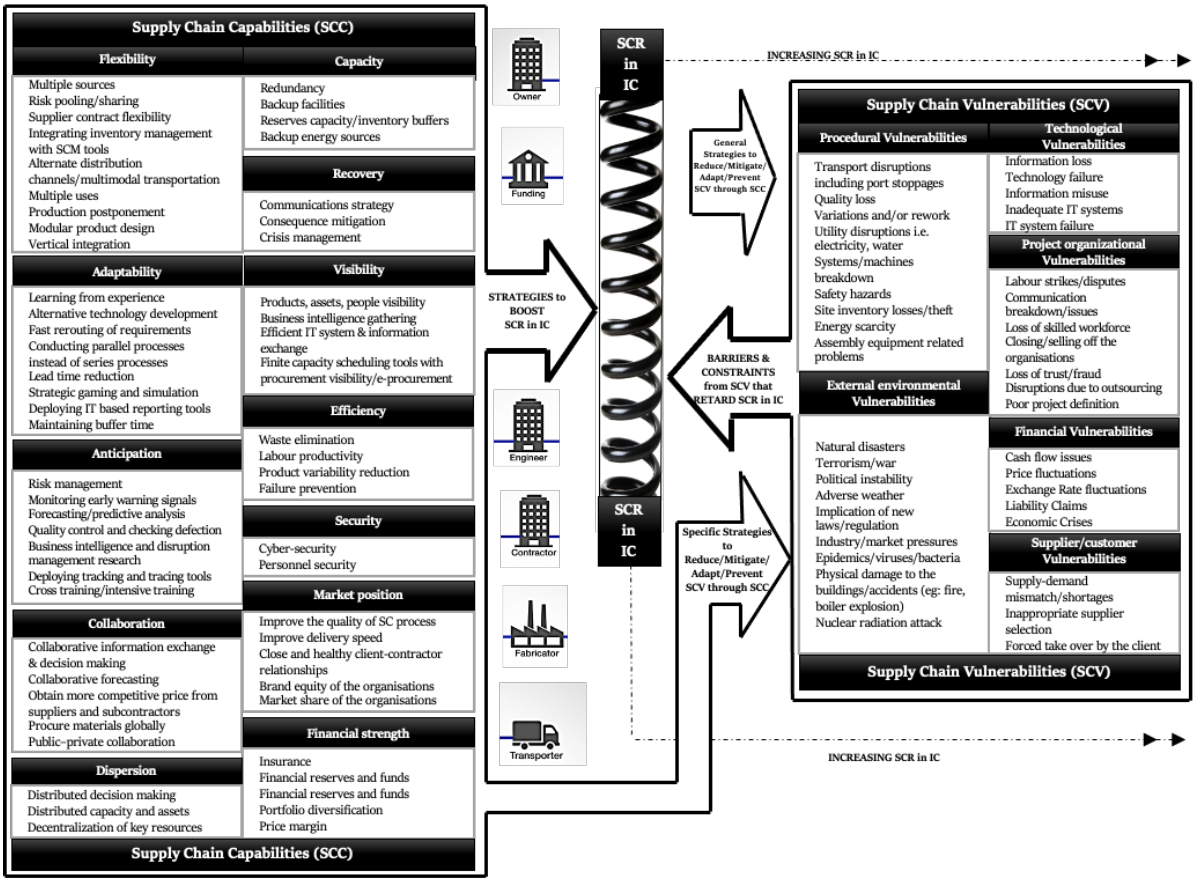


Figure 3.7: Envisaged Action Framework for Achieving SCR in IC

The developed framework was further explored and enriched by conducting a subject matter expert opinion survey, and a comprehensive questionnaire survey with industry experts on the IC in HK as elaborated in the forthcoming chapters. Thereby, a verified model for achieving SCR in IC was formulated by incorporating two comparative case study findings from HK and assessed the dynamic influence of SCC and SCV in achieving resilient supply chains in IC in

HK. Finally, a set of specific strategies was developed to reduce, mitigate, adapt and prevent SCV through SCC in IC as indicated in Figure 3.7 and presented in detail in Chapter 7. Moreover, this framework would be vital to IC stakeholders, not just in terms of identifying vulnerabilities, but also for formulating and/or nurturing adequate capabilities to deal with these vulnerabilities and thereby increase the resilience of IC supply chains; hence, enhancing supply chain performance and productivity.

3.7 Chapter Summary

This chapter attempted to conduct a state-of the-art review of SCR related concepts that have been implemented over the previous years as appropriate to the context of IC. Also, to bridge a long-neglected research gap, this chapter was designed to present the findings of comprehensive and systematic review of literature through meta-analysis of the various identified SCV and SCC over the past few decades as the key measures of SCR. Indeed, it was intended to cross-refer the identified SCC to the IC supply chains targeting enhanced resilience. Hence, these reviews provide both academic researchers and industry practitioners a comprehensive list of SCC to be incorporated into their practices. Identified SCV, SCC and the developed supply chain vulnerability and capability constructs facilitate an overview of SCR to enhance possible future developments of SCR in IC. Besides, the envisaged action framework presented in this chapter and illustrated in Figure 3.7 provides a platform for further empirical studies to refine, verify and validate these review findings specifically to the IC context in HK as conducted under this research and elaborated in the succeeding research chapters. Finally, this chapter unearths and provides a useful body of conceptual and experiential knowledge for academia and industry to instigate deeper research and development on SCR in IC to achieve enhanced supply chain performance that can reasonably withstand potential disruptions.

Chapter 4 Assessing the Criticality of Supply Chain Vulnerabilities in Industrialized Construction in Hong Kong[2]

4.1 Introduction

The previous chapters of this thesis introduced the research objectives, research methodology and reviewed the relevant literature confirming the research gap, thereby introducing the research rationale of this study. Having established that IC enables efficiencies from off-site-manufacture that help to overcome the perennial performance conundrum in the construction industry and having identified SCR as an emerging imperative in modern supply chain management, this chapter presents outcomes from an attempt to assess critical SCV and improve SCR in IC in a highly dense city of HK. Starting with the identification of Critical Supply Chain Vulnerabilities (CSCV), this study then developed a multi-level-multi-criteria mathematical model to evaluate the vulnerability level of IC supply chains in HK by soliciting experts' judgements and analyzing them using fuzzy synthetic evaluation. To the knowledge of the researcher, this is the first structured-evaluation model that measures the vulnerability level of IC. It, therefore, provides useful insights to industry stakeholders for well-informed decision making in achieving resilient, sustainable, and performance-enhanced supply chains, and partially fulfil the Objective 2 of this research.

Indeed , 80% of global organizations assign SCR the top priority in handling SCV (Sabahi & Parast, 2020). SCR provokes anticipation, flexibility, and visibility of supply chains to ensure high performance and customer value (Chowdhury et al., 2019). Thus, effective withstanding

---

[2] The core research and findings in this chapter have been peer-reviewed before publication in:

Ekanayake, E.M.A.C., Shen, G.Q., Kumaraswamy, M.M. and Owusu, E.K., 2020. 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., Kumaraswamy, M.M. and Owusu, E.K., 2021. A Fuzzy Synthetic Evaluation of Vulnerabilities Affecting Supply Chain Resilience of Industrialized Construction in Hong Kong. *Engineering, Construction and Architectural Management*. DOI 10.1108/ECAM-12-2020-1010.

of SCV could reduce additional cost implications, project delays, and safety hazards by boosting IC supply chain performance and productivity. Since SCV cannot be eliminated, SCR can be achieved by maintaining an appropriate balance between the associated vulnerabilities and capabilities (Pettit et al., 2019). For this purpose, identifying SCV, determining their levels of criticalities and impacts based on their level of vulnerabilities should be addressed first so as to identify and develop the appropriate capabilities that could help address those effectively.

However, there has been no known attempt to determine CSCV in IC in HK, while there were some studies on IC risk identification (Luo et al., 2019; Wang et al., 2019) and risk mitigation (Du et al., 2019; Enshassi et al., 2019). Neither these studies nor any others that the reviewer could access, facilitate the evaluation of the levels of vulnerabilities and their overall impact on the entire supply chain network. As a result, the understanding of industry stakeholders on the levels of vulnerability of IC supply chains is sparse; hence, conditions can deteriorate and even lead to project failures due to uninformed supply chain disruptions. Given the industry imperatives mentioned above and described in previous chapters, and the lack of theoretical underpinnings to formulate reliable solutions, this study was inspired and motivated to investigate the principles and practice of CSCV affecting SCR in IC, from the viewpoint of academic and industry experts and the practitioners in HK as presented at the beginning of this chapter. By focusing on the CSCV identified from this chapter, it is expected that industry professionals will be far better informed on the resilience imperatives for value-enhanced IC supply chains in HK.

The level of criticality of the vulnerabilities is further explained in this chapter, facilitating a better understanding of the critical vulnerabilities which enables decisions on developing appropriate capability measures to counteract them more effectively. Also, this chapter later presents the outcomes of the developed multi-level-multi-criteria mathematical model to evaluate levels of vulnerability of IC supply chains in HK. In order to achieve these chapter objectives, empirical research was conducted using an expert opinion survey and a general questionnaire survey, which are thoroughly described in Chapter 2. Hence, this chapter mainly discusses the findings generated from the empirical study as appropriate to CSCV and the assessment model of CSCV.

4.2 Research Design

As illustrated in Chapter 2, expert opinions were solicited through a questionnaire survey to determine CSCV and the assessment model of SCV. The questionnaire used for the survey consisted of 36 SCV extracted after the systematic review of literature as elaborated in Chapter 3 and after the pilot study as explicated in Chapter 2. A five-point Likert scale was adopted in the questionnaire, and the respondents were requested to grade the identified 36 SCV from 1 (not vulnerable) to 5 (extremely vulnerable). Further, additional rows were provided for open-ended responses to add any known SCV that were not captured in the preliminary study while grading them similarly as above.

Vulnerability is measured as a joint function of the likelihood of occurrence (probability) and the level of susceptibility (severity) (Pettit et al., 2013). Hence, this study generated an average vulnerability estimate based on these two factors by examining the relative importance of the criticality of the SCV following the lessons from Ameyaw et al. (2015) and Owusu et al. (2020). Further adhering to the studies of Ameyaw and Chan (2016) and Owusu et al. (2020), the impact of the SCV were calculated, referring to Equation (4.1) in this study.

$$\text{Impact (I)} = (\text{probability X severity})^\wedge 0.5 \tag{4.1}$$

Table 4.1: Evaluating CSCV in IC in HK

Code	CSCV affecting SCR in IC in HK	Probability				Severity				Overall Evaluation				
		Mean	SD	Sig	N-V	Mean	SD	Sig	N-V	SI	Impact	N-V	Overall Ranking	SWT
V03	Loss of skilled workforce	3.65	0.797	0.000	1.00	3.84	0.806	0.000	0.91	14.05	3.75	1.00	1	0.000
V10	Variations and/or rework	3.59	0.887	0.000	0.97	3.57	0.738	0.000	0.72	12.81	3.58	0.89	7	0.000
V02	Communication breakdown/issues	3.52	0.991	0.000	0.94	3.65	0.744	0.000	0.77	12.87	3.59	0.90	6	0.000
V08	Transport disruptions including port stoppages	3.51	1.018	0.000	0.93	3.89	0.815	0.000	0.95	13.73	3.70	0.97	2	0.000
V13	Safety issues	3.43	0.791	0.000	0.89	3.96	0.892	0.000	1.00	13.71	3.70	0.97	2	0.000
V09	Quality loss	3.43	0.933	0.000	0.89	3.92	0.818	0.000	0.97	13.55	3.68	0.96	4	0.000
V16	Supply-demand mismatch/shortages	3.32	0.857	0.000	0.84	3.92	0.969	0.000	0.97	13.19	3.63	0.93	5	0.000
V17	Inappropriate supplier selection	3.28	0.894	0.000	0.82	3.48	0.644	0.000	0.65	11.43	3.38	0.77	10	0.000
V19	Information loss	3.23	0.831	0.000	0.79	3.61	0.769	0.000	0.75	11.73	3.43	0.80	8	0.000
V20	Technology failure	3.20	0.822	0.000	0.78	3.43	0.720	0.000	0.61	10.99	3.32	0.73	12	0.000
V28	Implication of new laws/regulation	3.17	0.795	0.000	0.77	3.64	0.880	0.000	0.76	11.66	3.41	0.79	9	0.000
V29	Industry/market pressures	3.15	0.800	0.000	0.75	3.33	0.827	0.000	0.54	10.50	3.24	0.68	15	0.000
V22	Inadequate IT systems	3.15	0.865	0.000	0.75	3.09	1.029	0.000	0.36	9.73	3.12	0.61	20	0.000
V12	Systems/machines breakdown	3.13	0.827	0.000	0.75	3.51	0.935	0.000	0.67	11.06	3.33	0.73	12	0.000
V23	IT system failure	3.09	1.002	0.000	0.73	3.17	0.978	0.000	0.42	9.82	3.13	0.61	20	0.000
V06	Disruptions due to outsourcing	3.09	1.002	0.000	0.73	3.55	0.793	0.000	0.70	11.07	3.33	0.74	11	0.000
V33	Price fluctuations	2.96	0.892	0.000	0.66	3.51	0.828	0.000	0.67	10.53	3.24	0.68	15	0.000
V36	Cost overrun	2.96	0.845	0.000	0.66	3.45	0.810	0.000	0.63	10.34	3.22	0.67	17	0.000
V26	Political economy changes	2.96	0.951	0.000	0.66	3.32	0.903	0.000	0.53	9.89	3.15	0.62	19	0.000
V01	Labor strikes	2.91	1.055	0.000	0.64	3.61	1.051	0.000	0.75	10.75	3.28	0.71	14	0.000
V31	Physical damage to the buildings/accidents	2.89	0.879	0.000	0.63	3.48	0.978	0.000	0.65	10.24	3.20	0.66	18	0.000
V34	Exchange rate fluctuations	2.87	0.860	0.000	0.62	3.07	0.963	0.000	0.34	8.81	2.97	0.51	23	0.000

V21	Information misuse	2.81	0.926	0.000	0.59	3.39	0.787	0.000	0.58	9.69	3.11	0.60	22	0.000
V35	Liability claims	2.65	0.780	0.000	0.52	3.23	0.815	0.000	0.46	8.72	2.95	0.50	24	0.000

Note: SD = Standard Deviation, Sig = Significance,
N-V = normalized value [(mean – minimum mean)/(maximum mean – minimum mean)],
SI = Significance Index = [(probability mean)^2+(severity mean)^2]/2,
Impact = SI^0.5

Table 4.2: Results of the factor analysis

Code	**CSCV affecting SCR in IC in HK**	**Components**				
		1	2	3	4	5
Component 1	Economic SCV (ESCV)					
ESCV1	Exchange rate fluctuations	.867	-	-	-	-
ESCV2	Price fluctuations	.818	-	-	-	-
ESCV3	Liability claims	.812	-	-	-	-
ESCV4	Cost overrun	.746	-	-	-	-
ESCV5	Industry/market pressures	.648	-	-	-	-
ESCV6	Information misuse	.533	-	-	-	-
ESCV7	Economic policy changes	.455	-	-	-	-
Component 2	Technological SCV (TSCV)					
TSCV1	Technology failure	-	.883	-	-	-
TSCV2	IT system failure	-	.846	-	-	-
TSCV3	Inadequate IT systems	-	.746	-	-	-
TSCV4	Information loss	-	.656	-	-	-
TSCV5	Variations/rework	-	.511	-	-	-
Component 3	Procedural SCV (PSCV)					
PSCV1	Safety issues	-	-	.792	-	-
PSCV2	Implication of new laws/regulation	-	-	.781	-	-
PSCV3	Systems/machines breakdown	-	-	.743	-	-

PSCV4	Transport disruptions including port stoppages	-	-	.655	-	-	
PSCV5	Physical damage to the buildings/accidents	-	-	.546	-	-	
Component 4	Organisational SCV (OSCV)						
OSCV1	Communication breakdown/issues	-	-	-	.857	-	
OSCV2	Loss of skilled workforce	-	-	-	.663	-	
OSCV3	Disruptions due to outsourcing	-	-	-	.543	-	
OSCV4	Inadequate supplier selection	-	-	-	.537	-	
Component 5	Production-based SCV (PBSCV)						
PBSCV1	Quality loss	-	-	-	-	.820	
PBSCV2	Supply-demand mismatch/shortages	-	-	-	-	.756	
PBSCV3	Labor strikes	-	-	-	-	.637	
Eigenvalue		6.254	3.736	2.875	2.560	1.512	
Variance (%)		24.054	14.371	11.056	9.846	5.814	
Cumulative variance (%)		24.054	38.424	49.480	59.326	65.140	
KMO measure of sampling adequacy							.700
Bartlett's test of sphericity approximated chi-square							1228.963
Df							325
Sig.							.000

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Table 4.3: Weightings and membership functions for the CSCV and their overall components

CSCV Components	Probability of occurrence				
	Mean	**Weighting**	**MF for Level 3**	**MF for Level 2**	**MF for Level 1**
Overall	**75.94**	**1.00**			**0.03, 0.20, 0.40, 0.30, 0.07**
Economic CSCV	**20.36**	**0.27**		**0.03, 0.28, 0.47, 0.17, 0.05**	
ESCV1	2.87	0.141	0.04, 0.29, 0.45, 0.19, 0.03		
ESCV2	2.96	0.145	0.01, 0.32, 0.41, 0.20, 0.05		

ESCV3	2.65	0.130	0.01, 0.48, 0.36, 0.13, 0.01		
ESCV4	2.96	0.145	0.01, 0.29, 0.45, 0.20, 0.04		
ESCV5	3.15	0.155	0.01, 0.15, 0.59, 0.19, 0.07		
ESCV6	2.81	0.138	0.08, 0.25, 0.48, 0.15, 0.04		
ESCV7	2.96	0.145	0.05, 0.23, 0.51, 0.13, 0.08		
Technological CSCV	**16.25**	**0.21**		**0.03, 0.14, 0.45, 0.29, 0.08**	
TSCV1	3.20	0.197	0.03, 0.11, 0.57, 0.23, 0.07		
TSCV2	3.09	0.190	0.03, 0.28, 0.36, 0.24, 0.09		
TSCV3	3.15	0.194	0.03, 0.16, 0.52, 0.23, 0.07		
TSCV4	3.23	0.199	0.03, 0.13, 0.47, 0.33, 0.04		
TSCV5	3.59	0.221	0.03, 0.05, 0.36, 0.43, 0.13		
Procedural CSCV	**16.13**	**0.21**		**0.02, 0.18, 0.40, 0.35, 0.06**	
PSCV1	3.43	0.212	0.01, 0.11, 0.36, 0.48, 0.04		
PSCV2	3.17	0.197	0.01, 0.19, 0.43, 0.36, 0.01		
PSCV3	3.13	0.194	0.01, 0.20, 0.47, 0.28, 0.04		
PSCV4	3.51	0.217	0.01, 0.17, 0.28, 0.36, 0.17		
PSCV5	2.89	0.179	0.07, 0.23, 0.47, 0.23, 0.01		
Organizational CSCV	**13.55**	**0.18**		**0.01, 0.18, 0.33, 0.37, 0.12**	
OSCV1	3.52	0.260	0.00, 0.17, 0.32, 0.32, 0.19		
OSCV2	3.65	0.270	0.01, 0.04, 0.35, 0.48, 0.12		
OSCV3	3.09	0.228	0.01, 0.33, 0.28, 0.29, 0.08		
OSCV4	3.28	0.242	0.01, 0.19, 0.37, 0.36, 0.07		
Production-based CSCV	**9.65**	**0.13**		**0.04, 0.20, 0.30, 0.40, 0.06**	
PBSCV1	3.43	0.355	0.00, 0.19, 0.32, 0.37, 0.12		
PBSCV2	3.32	0.344	0.04, 0.12, 0.33, 0.49, 0.01		
PBSCV3	2.91	0.301	0.09, 0.29, 0.25, 0.33, 0.03		

CSCV Components	**Level of vulnerability**				
		Weighting	**MF for Level 3**	**MF for Level 2**	**MF for Level 1**
Overall	**84.63**	**1.00**			**0.02, 0.09, 0.36, 0.40, 0.13**
Economic CSCV	**23.29**	**0.28**		**0.01, 0.13, 0.44, 0.33, 0.08**	
ESCV1	3.07	0.132	0.03, 0.27, 0.40, 0.23, 0.08		
ESCV2	3.51	0.151	0.00, 0.09, 0.43, 0.36, 0.12		
ESCV3	3.23	0.139	0.00, 0.17, 0.49, 0.27, 0.07		

ESCV4	3.45	0.148	0.00, 0.11, 0.43, 0.37, 0.09	
ESCV5	3.33	0.143	0.04, 0.05, 0.49, 0.36, 0.05	
ESCV6	3.39	0.145	0.01, 0.09, 0.44, 0.40, 0.05	
ESCV7	3.32	0.143	0.01, 0.16, 0.41, 0.32, 0.09	
Technological CSCV	**16.88**	**0.19**		**0.04, 0.08, 0.41, 0.40, 0.07**
TSCV1	3.43	0.203	0.00, 0.08, 0.47, 0.40, 0.05	
TSCV2	3.17	0.188	0.08, 0.13, 0.35, 0.41, 0.03	
TSCV3	3.09	0.183	0.12, 0.09, 0.39, 0.37, 0.03	
TSCV4	3.61	0.214	0.00, 0.07, 0.36, 0.47, 0.11	
TSCV5	3.57	0.212	0.00, 0.03, 0.49, 0.36, 0.12	
Procedural CSCV	**18.48**	**0.22**		**0.01, 0.09, 0.29, 0.42, 0.20**
PSCV1	3.96	0.214	0.00, 0.07, 0.21, 0.41, 0.31	
PSCV2	3.64	0.197	0.01, 0.08, 0.31, 0.45, 0.15	
PSCV3	3.51	0.190	0.01, 0.13, 0.32, 0.40, 0.13	
PSCV4	3.89	0.211	0.00, 0.04, 0.27, 0.45, 0.24	
PSCV5	3.48	0.188	0.03, 0.12, 0.35, 0.36, 0.15	
Organizational CSCV	**14.52**	**0.17**		**0.00, 0.05, 0.39, 0.44, 0.12**
OSCV1	3.65	0.252	0.00, 0.05, 0.35, 0.49, 0.11	
OSCV2	3.84	0.264	0.00, 0.05, 0.25, 0.49, 0.20	
OSCV3	3.55	0.244	0.00, 0.08, 0.40, 0.41, 0.11	
OSCV4	3.48	0.240	0.00, 0.01, 0.56, 0.36, 0.07	
Production-based CSCV	**11.45**	**0.14**		**0.02, 0.08, 0.20, 0.46, 0.24**
PBSCV1	3.92	0.342	0.00, 0.05, 0.21, 0.49, 0.24	
PBSCV2	3.92	0.342	0.01, 0.09, 0.15, 0.45, 0.29	
PBSCV3	3.61	0.315	0.05, 0.08, 0.25, 0.43, 0.19	

Mean score values derived based on experts' assessment of SCV were used to ascertain the impact of each vulnerability. These detailed assessment results and the impact evaluation matrices are given in Table 4.1.

Following the studies of Osei-Kyei et al. (2020) and Adabre and Chan (2019), the descriptive means and normalization analysis was deployed in this study too, to determine the CSCV. Based on the normalization values (N-V>0.5), 26 SCV were identified as the CSCV and considered in the factor analysis. Statistical Mean (M), Standard Deviation (SD), and the normalization values for each supply chain vulnerability are shown in Table 4.1. SCV were ranked according to the M value. As several vulnerabilities received the same M score, those vulnerabilities were ranked considering their SD.

Thereafter, the data were first tested for their appropriateness and reliability since that is a pre-requisite to justify the results. A reliability test was conducted using Cronbach's alpha test tool in SPSS and the alpha coefficient of 0.863 showed that the 26 SCV are internally reliable or consistent. Data normality test is another important test that needs to be conducted to determine the nature of the type of data distribution (Owusu & Chan, 2019). Therefore, the Shapiro-Wilk test was conducted as it is commonly used to determine data distribution (Owusu & Chan, 2019) since it is 'the most powerful normality test' (Razali & Wah, 2011). The null hypothesis for this test stipulated that 'the data is normally distributed'. The null hypothesis is rejected if the test value is less than the stipulated p-value, using a standard significance level of 0.05. Table 4.1 presents the statistical results of the Shapiro-Wilk test. Thus, it can be concluded that the data in this study are non-normally distributed. Based on these results, it was decided to proceed with the factor analysis to determine CSCV components and fuzzy synthetic evaluation to develop the assessment model of SCV as elaborated in the succeeding sections of this chapter.

4.3 Identification of Critical Supply Chain Vulnerabilities (CSCV) and Respective Components through Factor Analysis

The Kaiser-Meyer-Olkin test (KMO) and Bartlett's test of sphericity were conducted to verify data for the factor analysis as described in Chapter 2. The value obtained for KMO in this study is 0.7, which is above the required minimum of 0.5. The Bartlett's test of sphericity statistic is 1228.963 with a significance level of 0.000. Therefore, the data set was appropriate for factor analysis, and the correlation matrix was not an identity matrix. The test statistics are clearly illustrated in Table 4.2.

Thereby, factor extraction was done using the principal component analysis approach to determine the relevant vulnerabilities. The eigenvalue was set as the criterion for selecting the vulnerabilities, where vulnerabilities with the eigenvalues less than one were eliminated (Chan et al., 2018). Therefore, only 26 CSCV with eigenvalues above one remained. Then varimax rotation was conducted for the retained 26 CSCV, which yielded five underlying components that explain 65.14% of the total variance (as shown in Table 4.2).

Only 24 CSCV were successfully loaded into the five underlying components, considering the similarities of the underlying factor themes. These five components are economic, technological, procedural, organizational, and production-based SCV. The naming was done using the common themes that were underlying the SCV (Owusu & Chan, 2019). However, when there was no clearly discernible common theme, naming was done using the underlying theme of the SCV, which are with higher factor loadings (Owusu & Chan, 2019; Le et al., 2014; Zhang et al., 2017). Two of the CSCV, namely 'poor project definition (V07)' and 'adverse weather (V27)', were excluded as their factor loading values were below 0.50. The factor loading is a measurement between the correlation coefficient of an original variable and an extracted component (Adabre & Chan, 2019). According to the literature, factor loadings higher than 0.5 are considered significant and adopted in components interpretation (Chan et al., 2018). Table 4.2 shows the SCV with factor loadings above 0.50, along with the developed five components. These five components were considered and analyzed further using fuzzy synthetic evaluation to derive SCV assessment model as elaborated in the forthcoming section.

4.4 Application of the soft computing approach- Fuzzy Synthetic Evaluation (FSE)

FSE, as a soft computing approach, was employed in this study to evaluate the impact of CSCV in IC in HK as discussed in Chapter 2. Accordingly, the following five steps were subsequently pursued to find the overall impact index and develop the model for evaluating the impact of CSCV in IC in HK. Furthermore, these five steps are clearly illustrated in Figure 4.1.

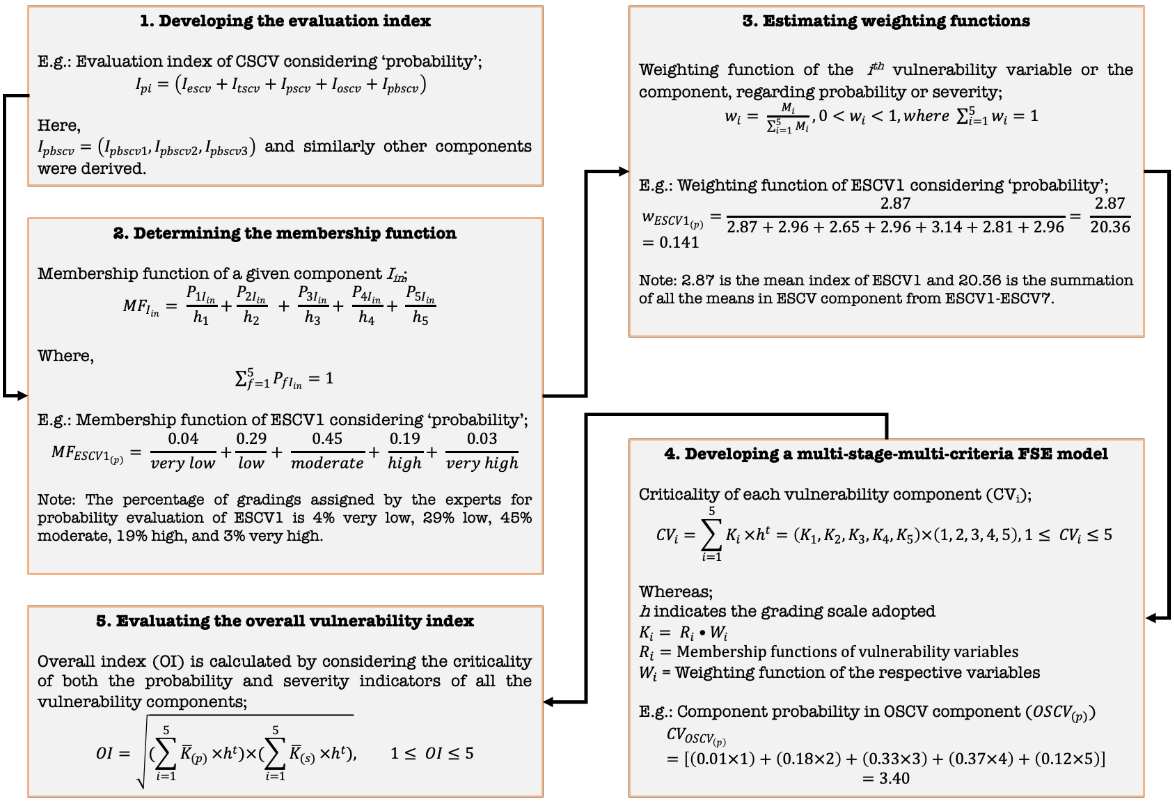


Figure 4.1: Workflow of the FSE modeling of SCV in this research

4.4.1. Developing the Evaluation Index

Following the studies of Li et al. (2013), Ameyaw et al. (2015), and Owusu et al. (2020), the evaluation index was developed by defining the CSCV components as the index systems at the first level.

$$I_{pi} = (I_1 + I_2 + I_3 + I_4 + I_5) \tag{4.2}$$

The individual CSCV within the components, as presented in Table 4.3, were then defined as the second level index system, as shown as follows:

$$I_{escv} = (I_{escv1}, I_{escv2}, I_{escv3}, I_{escv4}, I_{escv5}, I_{escv6}, I_{escv7}) \tag{4.2.1}$$

$$I_{tscv} = (I_{tscv1}, I_{tscv2}, I_{tscv3}, I_{tscv4}, I_{tscv5}) \tag{4.2.2}$$

$$I_{pscv} = \left(I_{pscv1}, I_{pscv2}, I_{pscv3}, I_{pscv4}, I_{pscv5}\right) \tag{4.2.3}$$

$$I_{oscv} = (I_{oscv1}, I_{oscv2}, I_{oscv3}, I_{oscv4}) \tag{4.2.4}$$

$$I_{pbscv} = \left(I_{pbscv1}, I_{pbscv2}, I_{pbscv3}\right) \tag{4.2.5}$$

These established FSE's input variables apply to both probability and severity indicators alike. The identified CSCV within their respective components were deemed as representative for input variables in the FSE calculations, as in Table 4.3.

4.4.2. Determining the Membership Function

The membership grade of CSCV and their respective component groups were generated through fuzzy mathematics, following the studies of Ameyaw et al. (2015) and Owusu et al. (2020). It is worth noted that the grading scale system used to assess both the probability and level of vulnerability of the CSCV were predetermined by a two-dimensional, five scale grading system where h = [1, 2, 3, 4, 5] and h_1= very low, h_2= low, h_3=neutral, h_4= high, h_5= very high, for both the severity and probability constructs. Moreover, membership Function

(MF) of a given component I_{in}, was computed using the following Equation (4.3) (Chan et al., 2011, Ameyaw et al., 2015, Owusu et al., 2020).

$$MF_{I_{in}} = \frac{P_{1I_{in}}}{h_1} + \frac{P_{2I_{in}}}{h_2} + \frac{P_{3I_{in}}}{h_3} + \frac{P_{4I_{in}}}{h_4} + \frac{P_{5I_{in}}}{h_5} \tag{4.3}$$

MF = Membership Function of a given component I_{in}, which represents the n^{th} individual vulnerability of a given component i ($i = I_1, I_2, I_3, I_4, I_5$). $P_{fI_{in}}$ ($f = 1, 2, 3, 4, 5$) denotes the percentage of respondents who assigned a grade for the individual vulnerabilities based on probability and severity. Further, $P_{fI_{in}}/h_i$ indicates the association of $P_{fI_{in}}$ and the appropriate grading scale without considering the mathematical function of the fraction. Similarly, '+' in Equation (4.3) denotes a notation instead of the addition implied in mathematics. Hence, Equation (4.3) can be converted to Equation (4.4) as follows.

$$MF_{I_{in}} = \left(P_{1I_{in}}, P_{2I_{in}}, P_{3I_{in}}, P_{4I_{in}}, P_{5I_{in}}\right) \tag{4.4}$$

The members applied in Equation (4.2.1) - Equation (4.2.5) range between 0 to 1. Their summation should be equal to one since they represent weighted average calculations. This is explicated in Equation (4.5).

$$\sum_{f=1}^{5} P_{fI_{in}} = 1 \tag{4.5}$$

The MF of a given component is created from the assessment of overall responses received from the expert survey as explicated in Equation (4.4). Thus, for instance, considering ESCV1, the percentage of gradings assigned by the experts for probability evaluation is 4% very low, 29% low, 45% moderate, 19% high, and 3% very high. Hence, according to Equation (4.3), MF of ESCV1(p) is as follows.

$$MF_{ESCV1_{(p)}} = \frac{0.04}{very\ low} + \frac{0.29}{low} + \frac{0.45}{moderate} + \frac{0.19}{high} + \frac{0.03}{very\ high} \quad (4.5.1)$$

As per Equation (4.4), $MF_{ESCV1_{(p)}}$ can be presented as: (0.04, 0.29, 0.45, 0.19, 0.03). Similarly, the level of vulnerability which is the severity indicator for ESCV1 can be formulated as shown in Equation (4.5.2). Therefore, $MF_{ESCV1_{(s)}}$ = (0.03, 0.27, 0.40, 0.23, 0.08).

$$MF_{ESCV1_{(s)}} = \frac{0.03}{very\ low} + \frac{0.27}{low} + \frac{0.40}{moderate} + \frac{0.23}{high} + \frac{0.08}{very\ high} \quad (4.5.2)$$

The same method of calculation was employed for all the other vulnerabilities, and the generated results are presented in Table 4.3. Thereby, the respective component groups' MF were derived using the computed weightings of the individual vulnerabilities within the components. The estimation of weighting functions is explained in the next section.

4.4.3. Estimating Weighting Functions

A weighting function here indicates the relative importance of each individual vulnerability or a component, based on the gradings assigned by the respondents (Ameyaw et al., 2015; Ameyaw & Chan, 2016). The normalized mean technique or analytic hierarchy process technique can be used to estimate the weighting functions (Cheng, 1997; Lee et al., 2008; Lo, 1999). The normalized mean method was used in this study since it is a straightforward method (Ameyaw et al., 2015; Lo, 1999; Owusu et al., 2020). The appropriate weight functions of the SCV were calculated by the following Equation (4.6).

$$w_i = \frac{M_i}{\sum_{i=1}^{5} M_i}, 0 < w_i < 1, where \sum_{i=1}^{5} w_i = 1 \quad (4.6)$$

w_i indicates the weighting function of the i^{th} individual vulnerability or the component, regarding probability or severity. M_i is the mean index of any individual vulnerability or a component as estimated from the survey data. As explicated in Equation (4.6) and following Equation (4.4), the summation of the mean within a weight function set must be one and can be represented in Equation (4.7).

$$w_i = (w_1, w_2, \dots, w_n) \quad (4.7)$$

Equation (4.7.1) was computed by considering ESCV1$_{(p)}$ as an example in calculating the $w_{ESCV1_{(p)}}$. Similarly, the weighting factor of the ESCV component was calculated and indicated in Equation (4.7.2). Thereby, a similar approach was adopted in computing all the weighting functions of individual vulnerabilities and components that belonged to both probability and severity indicators. These computed weighting functions are clearly presented in Table 4.3.

$$w_{ESCV1_{(p)}} = \frac{2.87}{2.87+2.96+2.65+2.96+3.14+2.81+2.96} = \frac{2.87}{20.36} = 0.141 \quad (4.7.1)$$

$$w_{ESCV_{(p)}} = \frac{20.34}{20.34+16.25+16.13+13.55+9.65} = \frac{20.34}{75.94} = 0.268 \quad (4.7.2)$$

The following computation was done by validating that the summation of the weighting functions within a component and total of the components must be equal to 1.

$$\sum_{i=1}^{5} w_{ESCV_{(p)}} = (0.141 + 0.145 + 0.130 + 0.145 + 0.155 + 0.138 + 0.145) = 1.0 \quad (4.7.3)$$

4.4.4. Developing A Multi-stage-multi-criteria FSE Model

FSE model for evaluating CSCV affecting IC in HK is a multicriteria, multistage process including three main stages. First, the MF and Weighting Factors (WF) of each vulnerability were computed, based on the gradings assigned by the experts. Second, the MF and WF of factor components were constructed, and the impact was estimated. Third, the overall indicator or the impact of vulnerabilities towards IC supply chains is estimated.

Beginning from evaluating the impact of individual components, a fuzzy matrix K_i was first determined for each component, using the estimated MF and WF of vulnerabilities within their respective component groups. The MFs determined under Equation (4.3) with functions of vulnerabilities within their respective components (for both probability and severity indicators) can be presented as in Equation (4.8).

$$R_i = \begin{vmatrix} MF_{I_{i1}} \\ MF_{I_{i2}} \\ MF_{I_{i3}} \\ \cdots \\ MF_{I_{in}} \end{vmatrix} = \begin{vmatrix} P_{1I_{i1}} & P_{2I_{i1}} & P_{3I_{i1}} & P_{4I_{i1}} & P_{5I_{i1}} \\ P_{1I_{i2}} & P_{2I_{i2}} & P_{3I_{i2}} & P_{4I_{i2}} & P_{5I_{i2}} \\ P_{1I_{i3}} & P_{2I_{i3}} & P_{3I_{i3}} & P_{4I_{i3}} & P_{5I_{i3}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{1I_{in}} & P_{2I_{in}} & P_{3I_{in}} & P_{4I_{in}} & P_{5I_{in}} \end{vmatrix} \tag{4.8}$$

For instance, this assessment can be done to the component $OSCV_{(p)}$, and the criticality level of the component can be represented as follows.

$$R_{OSCV_{(p)}} = \begin{vmatrix} MF_{OSCV1} \\ MF_{OSCV2} \\ MF_{OSCV3} \\ MF_{OSCV4} \end{vmatrix} = \begin{vmatrix} 0.00 & 0.17 & 0.32 & 0.32 & 0.19 \\ 0.01 & 0.04 & 0.35 & 0.48 & 0.12 \\ 0.01 & 0.33 & 0.28 & 0.29 & 0.08 \\ 0.01 & 0.19 & 0.37 & 0.36 & 0.07 \end{vmatrix} \tag{4.8.1}$$

The matrix K_i can be computed using the established function R_i, and WF set [$w_i = (w_1, w_2, w_3, ..., w_n)$] of the individual vulnerabilities within their respective components as follows.

$$K_i = R_i \bullet W_i = (k_{i1}, k_{i2}, k_{i3}, \dots, k_{in}) \tag{4.9}$$

Hence,

$$K_i = (w_1, w_2, w_3, \dots, w_n) \bullet \begin{vmatrix} P_{1I_{i1}} & P_{2I_{i1}} & P_{3I_{i1}} & P_{4I_{i1}} & P_{5I_{i1}} \\ P_{1I_{i2}} & P_{2I_{i2}} & P_{3I_{i2}} & P_{4I_{i2}} & P_{5I_{i2}} \\ P_{1I_{i3}} & P_{2I_{i3}} & P_{3I_{i3}} & P_{4I_{i3}} & P_{5I_{i3}} \\ \dots & \dots & \dots & \dots & \dots \\ P_{1I_{in}} & P_{2I_{in}} & P_{3I_{in}} & P_{4I_{in}} & P_{5I_{in}} \end{vmatrix}$$
$$= (k_{i1}, k_{i2}, k_{i3}, \dots, k_{in}) \tag{4.9.1}$$

In Equation (4.9.1), K_{in} indicates the membership degree of grading scale $h_{i,}$ in terms of a given component. Hence, the fuzzy evaluation matrix for the component OSCV(p), developed by integrating $R_{OSCV_{(p)}}$ and $W_{OSCV_{(p)}}$ can be mathematically presented as in Equation (4.9.2). Explicating further $K_{OSCV_{(p)}}$ denotes the fuzzy matrix for the probability indicators of the identified organizational supply chain vulnerability component. Similarly, K_i values for all the components (considering both probability and severity) were computed. These computed matrices are shown in Table 4.3 in the column 'MF at level 2'.

$$K_{OSCV_{(p)}} = (0.260, 0.270, 0.228, 0.242) \begin{vmatrix} 0.00 & 0.17 & 0.32 & 0.32 & 0.19 \\ 0.01 & 0.04 & 0.35 & 0.48 & 0.12 \\ 0.01 & 0.33 & 0.28 & 0.29 & 0.08 \\ 0.01 & 0.19 & 0.37 & 0.36 & 0.07 \end{vmatrix} =$$
$$(0.01, 0.18, 0.33, 0.37, 0.12) \tag{4.9.2}$$

Hence, the criticality of each vulnerability component (CV_i) can be calculated using the following Equation (4.10), whereas h indicates the grading scale adopted in the questionnaire survey.

$$CV_i = \sum_{i=1}^{5} K_i \times h^t = (K_1, K_2, K_3, K_4, K_5) \times (1, 2, 3, 4, 5), 1 \le CV_i \le 5 \tag{4.10}$$

For instance, criticality based on component probability in OSCV component ($OSCV_{(p)}$) was derived as follows.

$$CV_{OSCV_{(p)}} = [(0.01 \times 1) + (0.18 \times 2) + (0.33 \times 3) + (0.37 \times 4) + (0.12 \times 5)]$$
$$= 3.40 \tag{4.10.1}$$

Analogous to the calculation above, $OSCV_{(s)}$ which is the criticality based on component severity in OSCV component was calculated as in Equation (4.10.2).

$$CV_{OSCV_{(s)}} = [(0.00 \times 1) + (0.05 \times 2) + (0.39 \times 3) + (0.44 \times 4) + (0.12 \times 5)]$$
$$= 3.64 \tag{4.10.2}$$

Thus, after calculating both the probability and the severity indicators of a component, the overall impact of a component can be calculated by the following Equation (4.11). Table 4.4 presents the impact of all the components, computed using Equation (4.11).

$$CV_{OSCV} = \sqrt{3.4 \times 3.64} = 3.52 \tag{4.11}$$

4.4.5. Evaluating the Overall Vulnerability Index

In this step, the fuzzy matrix $\bar{R}$ was introduced to evaluate the overall criticality levels of SCV for both probability and severity indicators as in Equation (4.12).

$$\bar{R} = \begin{vmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \end{vmatrix} = \begin{vmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} \\ k_{31} & k_{32} & k_{33} & k_{34} & k_{35} \\ k_{41} & k_{42} & k_{43} & k_{44} & k_{45} \\ k_{51} & k_{52} & k_{53} & k_{54} & k_{55} \end{vmatrix} \tag{4.12}$$

K_1- K_5 represent the five components initiated after the factor analysis, namely, ESCV, TSCV, PSCV, OSCV, and PBSCV. Analogous to Equation (4.12), overall probability and severity functions of SCV evaluation can be formulated as in Equation (4.12.1).

$$\overline{R_{(p)}} = \begin{vmatrix} 0.03 & 0.28 & 0.47 & 0.17 & 0.05 \\ 0.03 & 0.14 & 0.45 & 0.29 & 0.08 \\ 0.02 & 0.18 & 0.40 & 0.35 & 0.06 \\ 0.01 & 0.18 & 0.33 & 0.37 & 0.12 \\ 0.04 & 0.20 & 0.30 & 0.40 & 0.06 \end{vmatrix} \, and$$

$$\overline{R_{(s)}} = \begin{vmatrix} 0.01 & 0.13 & 0.44 & 0.33 & 0.08 \\ 0.04 & 0.08 & 0.41 & 0.40 & 0.07 \\ 0.01 & 0.09 & 0.29 & 0.42 & 0.20 \\ 0.00 & 0.05 & 0.39 & 0.44 & 0.12 \\ 0.02 & 0.08 & 0.20 & 0.46 & 0.24 \end{vmatrix} \tag{4.12.1}$$

This matrix $\bar{R}$ was then normalized using the apropos WF set to arrive at $\bar{K}$.

$$\overline{K_\iota} = \overline{R_\iota} \bullet \overline{W_\iota} = (\acute{w}_1, \acute{w}_2, \acute{w}_3, \acute{w}_4, \acute{w}_5) \times \begin{vmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} \\ k_{31} & k_{32} & k_{33} & k_{34} & k_{35} \\ k_{41} & k_{42} & k_{43} & k_{44} & k_{45} \\ k_{51} & k_{52} & k_{53} & k_{54} & k_{55} \end{vmatrix}$$

$$= \left(\acute{K}_1, \acute{K}_2, \acute{K}_3, \acute{K}_4, \acute{K}_5\right) \tag{4.13}$$

It is emphasized that $\overline{K_\iota}$ represents the fuzzy matrix for either or both probability and severity indicators of the SCV components. The fuzzy matrix in Equation (4.13) can be formulated using the grading scale (h=1,2,3,4,5) established in this study as given in Equation (4.14) where V_i implies SCV' criticality index i (i = *probability or severity indicators*).

$$V_i = \sum_{i=1}^{5} \overline{K}_i \times h^t = \left(\acute{K}_1, \acute{K}_2, \acute{K}_3, \acute{K}_4, \acute{K}_5\right) \times (1, 2, 3, 4, 5), 1 \leq V_i \leq 5 \tag{4.14}$$

Table 4.4: Overall impact calculations of SCV affecting SCR in IC in HK

Category	Probability		Severity		Overall			
	Index	Coefficient	Index	Coefficient	Impact	Coefficient	Coefficient Symbols	Ranking
ESCV	2.92	0.27	3.33	0.28	3.12	0.27	C_{ESCV}	5
TSCV	3.26	0.21	3.39	0.20	3.32	0.21	C_{TSCV}	4
PSCV	3.24	0.21	3.71	0.22	3.47	0.22	C_{PSCV}	3
OSCV	3.40	0.18	3.64	0.17	3.52	0.17	C_{OSCV}	2
PBSCV	3.23	0.13	3.82	0.14	3.52	0.13	C_{PBSCV}	1
Total		1.00		1.00		1.00		
OI	**3.19**		**3.54**		**3.36**			

This 'defuzzification approach' enables transforming fuzzy members into a crisp output using the grading scale that is vital for clear decision making (Owusu et al., 2020, Osei-Kyei et al., 2019). Finally, the Overall Impact of the SCV (OI) should be calculated by integrating both the probability and severity indicators. Based on Owusu et al. (2020), OI was calculated by using Equation (4.15) by capturing both the indicators.

$$OI = \sqrt{(\sum_{i=1}^{5} \overline{K}_{(p)} \times h^t) \times (\sum_{i=1}^{5} \overline{K}_{(s)} \times h^t)}, \qquad 1 \leq OI \leq 5 \tag{4.15}$$

The ultimate fuzzy evaluation matrix was derived by normalizing the obtained fuzzy matrix for overall SCV indicators using the apropos WF values. Hence, the following calculations were first separately conducted to derive individual overall impacts of probability and severity indicators. And then, the overall impact index of SCV affecting SCR in IC in HK was evaluated using Equation (4.15.3).

$$\overline{K}_{(p)} = (0.268, 0.214, 0.212, 0.178, 0.127) \times \begin{vmatrix} 0.03 & 0.28 & 0.47 & 0.17 & 0.05 \\ 0.03 & 0.14 & 0.45 & 0.29 & 0.08 \\ 0.02 & 0.18 & 0.40 & 0.35 & 0.06 \\ 0.01 & 0.18 & 0.33 & 0.37 & 0.12 \\ 0.04 & 0.20 & 0.30 & 0.40 & 0.06 \end{vmatrix}$$

$$= (0.03, 0.20, 0.40, 0.30, 0.07) \tag{4.15.1}$$

$$\overline{K}_{(s)} = (0.275,0.199,0.218,0.172,0.135) \times \begin{vmatrix} 0.01 & 0.13 & 0.44 & 0.33 & 0.08 \\ 0.04 & 0.08 & 0.41 & 0.40 & 0.07 \\ 0.01 & 0.09 & 0.29 & 0.42 & 0.20 \\ 0.00 & 0.05 & 0.39 & 0.44 & 0.12 \\ 0.02 & 0.08 & 0.20 & 0.46 & 0.24 \end{vmatrix}$$

$$= (0.02, 0.09, 0.36, 0.40, 0.13) \qquad (4.15.2)$$

$$OI =$$

$$\sqrt{[(1 \times 0.03) + (2 \times 0.20) + (3 \times 0.40) + (1 \times 0.30) + (1 \times 0.07)]} \times$$

$$\sqrt{[(1 \times 0.02) + (2 \times 0.09) + (3 \times 0.36) + (1 \times 0.40) + (1 \times 0.13)]}$$

$$= 3.36 \qquad (4.15.3)$$

4.5 Discussion

According to the previous literature findings, a few studies targeted risk identification in IC. Wu et al. (2019) developed four risk categories (general, design-related, construction-related, people and organizational-related) using a questionnaire survey conducted in China and identified resilience performance as a risk item. A study by Enshassi et al. (2019) developed a framework for mitigating tolerance-based risks in IC. Wang et al. (2019) also identified risks at each stage of the construction process. These authors also identified the ten most critical risks, including high cost, an inadequate workforce, inadequate training and policy-related issues.

However, all these studies discussed risks without focusing on the supply chain or SCR. Besides, vulnerability is not the same as risk, as differentiated in Chapter 3. The levels of vulnerability also vary with the withstanding capacity of supply chains (Ekanayake et al., 2020). Focusing specifically on the IC supply chains (targeting SCR), this study identified CSCV, specifically in the context of HK through an empirical research exercise. Therefore, this categorization includes organizational, procedural, technological, economic and production-based SCV as discussed in the subsequent sections, where their underlying CSCV are discussed for each of these components. The findings are reinforced by indicating the current industrial context as gleaned from the interviews of experts.

Figure 4.2 presents a profile of CSCV with the vulnerability levels obtained from relevant significance analysis. The first ranking vulnerability is ‘loss of skilled workforce’ (V03) with an M value of 3.653. Without skilled labor, on-site assembly of components is impossible. Besides, in the current practice, this labor should be extensively trained, while several mock-up sessions should be conducted to avoid safety hazards and tolerance issues during the actual installation of the prefabricated components. Therefore, the respondents have ranked this as the most critical of the SCV. Although Wang et al. (2019) identified the high overall cost as the top risk in IC in Mainland China, in HK, the highest vulnerability is due to the loss of skilled labor. Further, Luo et al. (2019) identified three major stakeholders-associated supply chain risks in IC, including poor planning, poor control of workflows, and inadequate information sharing. However, considering the entire IC supply chain process, the highest vulnerability is due to the loss of skilled workforce, the next ranked is variations, while communication issues are ranked third.

Being specific to the fuzzy synthetic evaluation of CSCV, the indices obtained from the fuzzy analysis revealed that three of the SCV components (PBSCV, OSCV, and PSCV) are more critical compared to the other two components (TSCV and ESCV). Hence, it can be stated that IC projects in HK are not so vulnerable to the negative economic changes and technological disturbances, demarcating their adoptive capabilities for withstanding economic and technological disruptions. ‘Variations/rework’ was ranked as the second CSCV considering the mean value of the responses, although it is included in the TSCV component. That may explain why this vulnerability has received the least factor loading within the specific component. Besides, it is worth emphasizing that a few of the vulnerability indices of the individual SCV within the specified components may vary.

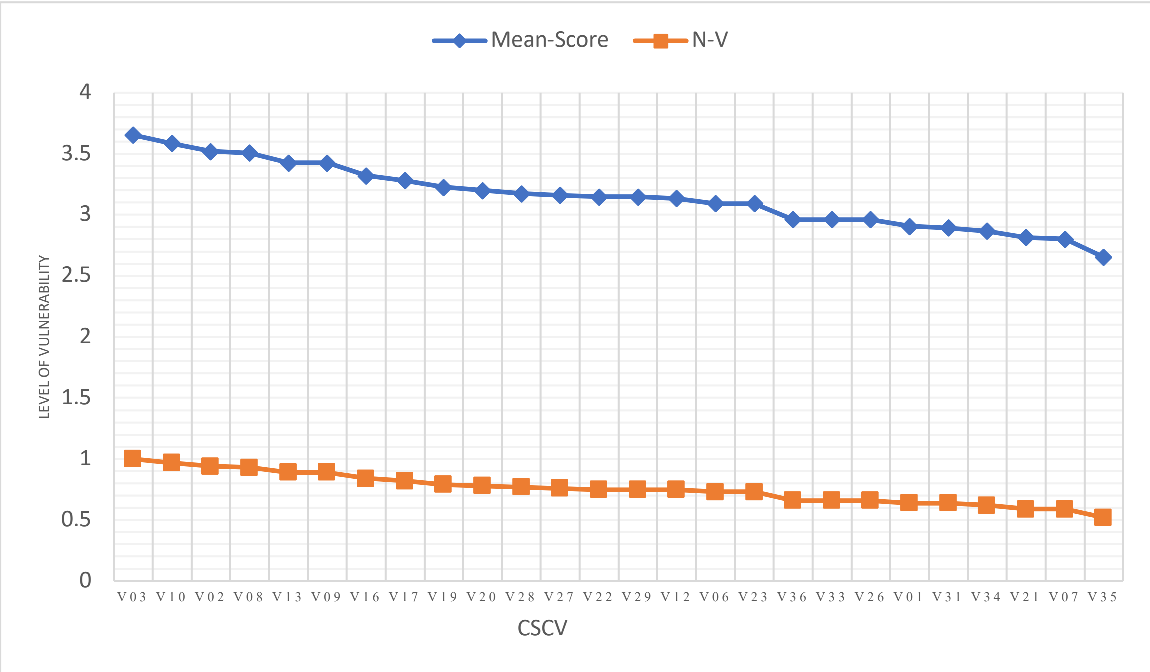


Figure 4.2: Critical Supply Chain Vulnerabilities (CSCV) affecting supply chain resilience in IC in HK

Production-based Supply Chain Vulnerabilities (PBSCV)

Component 5 (PBSCV) reflects the SCV related to the production of IC with the overall vulnerability impact of 3.52, which is the highest. PBSCV accounts for 5.814 variance percentage, with a significant M value (3.217), including three SCV with higher factor loadings (quality loss, supply-demand mismatch/shortages, and labor strikes/disputes). Quality loss as the sixth CSCV with 3.43 mean value accounts for the most top factor loading within the component. In HK, quality shortfalls are mainly due to tolerance failures (Ekanayake et al., 2019) and were visible in the projects. Unless a reasonable tolerance is provided, if a unit is cast with even a 1 mm error, it becomes vulnerable to on-site assembly problems. It can cause considerable cost and time overrun (Ekanayake et al., 2019).

As another supply chain vulnerability affects the IC production, supply-demand shortages are due to resource scarcity (Zhai et al., 2017), supply-demand mismatches even cause quality issues and hence, create cascading impacts towards supply chains. Sometimes, manufacturing factories supply incorrect orders, causing assembly delays (Ekanayake et al., 2020). Besides, the accumulated supply-demand vulnerabilities result in unmet client needs. Labor is also a problematic resource in HK because of heightened labor costs and lack of skilled labor (Ekanayake et al., 2019). However, labor strikes apply to the manufacturing stage, causing supply shortages, excess cost and time implications and quality shortfalls. Therefore, the attention of the industry stakeholders should be encouraged, since this is needed to withstand these CSCV, at the first instance to achieve resilient SCs in HK.

Organizational Supply Chain Vulnerabilities (OSCV)

OSCV refers to the vulnerabilities arising from inadequate and/or inappropriate organizational strategies and management decisions, from the staff within the organization as well as human resources availability, with 9.846% variance. This is the component with the highest mean score of 3.387, indicating the significance of the construct to the CSCV in IC in HK. The impact of OSCV in achieving SCR in IC in HK is 3.52 and was seen to be the second highest among all. Communication breakdown (Mean score-3.52) in this category was the third significant vulnerability among all the vulnerabilities. Once there is a communication failure during a disruption, the entire process of recovery may collapse. Also, these result in industrial disputes and supply chain inefficiencies (Luo et al., 2019) and exert substantial cascading impacts on other IC vulnerabilities, such as variations/rework (Luo et al., 2019). Hence, better implementation of IC projects requires effective communication between the project parties (Kisi et al., 2019). Although Li et al. (2011) suggested a virtual prototyping technology-based effective and efficient collaboration and communication platform for IC in HK, these features still cannot be seen in the practice.

Skilled workers are a very critical resource in IC in HK as demand far exceeds availability. Skilled workers are essential from the factory to project delivery in IC since handling the prefabricated units is not easy but requires specific skill-sets (Ekanayake et al., 2019). The labor cost is very high in HK, and according to the experts' opinions, procuring prefabricated components from Mainland China is more cost-effective as the cost of labor is lower there. The shortage of skilled workforce thus becomes another critical supply chain vulnerability in this OSCV component.

IC supply chains need outsourcing since modules are manufactured in a factory environment in Mainland China and pose significant challenges such as demand uncertainty, assembly problems (J. Wang et al., 2018), and poor visibility of supply chains (Zainal & Ingirige, 2018a). In HK, these disruptions arise mostly from transportation and on-site logistics-related vulnerabilities. Too early or late deliveries of outsourced units cause storage problems and affect the supply chain process severely (Ekanayake et al., 2019). As IC projects in HK are vulnerable due to outsourcing (Ekanayake et al., 2019), the decision of self-manufacturing and vertical integration of supply chain processes could provide a solution (Han et al., 2017). In this regard, an HK company had set up an in-house prefabrication plant, which they had expected to bring them more benefits than in most outsourcing exercises, e.g., by flexible decisions on storage buffers to avoid disruptions.

Inappropriate supplier selection is the least loaded vulnerability within this category. Construction supply chains are vulnerable to single supplier dependency as it is challenging to find sub-contractor or supplier backups in one contract. Proper selection of suppliers is a crucial step to fortify the application of IC, since purchasing prefabricated products accounts for about

70% of the total cost (Langston, 2016). Moreover, contracting companies have experienced delays due to inadequate supplier selection, and the concern is still essential as the industry is still vulnerable (Ekanayake et al., 2019). All these vulnerabilities arise from the organizational level, necessitating improved organizational capacities in withstanding adverse effects.

Procedural Supply Chain Vulnerabilities (PSCV)

PSCV refers to the disruptions arising from the operation at any node of the supply chain. The PSCV component displays an 11.056 variance percentage, along with the third-highest overall mean score value. PSCV includes safety issues, the implication of new laws/regulation, systems/machines breakdown, transport disruptions including port stoppages, and physical damage to the buildings/accidents. Experts highlighted these vulnerabilities as the common SCV in IC in HK. The PSCV component is also within the 'critical' range according to the FSE results with their respective overall index and associated model coefficient values of 3.47 and 0.22.

As the largest contributing vulnerability to the component, safety issues occupy the highest factor loading, and this is also with the second-highest M value within the category. Site safety has become a serious concern during on-site assembly (Zhai & Huang, 2017), since the process consists of the lifting of heavy and oversized units, unclear instructions and lack of training regarding installation, collisions with other components, and due to near misses (Ekanayake, Shen, & Kumaraswamy, 2020). On the other hand, the installation programs are sometimes not very clear or realistic, causing difficulties to on-site workers in understanding the expected methods and protocols. Therefore, accidents are likely during the installation, especially from collisions with other components and occasionally even with workers (Li et al., 2011). Further, near misses cause frequent disruptions that IC supply chains observe while installing components in HK. However, such problems are not adequately minimized through novel safety technologies; hence are currently avoided by employing skilled workers and careful monitoring of the supply chain process. The projects are usually just guided by Gantt charts, while the site foreman's experience also matters (Li et al., 2011). Hence, reliable, clear instructions during the installation are essential to overcome severe safety issues. If not, many more technicians, forepersons, and safety officers will be required to manage the on-site assembly process, accumulating the management costs (Li et al., 2011). That is why the HK Housing Authority maintains a specific safety management system, including quarterly safety audits and checks to predict and withstand safety-related disruptions. The contractors need to fulfil the assessment requirements. Those who are unable to do so, will be excluded from future tenders, or the current contract will be stopped if there is a severe safety problem.

The implication of new laws and regulations can be either motivational or demotivational. In 2019, the HK economy was affected by multiple street demonstrations, while transportation routes were also disturbed. Machine breakdowns occur due to poor or negligent maintenance (J. Wang et al., 2018), and the system can fail, for instance, with failures in the manufacturing plant (Li et al., 2018). Also, this supply chain vulnerability includes material hoists, cranes, and tower crane breakdowns during the prefabricated component installations. According to the experts' opinions, these breakdowns are frequent in HK. These cause small disruptions and delays, but if not managed well, the delays will accumulate. Further, the contractors usually agree in advance with the suppliers, to enable rapid repairs/maintenance for quick remobilization of these plants, hence, minimizing the delays. Although Meinel and Abegg (2017) highlighted physical damage due to buildings collapsing as an SCV and this severely impacts IC, industry practitioners argue that reusability of the prefabricated units may be increased in IC after a disruption compared to the conventional construction practices.

On the other hand, transport disruptions are inherent in IC in HK, as the prefabricated components are transported from factories in Mainland China, hence, not limited to vehicle breakdowns, insufficient transportation capacity, and too late or too early delivery (J. Wang et al., 2018). The leading causes underlying these, are damages to the units in transport, delays from traffic jams, inefficiencies of customs clearance (Zhai & Huang, 2017). Also, the industry is also vulnerable to the impacts of any relevant new laws and regulations (Ekanayake, Shen, & Kumaraswamy, 2020). Although there is still no recorded major problem due to these SCV, developing appropriate capabilities may improve their withstanding ability with associated cost and time benefits since these vulnerabilities are common.

Technological Supply Chain Vulnerabilities (TSCV)

TSCV includes five technology-based CSCV with a total variance of 14.371. TSCV has the second highest mean score of 3.250. The highest factor loading is by the supply chain vulnerability 'technology failure' with a significant M value of 3.200, indicating high factor significance. IC supply chains are considerably susceptible to technological problems (J. Wang et al., 2018). Further, a shortage of industrial technology management personnel during construction is a vulnerability in implementing IC (Wang et al., 2019). Also, there are technical failures such as from latent defects due to imperfect joining and water leakage problems (Wu et al., 2019). As a solution, the monolithic leakage-free Semi-Precast System was specially designed to meet the requirements of the HK Housing Authority (Chiang et al., 2006). However, these systems are not adopted in all the IC projects, causing technical failures.

Besides, the fragmentation of the sequential design-construction process in the IC supply chains often results in information loss/misuse in the industry (Ekanayake et al., 2019). Information sharing with the supply chain members is quite complicated, while implementing the information systems is costly (Tran et al., 2016). However, inadequate information sharing tends to trigger supply chain operational problems. For instance, a delay in constructing a column resulted from the allocated space being inadequate. This was due to insufficient information sharing (Ekanayake et al., 2019), leading to reworks and/or variations. This highlights the imperative for more effective supply chain collaboration, requesting substantial attention to technical and social aspects of information sharing in equal measure (Wu et al., 2019).

In these circumstances, BIM and RFID enabled IT platforms were seen as helping to achieve real-time visibility and traceability of IC supply chains (Zhong et al., 2017). Also, an IKEA model and virtual prototyping technologies were suggested (Li et al., 2011). Information loss, IT system failure, and information misuse are CSCV, which affect the normal flow of IC. Therefore, some previous studies even considered the formalization of information flow for facilitating disturbance-free IC supply chains (Li et al., 2011). Further, these technological breakdowns result in industrial disputes and supply chain inefficiencies and exert strong direct influences on other IC vulnerabilities, such as design changes/variations/rework (Luo et al., 2019).

Variations/rework in IC supply chains are due to fragmentation of the supply chain, subcontracting, unrealistic scheduling, noncompliance with the specification, lack of explicit instruction to workers, the untimely supply of materials, ineffective project management, poor documentation, and lack of skilled labor (Shahparvari et al., 2019). Compared to traditional construction supply chains, the disruptions of rework are less in IC as early planning and design are available (Kisi et al., 2019). However, rework costs are observed because of the usual offsite production of prefabricated components (mostly in China) and their transportation to HK (Li et al., 2011).

Moreover, significant problems occur during the transport of oversized components to regions where the transportation infrastructure is minimal, and where access to construction sites is narrow, as indicated by the industry experts. Therefore, the supply chain disruptions should receive attention from the beginning of the supply chain process without passing problems over to the on-site assembly stage, mitigating cost, and time overruns. However, IC supply chains are still struggling with vulnerabilities due to variation/rework, endangering budget and schedule. Therefore, variations/rework as a supply chain vulnerability, has received the highest mean score within the component, demarcating the factor significance. As a solution, Shahparvari et al. (2019) suggested the integration of robotics, digital twins, and artificial intelligence together with the IC process.

Economic Supply Chain Vulnerabilities (ESCV)

This component consists of seven underlying SCV which are closely related to the disruptions due to the economic changes, and hence, named ESCV. ESCV component occupies the highest variance percentage, i.e., 24.054, with the highest supply chain vulnerability content. However, this is the component with the least mean score value. According to the respondents' arguments, although these disruptions may cause severe impacts to the IC supply chains in HK, these disruptions are not frequent. So currently, the effect is not very high but considerable. According to the experts' opinions, the construction industry in HK is suffering from the scarcity of materials such as river sand, while these inputs are obtained from Mainland China and affected by price fluctuations. Exchange rate fluctuations also affect imports, such as of prefabricated components, joints, and other materials that are not manufactured in HK. Most prefabricated components are almost impossible to effectively modify after producing them, leading to rework and cost overruns in the event of mistakes (Li et al., 2011). This may be why respondents assigned the highest mean score within the component to ‘cost overrun’ as proven by Wang et al. (2019).

IC in HK is no exception to cost overrun due to design, manufacture, and assembly problems (Li et al., 2011). However, having greater control over manufacturing reduces the chance of cost overruns (Ekanayake et al., 2020). Supply chain uncertainties usually hamper on-time delivery of IC components. For example, tardiness in delivery, which is often witnessed in IC in HK, is a significant cause of cost overrun (Mok et al., 2015). Although ‘buffer space hedging’ is possible, it contributes to increased site congestion, which is another cause of serious cost overrun (Zhai et al., 2019a). Therefore, the authors suggested an on-site production time variation reduction decision scenario to optimize the process. Pressure from the market or the industry triggers SCV in IC that appears as lack of demand and social acceptance due to the negative public perception of prefabrication and the general risk-averse attitude of the construction industry (Wang et al., 2019). In HK, it is proven that IC facilitates cost savings through for example, waste reduction in projects (Ekanayake et al., 2019) and IC is thus suggested as a way forward in addressing current construction industry performance shortfalls.

Economic policy changes are also another significant supply chain vulnerability (Wu et al., 2019) within the ESCV component. Top-down policy support, including preferential tax concessions, subsidies, and loans, play a critical role in promoting IC (Jiang et al., 2018). In early 2002 in HK, the government began to offer incentives to promote IC adoption. Hence, non-structural prefabricated external walls “may upon application and subject to conditions, be exempted from Gross Floor Area (GFA) and/or Site Coverage (SC) calculations under the Buildings Ordinance” (Joint Practice Note, 2002). However, due to the government policy from the early 1980s, the HK Housing Authority was the only major client adopting industrialized public housing construction, hence, affecting the growth of this sub-sector. The mandatory policies on the adoption of IC in specific sectors may encourage the implementation of IC (Wang et al., 2019). Similarly, changes to market conditions and related laws and regulations may generate vulnerabilities in IC (Wang et al., 2019). Also, fragmented IC supply chains often result in information loss/misuse in the industry (Ekanayake et al., 2019; Wu et al., 2019). However, according to industry experts, the loss of information is quite rare in HK. Still, information misuse can cause errors and resulting rework in design configuration, can in turn cause disruptions to the IC process. Hence, despite an excellent information sharing platform, it may still be challenging to achieve outstanding performance in IC supply chains.

Moreover, TSCV and ESCV components have received lower impact indices, highlighting their lower contribution towards the subject matter. However, their respective impact indices of 3.32 and 3.12 reflect that the industry is even moderately vulnerable to the associated disruptions. As an exception to the results, 'Variations and/or rework' the second most CSCV, was also grouped in TSCV. Although fragmentation of the IC supply chains results in these vulnerabilities (Shahparvari et al., 2019), the impact is less in IC compared to the traditional construction supply chains with the availability of early planning and design (Kisi et al., 2019).

Under these circumstances, even IC in HK would be benefitted from the integration of robotics, digital twin, and artificial intelligence together with the IC process as indicated by Shahparvari et al. (2019). All the ESCV are due to economic changes, which are out of control of the internal organizational structure. According to the industry feedback, although these disruptions may cause severe impacts, these are not frequent, and at the current stage, the effect is not very high but considerable in HK.

Finally, analogous to the FSE analysis results, a mathematical model for evaluating vulnerabilities affecting SCR in IC in HK was developed as presented in Equation 4.16. In

Equation 4.16, the coefficients assigned to CSCV components correspond to the respective normalized values.

$$OI = [C_{ESCV}|CV_{ESCV}|] + [C_{TSCV}|CV_{TSCV}|] + [C_{PSCV}|CV_{PSCV}|] + [C_{OSCV}|CV_{OSCV}|] + [C_{PBSCV}|CV_{PBSCV}|] \quad (4.16)$$

4.6 Chapter Summary

This chapter enabled the useful mathematical modeling of SCV affecting SCR in IC in HK by applying statistical analysis and fuzzy set theory to the data that was collected for this purpose. Further, this chapter presented the criticality level of each supply chain vulnerability and the overall impact of each of them on IC. Twenty-four SCV were offered as the critical vulnerabilities associated with IC in HK through the factor analysis of collected data. Factor analysis also enabled a well-justified grouping of these CSCV into five underlying components, namely, economic, technological, procedural, organizational and production-based as explicated clearly in this chapter. Thereby, a soft computing approach-FSE was facilitated in developing the multi-level-multi-criteria fuzzy mathematical model for assessing SCV as the major outcome of this chapter. The model showed that the OI is 3.36, indicating the IC supply chains are considerably vulnerable to the disruptions. Production-based vulnerabilities (impact-3.52) have the highest impact among all the vulnerability components.

Findings presented in this chapter would motivate IC project professionals to appreciate and address the CSCV in the context of five components and thereby develop adequate specific capabilities to successfully withstand these CSCV. Besides, this chapter contributes to the body of knowledge by evaluating SCV associated with IC projects in HK. To the knowledge of the researcher, this is the first structured-evaluation model that measures the vulnerability level of IC, providing useful insights to industry stakeholders for well-informed decision making in achieving resilient, sustainable, and performance-enhanced supply chains. Indeed, findings of Chapter 4 triggered several attempts to detect critical supply chain capabilities and map CSCV with appropriate capabilities in developing an envisaged powerful assessment model for evaluating SCR in IC in HK as discussed in the forthcoming chapters.

Chapter 5 Assessing the Criticality and the Practice of Supply Chain Capabilities in Industrialized Construction in Hong Kong[3]

5.1 Introduction

Inspired by multiple benefits, including competitive advantages from developing resilient supply chains and having identified Supply Chain Capabilities (SCC) as essential precursors to SCR, this chapter reports on a vital segment of a study on SCC for IC in HK. This chapter further focuses here on Critical Supply Chain Capabilities (CSCC) and development of effective assessment models to evaluate CSCC by improving resilience in IC in one of many high-density cities worldwide: Hong Kong.

Explicating further regarding the rationale behind this chapter, SCR can only be improved by improving the appropriate SCC (Pettit et al., 2013). Therefore, it is essential to identify the appropriate SCC, especially the CSCC and to know their relative levels of importance in the IC supply chains. However, there is no known previous attempt to determine CSCC in IC and to thereby improve SCR, despite more extensive research being needed for the specific development of IC supply chains. Also, the literature is sparse on how SCR is measured and evaluated since only a few articles attempted to assess SCR (Kamalahmadi & Parast, 2016). The research gap is significant since it is difficult to respond or react adequately without a proper assessment of SCR (Tan, 2020) using its two fundamental dimensions of vulnerabilities and capabilities (Pettit et al., 2013). Further, the supply chain configurations and their levels

---

[3] The core research and findings in this chapter have been peer-reviewed before publication in:

Ekanayake, E.M.A.C., Shen, G.Q., and Kumaraswamy, M.M., 2020. 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., and Kumaraswamy, M.M., 2021. A Fuzzy Synthetic Evaluation of Capabilities for Improving Supply Chain Resilience of Industrialized Construction: A Hong Kong Case Study. *Production Planning and Control.* DOI: 10.1080/09537287.2021.1946330.

of vulnerability differ across jurisdictions. Therefore, a jurisdiction-(HK)-specific separate study for IC was needed to determine the SCC to withstand associated disruptions in IC.

In this regard, beginning from the identification of appropriate SCC, this study then developed multi-stage-mathematical models to evaluate the adoption of SCC of IC in HK by soliciting experts' judgements and analyzing them using fuzzy synthetic evaluation. These evaluation models are, to the knowledge of the researcher, the first set of structured models designed to assess SCC of IC, also providing useful insights to practitioners for well-informed decision making in formulating strategies to initiate and nurture resilient supply chains in IC in HK. Also, the levels of the current practice in terms of the relevant SCC were assessed, thereby highlighting a practice gap in the industry through the developed models. Moreover, the findings of Chapter 5 facilitate partially fulfilling of the Objective 2 of this research. Hence, this chapter mainly discusses the findings generated from the empirical study as appropriate to CSCC and the assessment models of CSCC.

5.2 Research Design

In line with Chapter 2, expert opinions were solicited through a questionnaire survey to determine CSCC and the assessment models of SCC. The questionnaire used for the survey consisted of 57 SCC measurement items extracted after the systematic review of literature as elaborated in Chapter 3 and after the pilot study as explicated in Chapter 2. All the 57 SCC measurement items used in this study are presented in Table 5.1.

Table 5.1: SCC measurement items extracted from the literature review in Chapter 3

NO	SCC measurement items	References
C01	Modular product design	[1] [2] [37]
C02	Multiple uses	[1] [2] [5] [19]
C03	Supplier contract flexibility	[1] [2] [5] [17] [19] [20] [28] [29] [30] [32] [35] [37] [39] [40] [42] [43]

C04	Multiple sources/suppliers	[1] [2] [4] [7] [8] [10] [11] [14] [15] [19] [20] [21] [22] [23] [29] [30] [35] [37] [38] [39] [40] [42]
C05	Alternate distribution channels/multimodal transportation	[1] [2] [5] [20] [28] [29] [30] [35] [37] [38] [39] [42]
C06	Risk pooling/sharing	[1] [2] [4] [7] [8] [10] [16] [20] [28] [30]
C07	Production postponement	[1] [2] [28] [38]
C08	Vertical integration	[14] [28] [33] [39] [41]
C09	Integrating inventory management with SCM tools	[1] [2] [16] [18] [27] [28] [33] [35] [37]
C10	Reserves capacity/inventory buffers (materials, equipment & labor)	[1] [2] [7] [15] [23] [20] [21] [28] [29] [30] [32] [34] [35] [37] [38] [43]
C11	Redundancy	[1] [2] [7] [9] [14] [19] [20] [21] [35] [43]
C12	Backup equipment facilities	[1] [2] [5] [15] [16] [19] [24] [27] [30] [32] [35] [40] [43]
C13	Backup utilities	[1] [2] [29] [30] [32]
C14	Waste elimination	[1] [2] [3] [4] [19] [25] [26] [28] [29] [32] [38]
C15	Higher labor productivity	[1] [2] [5] [19] [28] [29] [32]
C16	Avoid variations/rework	[1] [2]
C17	Failure prevention	[1] [2]
C18	Products, assets, people visibility	[1] [2] [4] [7] [8] [9] [10] [30] [33] [38] [40] [42] [43]
C19	Business intelligence gathering	[1] [2] [38]
C20	Efficient IT system & information exchange	[1] [2] [29] [30] [32] [33] [36] [38] [41] [43]
C21	Finite capacity scheduling tools with procurement visibility/e-procurement	[18] [38]
C22	Fast rerouting of requirements	[1] [2] [5] [20] [29] [30] [33] [44]
C23	Lead time reduction	[1] [2]
C24	Conducting process simulation	[1] [2]
C25	Alternative innovative technology development	[1] [2] [13] [16] [29] [43]
C26	Learning from experience	[1] [2] [5] [12] [19] [20]
C27	Deploying IT based reporting tools	[16] [29] [30] [32] [33]
C28	Maintaining buffer time	[27] [34]
C29	Conducting parallel operations	[7] [19] [28] [38]
C30	Monitoring early warning signals	[1] [2] [19] [20] [29] [30] [43]
C31	Forecasting/predictive analysis	[1] [2] [19] [20] [29] [32] [37] [43]
C32	Risk management	[1] [2] [4] [5] [6] [7] [9] [30] [31] [34] [38] [43]
C33	Cross training/intensive training	[14] [29] [30] [41] [43]
C34	Deploying tracking and tracing tools	[16] [30] [32] [43]
C35	Quality control	[1] [2] [29] [32]
C36	Business intelligence and disruption management research	[10] [19] [30]
C37	Distributed decision making	[1] [2] [33] [44]
C38	Distributed capacity and assets	[1] [2] [44]
C39	Decentralization of key resources	[1] [2] [44]
C40	Professional response team	[1] [2] [29] [30] [43]

C41	Effective communications strategy	[1] [2] [28] [29] [30] [43]
C42	Consequence mitigation	[1] [2] [29] [30] [34] [43] [44]
C43	Collaborative information exchange & decision making	[1] [2] [13] [18] [20] [28] [29] [30] [32] [33] [37] [38] [40] [42] [43]
C44	Collaborative forecasting	[1] [2] [30] [38] [43]
C45	Obtain more competitive price from suppliers and subcontractors	[17]
C46	Procure materials globally	[17]
C47	Public–private collaboration	[14] [43]
C48	Strong reputation for quality	[5] [14] [17] [19] [20] [22] [23] [28]
C49	Market share of the organisations	[1] [2] [5]
C50	Close and healthy client-contractor relationships	[1] [2] [6] [14] [17] [28] [29] [32] [33] [37]
C51	Faster delivery	[5] [17] [19] [20] [22] [23] [28]
C52	Cyber-security	[1] [2] [29] [32]
C53	Personnel security	[1] [2] [29] [32]
C54	Financial reserves and funds	[1] [2] [17] [29] [30] [32]
C55	Good insurance coverage	[1] [2] [22] [23] [29] [32]
C56	Portfolio diversification	[1] [2] [28] [29] [32]
C57	Good price margin	[1] [2] [29] [32] [38] [43]

1=(Zainal and Ingirige, 2018); 2=(Pettit et al., 2013); 3=(Mensah and Merkuryev, 2014); 4=(Soni et al., 2014); 5=(Tang, 2006); 6=(Bueno-Solano and Cedillo-Campos, 2014); 7=(Christopher and Peck, 2004); 8=(Jüttner and Maklan, 2011); 9=(Scholten et al., 2014); 10=(Johnson et al., 2013); 11=(Lengnick-Hall et al., 2011); 12=(Kristianto et al., 2014); 13=(Scholten and Schilder, 2015); 14=(A. Ali et al., 2017); 15=(Ivanov et al., 2017); 16=(Brusset and Teller, 2017); 17=(Lim et al., 2011); 18=(Vaidyanathan and O'Brien, 2004); 19=(Sheffi and Rice, 2005); 20=(Peck, 2005); 21=(Tomlin, 2006); 22=(Dong and Tomlin, 2012); 23=(Wang et al., 2010); 24=(Kim and Tomlin, 2013); 25=(Panova and Hilletofth 2018); 26=(Wedawatta et al. 2010); 27=(Zavala et al. 2018); 28=(Chaghooshi et al., 2018); 29=(Chowdhury and Quaddus, 2017); 30=(Chowdhury and Quaddus, 2016); 31=(Ambulkar et al., 2015); 32=(Chowdhury and Quaddus, 2015); 33=(Wieland and Wallenburg, 2013); 34=(Colicchia et al., 2010); 35=(Purvis et al., 2016); 36=(Singh and Singh, 2019); 37=(Shahbaz et al., 2019); 38=(Rajesh, 2019); 39=(Gosling et al., 2013); 40=(Namdar et al., 2018); 41=(Riley et al., 2016); 42=(Mandal et al., 2016); 43=(Machado et al., 2018); 44=(Treiblmaier, 2018)

After careful consideration of all these measurement items during the pilot study, the experts recommended removing 'brand equity of the organizations' as they thought this measurement item is not highly influential in the construction industry since IC is practiced in the industry by reputed construction organizations which had already developed significant brand equity within the industry. Although the experts did not 'highly agree' with the supply chain capability measurement item of 'conducting parallel processes instead of series processes', they suggested retaining this measurement item for reconsideration, after the primary data collection. Thereby, the criticality and the application of the identified SCC measurement items were assessed using a five-point Likert scale as the linguistic terms for the FSE technique (Owusu et al., 2020). Further, additional rows were provided for open-ended responses to add any known SCC measurement items that were not captured in the preliminary study while grading them similarly as above.

In this study, the importance or the criticality of the SCC measurement items and their current levels in present practice were separately assessed using the questionnaire survey. Mean score values obtained based on the assessment of the experts were used to establish the 'importance' and the 'current practice' of each SCC measurement item. The details of the survey results are given in Table 5.2.

Table 5.2: Evaluating the CSCC measurement items

CSCC Measurement Item	Level of importance			Level of current practice		
	Mean	SD	N-V	Mean	SD	N-V
C35	4.413	0.660	1.00	3.800	0.735	0.83
C55	4.373	0.785	0.96	3.907	0.701	0.92
C54	4.347	0.707	0.93	3.693	0.788	0.74
C16	4.253	0.660	0.83	3.440	0.663	0.53
C40	4.240	0.612	0.81	3.747	0.680	0.79
C26	4.240	0.803	0.81	3.893	0.938	0.91
C17	4.187	0.630	0.75	3.440	0.793	0.53
C41	4.187	0.651	0.75	3.547	0.664	0.62
C50	4.187	0.800	0.75	4.000	0.717	1.00
C05	4.180	0.734	0.75	3.213	0.703	0.34
C01	4.173	0.724	0.74	3.680	0.701	0.73
C42	4.147	0.651	0.71	3.413	0.718	0.51
C15	4.147	0.748	0.71	3.680	0.808	0.73
C02	4.133	0.741	0.70	3.640	0.671	0.70
C14	4.107	0.764	0.67	3.253	0.773	0.38
C45	4.107	0.781	0.67	3.573	0.720	0.64
C28	4.093	0.903	0.65	3.533	0.759	0.61
C18	4.080	0.712	0.64	3.347	0.626	0.46
C48	4.067	0.622	0.60	4.000	0.678	1.00

C37	4.067	0.704	0.62	3.893	0.798	0.91
C43	4.067	0.704	0.62	3.720	0.689	0.77
C51	4.053	0.634	0.61	3.867	0.811	0.89
C53	4.053	0.884	0.61	3.400	0.822	0.50
C08	4.040	0.646	0.59	3.067	0.723	0.22
C07	4.040	0.706	0.59	2.973	0.677	0.14
C30	4.040	0.725	0.59	3.347	0.668	0.46
C34	4.040	0.725	0.59	3.600	0.900	0.67
C19	4.040	0.743	0.59	3.827	0.778	0.86
C04	4.040	0.779	0.59	3.213	0.776	0.34
C22	4.027	0.735	0.58	3.360	0.799	0.47
C13	4.027	0.771	0.58	3.627	0.767	0.69
C06	4.013	0.688	0.57	3.333	0.664	0.44
C52	4.013	0.878	0.57	3.720	0.689	0.77
C11	4.000	0.697	0.55	3.200	0.753	0.33
C12	4.000	0.735	0.55	3.213	0.759	0.34
C56	4.000	0.805	0.55	3.320	0.701	0.43
C44	4.000	0.870	0.55	3.560	0.793	0.63
C20	3.987	0.811	0.54	3.533	0.600	0.61
C23	3.980	0.743	0.53	3.520	0.828	0.60
C57	3.980	0.892	0.53	3.200	0.900	0.33
C33	3.977	0.715	0.53	3.360	0.816	0.47
C25	3.973	0.735	0.52	3.467	0.704	0.56

N-V = normalized value [(mean – minimum mean)/(maximum mean – minimum mean)]

Thereafter, the Cronbach's alpha test and Shapiro-Wilk test using SPSS version 25 were conducted to test the data normality and reliability. The respective test statistics of 0.867 and 0.849 confirmed that both the factors of 'importance' and 'current practice' are internally reliable and consistent (Santos, 1999) whereas the data is non-normally distributed (Gel et al., 2007).

The data normalization process was then undertaken before moving to the factor analysis to screen out CSCC measurement items following the studies of Adabre and Chan (2019) and Osei-Kyei et al. (2020). Therefore, measurement items above 0.5 (normalized value) were regarded as critical and considered in the factor analysis (Adabre & Chan, 2019; Osei-Kyei et al., 2020). Statistical Mean (M), Standard Deviation (SD), and the normalization (N) values for each SCC measurement item were calculated and presented in Table 1. Where some measurement items received a similar M value, the measurement items which received the least SD were ranked first. Based on the normalization values (N>0.5), 42 SCC measurement items were identified as critical and considered them in the factor analysis. With these results, it was proceeded with the factor analysis to determine CSCC components and fuzzy synthetic evaluation to develop the assessment models of SCC as elaborated in the succeeding sections of this chapter.

5.3 Identification of Critical Supply Chain Capabilities (CSCC) and Respective Components through Factor Analysis

The respective test statistics of the Kaiser-Meyer-Olkin test (KMO=0.810) and Bartlett’s test of sphericity statistic (3370.583 with a significance level of 0.000) indicated that the data set is appropriate for factor analysis and the correlation matrix is not an identity matrix (Kaiser, 1974). Then, the study proceeded with factor analysis. First, factor extraction was conducted using the principal component analysis and the measurement items with the eigenvalues less than one were eliminated (Chan et al., 2018). Therefore, only 42 CSCC measurement items with eigenvalues above 1 remained. The varimax rotation was done for these 42-measurement items, which generated nine underlying CSCC components, explaining 79.77% of the total variance. Only 41 measurement items were successfully loaded into the nine CSCC components since their factor loadings were above 0.40, and they were considered as significant measurement items (Li et al., 2011).

'Backup utilities (C13)' was excluded from the list since the factor loading was below 0.4. According to the respondents, utility disruptions are infrequent in IC in HK, and the supply chains are not susceptible to these disruptions. Hence, they did not perceive any need for backup utility sources which may also consume cost and time. Table 5.3 summarizes the measurement items and respective factor loadings along with the developed nine CSCC components. Component naming was done based on the common themes that were underlying the measurement items. If there was no clear underlying common theme; naming was done based on the measurement items with higher factor loadings (Owusu & Chan, 2019; Zhang et al., 2017). These nine CSCC components are resourcefulness, flexibility, capacity, adaptability, efficiency, financial strength, visibility, anticipation, and dispersion and these CSCC were considered and analyzed further using fuzzy synthetic evaluation to derive SCC assessment models as elaborated in the forthcoming section.

5.4 Application of the soft computing approach- Fuzzy Synthetic Evaluation (FSE)

FSE, as a soft computing approach, was employed in this study to evaluate the importance and the current practice of CSCC in IC in HK as discussed in Chapter 2. Accordingly, the following five steps guided this study to develop SCC indices and the models to evaluate CSCC for improving SCR in IC in HK. Also, these five steps are clearly illustrated in Figure 5.1.

5.4.1. Developing the evaluation index system

First, an evaluation index was created [Equation (5.1)] by defining CSCC components as the first level index system. In generating the following FSE equations, this study followed the studies of Ameyaw et al. (2015), Li et al. (2013), and Owusu et al. (2020).

$$U = \left(U_{res}, U_{fle}, U_{cap}, U_{ada}, U_{eff}, U_{fis}, U_{vis}, U_{ant}, U_{dis}\right) \qquad (5.1)$$

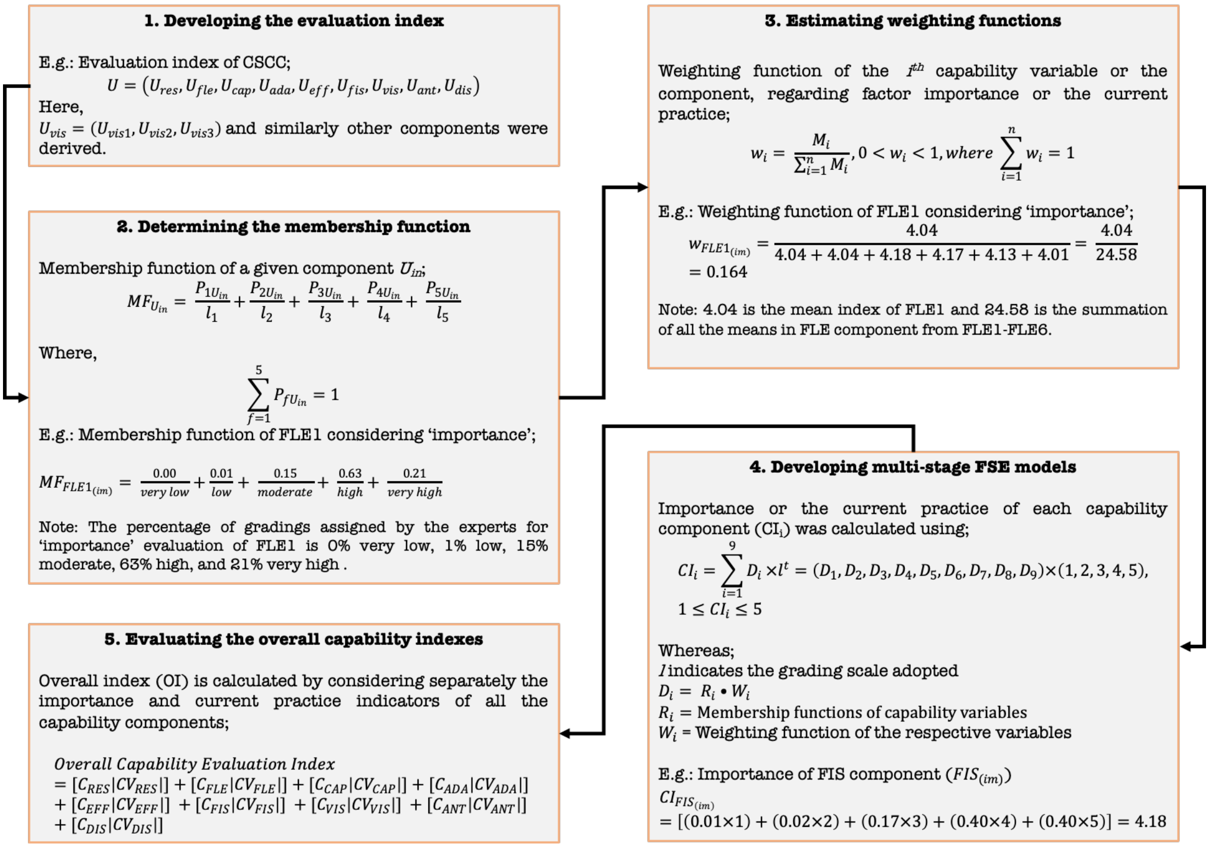


Figure 5.1: Workflow of the FSE modeling of SCC in this research

The second level index system was then defined by considering the individual CSCC measurement items within the SCC components, as shown in Table 5.4.

$$U_{res} = (U_{res1}, U_{res2}, U_{res3}, U_{res4}, U_{res5}, U_{res6}, U_{res7}) \quad (5.1.1)$$

$$U_{fle} = (U_{fle1}, U_{fle2}, U_{fle3}, U_{fle4}, U_{fle5}, U_{fle6}) \quad (5.1.2)$$

$$U_{cap} = (U_{cap1}, U_{cap2}, U_{cap3}, U_{cap4}, U_{cap5}) \quad (5.1.3)$$

$$U_{ada} = (U_{ada1}, U_{ada2}, U_{ada3}, U_{ada4}, U_{ada5}) \quad (5.1.4)$$

$$U_{eff} = (U_{eff1}, U_{eff2}, U_{eff3}, U_{eff4}, U_{eff5}) \quad (5.1.5)$$

$$U_{fis} = (U_{fis1}, U_{fis2}, U_{fis3}, U_{fis4}) \quad (5.1.6)$$

$$U_{vis} = (U_{vis1}, U_{vis2}, U_{vis3}) \quad (5.1.7)$$

$$U_{ant} = (U_{ant1}, U_{ant2}, U_{ant3}, U_{ant4}, U_{ant5}) \quad (5.1.8)$$

$$U_{dis} = (U_{dis1}) \quad (5.1.9)$$

The aforementioned index systems are the input variables to the FSE and apply to both 'importance' and 'current level of practice' indicators.

5.4.2. Determining the Membership Function

Fuzzy mathematics was employed to generate the membership grades of CSCC measurement items and their respective component groups. Also, the grading scale used to assess the importance, and the current practice of the SCC measurement items was a five-scale grading system where $l = [1, 2, 3, 4, 5]$; l_1 = very low, l_2= low, l_3=neutral, l_4= high, l_5= very high. After that, Equation (5.2) was used to calculate the Membership Function (MF) of a given CSCC component U_{in}.

$$MF_{U_{in}} = \frac{P_{1U_{in}}}{l_1} + \frac{P_{2U_{in}}}{l_2} + \frac{P_{3U_{in}}}{l_3} + \frac{P_{4U_{in}}}{l_4} + \frac{P_{5U_{in}}}{l_5} \tag{5.2}$$

MF of a given component U_{in} indicates the nth capability measurement item of the given component i ($i = I_1, I_2, I_3, I_4, I_5, I_6, I_7, I_8, I_9$).

$P_{fU_{in}}$ $(f = 1, 2, 3, 4, 5)$ indicates the percentage of respondents who graded the capability measurement items using the grading scale for level of importance and the current practice measures. In addition, $P_{fU_{in}}/l_i$ indicates the association of $P_{fU_{in}}$ and the appropriate grading scale. Also, '+' in Equation (3) denotes a notation, hence generating Equation (5.3) as follows.

$$MF_{U_{in}} = \left(P_{1U_{in}}, P_{2U_{in}}, P_{3U_{in}}, P_{4U_{in}}, P_{5U_{in}}\right) \tag{5.3}$$

The members used in Equation (5.1.1) - Equation (5.1.9) range between ‘0’ to ‘1’. Besides, their summation should be equal to one since they represent weighted average calculations. Equation (5.4) explicates this requirement further.

$$\sum_{f=1}^{5} P_{fU_{in}} = 1 \tag{5.4}$$

Further to Equation (5.4), MFs of the components were created by assessing the experts’ overall responses. For instance, considering FLE1, the experts’ assigned grading percentages for criticality evaluation are 0% very low, 1% low, 15% moderate, 63% high, and 21% very high. Hence, the MF of $FLE1_{(im)}$ is as follows.

$$MF_{FLE1_{(im)}} = \frac{0.00}{very\ low} + \frac{0.01}{low} + \frac{0.15}{moderate} + \frac{0.63}{high} + \frac{0.21}{very\ high} \tag{5.4.1}$$

As per Equation (5.4), $MF_{FLE1_{(im)}}$ can be presented as: (0.00, 0.01, 0.15, 0.63, 0.21). Similarly, the current practice indicator for FLE1 can be formulated as shown in Equation (5.4.2). Therefore, $MF_{FLE1_{(cp)}}$ = (0.00, 0.20, 0.56, 0.21, 0.27).

$$MF_{FLE1_{(cp)}} = \frac{0.00}{very\ low} + \frac{0.20}{low} + \frac{0.56}{moderate} + \frac{0.21}{high} + \frac{0.27}{very\ high} \tag{5.4.2}$$

Accordingly, a similar approach was used to calculate the MFs of all the measurement items, and the generated results are given in MF for Level 3 in Table 5.5. After that, MFs of all the component groups were calculated using the individual components' computed weightings. The following section further explicates the calculations.

5.4.3. Estimating Weighting Functions

The Weighting Function (WF) shows the relative importance of each measurement item or a component based on the respondents' gradings of the measurement items and the components (Ameyaw et al., 2015; Owusu et al., 2020). Although both the normalized mean technique and analytic hierarchy process technique can be used to calculate the weighting functions (Lee et al., 2008; Lo, 1999), this study used the normalized mean method based on Equation (5.5) since it is a straightforward method (Ameyaw et al., 2015; Lo, 1999).

$$w_i = \frac{M_i}{\sum_{i=1}^{n} M_i}, 0 < w_i < 1, where \sum_{i=1}^{n} w_i = 1 \quad (5.5)$$

w_i= weighting function of the i^{th} capability measurement item or the component, regarding factor importance or the current practice. M_i = mean index of any capability measurement item or a component as estimated from the questionnaire survey data. The summation of the mean within a weight function set must be equal to one and also can be represented in Equation (5.6).

$$w_i = (w_1, w_2, \dots, w_n) \quad (5.6)$$

Considering $FLE1_{(im)}$ as an example, Equation (5.6.1) was computed by calculating the $w_{FLE1_{(im)}}$. Similarly, the weighting factor of the FLE component was calculated and denoted in Equation (5.6.2). A similar approach was then deployed for calculating all the weighting functions of measurement items and the respective components that belonged to both the importance and level of current practice indices, as presented in Table 5.5 and Table 5.6.

$$w_{FLE1_{(im)}} = \frac{4.04}{4.04+4.04+4.18+4.17+4.13+4.01} = \frac{4.04}{24.58} = 0.164 \quad (5.6.1)$$

$$w_{FLE_{(im)}} = \frac{24.58}{28.37+24.58+20.57+20.31+20.93+16.70+12.11+20.44+4.07} = \frac{24.58}{168.09} = 0.146 \qquad (5.6.2)$$

Equation (5.6.3) confirms that the summation of the weighting functions within a component and total of the components equal to 1.

$$\sum_{i=1}^{6} w_{FLE_{(im)}} = (0.164 + 0.164 + 0.170 + 0.170 + 0.168 + 0.163) = 1.0 \qquad (5.6.3)$$

5.4.4. Developing Multi-stage-multi-criteria FSE models

Developing a FSE model for evaluating CSCC improving IC in HK is a multi-stage process including three main stages; (i) calculation of the MF and WF of each capability measurement item based on the experts' gradings, (ii) computation of the MF and WF of CSCC components, (iii) calculation of the overall index for assessing CSCC improving SCR in IC in HK.

A fuzzy matrix D_i was first determined to evaluate the impact of individual components with the use of the calculated MF and WF of measurement items within their respective component groups. Following the MFs determined under Equation (5.2), functions of measurement items within their respective capability components (for both importance and level of current practice indices) can be presented as follows in Equation (5.7).

$$R_i = \begin{vmatrix} MF_{U_{i1}} \\ MF_{U_{i2}} \\ MF_{U_{i3}} \\ \cdots \\ MF_{U_{in}} \end{vmatrix} = \begin{vmatrix} P_{1U_{i1}} & P_{2U_{i1}} & P_{3U_{i1}} & P_{4U_{i1}} & P_{5U_{i1}} \\ P_{1U_{i2}} & P_{2U_{i2}} & P_{3U_{i2}} & P_{4U_{i2}} & P_{5U_{i2}} \\ P_{1U_{i3}} & P_{2U_{i3}} & P_{3U_{i3}} & P_{4U_{i3}} & P_{5U_{i3}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{1U_{in}} & P_{2U_{in}} & P_{3U_{in}} & P_{4U_{in}} & P_{5U_{in}} \end{vmatrix} \qquad (5.7)$$

Table 5.3: Results of the factor analysis

Code	CSCC improving SCR in IC in HK with respective measurement items	Components 1	2	3	4	5	6	7	8	9
Component 1	Resourcefulness (RES)									
RES1	Personnel security	.768	-	-	-	-	-	-	-	-
RES2	Collaborative information exchange & decision making	.702	-	-	-	-	-	-	-	-
RES3	Collaborative forecasting	.656	-	-	-	-	-	-	-	-
RES4	Cyber-security	.655	-	-	-	-	-	-	-	-
RES5	Obtain more competitive price from suppliers and subcontractors	.607	-	-	-	-	-	-	-	-
RES6	Multiple sources/suppliers	.588	-	-	-	-	-	-	-	-
RES7	Maintaining buffer time	.581	-	-	-	-	-	-	-	-
Component 2	Flexibility (FLE)									
FLE1	Vertical integration	-	.761	-	-	-	-	-	-	-
FLE2	Production postponement	-	.756	-	-	-	-	-	-	-
FLE3	Alternate distribution channels/multimodal transportation	-	.691	-	-	-	-	-	-	-
FLE4	Modular product design	-	.675	-	-	-	-	-	-	-
FLE5	Multiple uses	-	.641	-	-	-	-	-	-	-
FLE6	Risk pooling/sharing	-	.638	-	-	-	-	-	-	-
Component 3	Capacity (CAP)									
CAP1	Backup equipment facilities	-	-	.819	-	-	-	-	-	-
CAP2	Redundancy	-	-	.657	-	-	-	-	-	-
CAP3	Consequence mitigation	-	-	.567	-	-	-	-	-	-
CAP4	Effective communications strategy	-	-	.511	-	-	-	-	-	-
CAP5	Professional response team	-	-	.500	-	-	-	-	-	-
Component 4	Adaptability (ADA)									
ADA1	Strong reputation for quality	-	-	-	.839	-	-	-	-	-
ADA2	Lead time reduction	-	-	-	.704	-	-	-	-	-

ADA3	Faster delivery	-	-	-	.674	-	-	-	-	-
ADA4	Close and healthy client-contractor relationships	-	-	-	.521	-	-	-	-	-
ADA5	Fast rerouting of requirements	-	-	-	.429	-	-	-	-	-
Component 5	Efficiency (EFF)									
EFF1	Failure prevention	-	-	-	-	.730	-	-	-	-
EFF2	Avoid variations/rework	-	-	-	-	.725	-	-	-	-
EFF3	Higher labor productivity	-	-	-	-	.668	-	-	-	-
EFF4	Waste elimination	-	-	-	-	.531	-	-	-	-
EFF5	Learning from experience	-	-	-	-	.497	-	-	-	-
Component 6	Financial Strength (FIS)									
FIS1	Good price margin	-	-	-	-	-	.876	-	-	-
FIS2	Portfolio diversification	-	-	-	-	-	.804	-	-	-
FIS3	Financial reserves and funds	-	-	-	-	-	.468	-	-	-
FIS4	Good insurance coverage	-	-	-	-	-	.407	-	-	-
Component 7	Visibility (VIS)									
VIS1	Efficient IT system & information exchange	-	-	-	-	-	-	.849	-	-
VIS2	Business intelligence gathering	-	-	-	-	-	-	.766	-	-
VIS3	Products, assets, people visibility	-	-	-	-	-	-	.511	-	-
Component 8	Anticipation (ANT)									
ANT1	Deploying tracking and tracing tools	-	-	-	-	-	-	-	.731	-
ANT2	Monitoring early warning signals	-	-	-	-	-	-	-	.653	-
ANT3	Alternative innovative technology development	-	-	-	-	-	-	-	.556	-
ANT4	Quality control	-	-	-	-	-	-	-	.528	-
ANT5	Cross training/intensive training	-	-	-	-	-	-	-	.484	-
Component 9	Dispersion (DIS)									
DIS1	Distributed decision making	-	-	-	-	-	-	-	-	.783

Eigenvalue	18.488	3.094	2.579	2.218	1.928	1.692	1.291	1.146	1.069	
Variance (%)	44.018	7.368	6.140	5.281	4.591	4.027	3.075	2.728	2.545	
Cumulative variance (%)	44.018	51.386	57.525	62.806	67.397	71.425	74.500	77.228	79.773	
KMO measure of sampling adequacy										.810
Bartlett's test of sphericity approximated chi-square										3370.583
Df										861
Sig.										.000

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Table 5.4: Weightings for the measurement items and their overall CSCC components

Code	CSCC Measurement Items and Components	Weightings for importance				Weightings for current practice			
		Mean	Weighting	Total Mean	Component Weighting	Mean	Weighting	Total Mean	Component Weighting
RES1	Personnel security	4.05	0.143			3.40	0.138		
RES2	Collaborative information exchange & decision making	4.07	0.143			3.72	0.150		
RES3	Collaborative forecasting	4.00	0.141			3.56	0.144		
RES4	Cyber-security	4.01	0.141			3.72	0.150		
RES5	Obtain more competitive price from suppliers and subcontractors	4.11	0.145			3.57	0.145		
RES6	Multiple sources/suppliers	4.04	0.142			3.21	0.130		
RES7	Maintaining buffer time	4.09	0.144			3.53	0.143		
	Resourcefulness (RES)			28.37	0.169			24.72	0.171
FLE1	Vertical integration	4.04	0.164			3.07	0.154		
FLE2	Production postponement	4.04	0.164			2.97	0.149		
FLE3	Alternate distribution channels/multimodal transportation	4.18	0.170			3.21	0.161		
FLE4	Modular product design	4.17	0.170			3.68	0.185		
FLE5	Multiple uses	4.13	0.168			3.64	0.183		
FLE6	Risk pooling/sharing	4.01	0.163			3.33	0.167		

	Flexibility (FLE)			24.58	0.146			19.91	0.138
CAP1	Backup equipment facilities	4.00	0.194			3.21	0.188		
CAP2	Redundancy	4.00	0.194			3.20	0.187		
CAP3	Consequence mitigation	4.15	0.202			3.41	0.199		
CAP4	Effective communications strategy	4.19	0.204			3.55	0.207		
CAP5	Professional response team	4.24	0.206			3.75	0.219		
	Capacity (CAP)			20.57	0.122			17.12	0.118
ADA1	Strong reputation for quality	4.07	0.200			4.00	0.213		
ADA2	Lead time reduction	3.98	0.196			3.52	0.188		
ADA3	Faster delivery	4.05	0.200			3.87	0.206		
ADA4	Close and healthy client-contractor relationships	4.19	0.206			4.00	0.213		
ADA5	Fast rerouting of requirements	4.03	0.198			3.36	0.179		
	Adaptability (ADA)			20.31	0.121			18.75	0.130
EFF1	Failure prevention	4.19	0.200			3.44	0.194		
EFF2	Avoid variations/rework	4.25	0.203			3.44	0.194		
EFF3	Higher labor productivity	4.15	0.198			3.68	0.208		
EFF4	Waste elimination	4.11	0.196			3.25	0.184		
EFF5	Learning from experience	4.24	0.203			3.89	0.220		
	Efficiency (EFF)			20.93	0.125			17.71	0.123
FIS1	Good price margin	3.98	0.238			3.20	0.227		
FIS2	Portfolio diversification	4.00	0.240			3.32	0.235		
FIS3	Financial reserves and funds	4.35	0.260			3.69	0.262		
FIS4	Good insurance coverage	4.37	0.262			3.91	0.277		
	Financial Strength (FIS)			16.70	0.099			14.12	0.098
VIS1	Efficient IT system & information exchange	3.99	0.329			3.53	0.330		
VIS2	Business intelligence gathering	4.04	0.334			3.83	0.357		
VIS3	Products, assets, people visibility	4.08	0.337			3.35	0.313		
	Visibility (VIS)			12.11	0.072			10.71	0.074
ANT1	Deploying tracking and tracing tools	4.04	0.198			3.60	0.205		

ANT2	Monitoring early warning signals	4.04	0.198			3.35	0.190		
ANT3	Alternative innovative technology development	3.97	0.194			3.47	0.197		
ANT4	Quality control	4.41	0.216			3.80	0.216		
ANT5	Cross training/intensive training	3.98	0.195			3.36	0.191		
	Anticipation (ANT)			20.44	0.122			17.57	0.122
DIS1	Distributed decision making	4.07	1.000			3.89	1.000		
	Dispersion (DIS)			4.07	0.024			3.89	0.027
	Total			168.0	1.000			144.49	1.000

Table 5.5: Membership functions for the CSCC components and their measurement items

CSCC Components	Level of importance			Level of current practice		
	Weighting	MF for Level 3	MF for Level 2	Weighting	MF for Level 3	MF for Level 2
Resourcefulness (RES)			0.00, 0.03, 0.22, 0.41, 0.34			0.00, 0.07, 0.39, 0.45, 0.09
RES1	0.143	0.00, 0.07, 0.16, 0.43, 0.35		0.138	0.00, 0.17, 0.29, 0.49, 0.04	
RES2	0.143	0.00, 0.01, 0.17, 0.55, 0.27		0.150	0.00, 0.01, 0.37, 0.49, 0.12	
RES3	0.141	0.00, 0.05, 0.21, 0.41, 0.32		0.144	0.00, 0.08, 0.39, 0.43, 0.11	
RES4	0.141	0.00, 0.08, 0.13, 0.48, 0.31		0.150	0.00, 0.05, 0.25, 0.61, 0.08	
RES5	0.145	0.00, 0.00, 0.25, 0.39, 0.36		0.145	0.00, 0.01, 0.52, 0.35, 0.12	
RES6	0.142	0.00, 0.00, 0.28, 0.40, 0.32		0.130	0.01, 0.15, 0.48, 0.33, 0.03	
RES7	0.144	0.00, 0.01, 0.32, 0.23, 0.44		0.143	0.01, 0.03, 0.47, 0.40, 0.09	
Flexibility (FLE)			0.00, 0.00, 0.22, 0.51, 0.27			0.00, 0.10, 0.52, 0.33, 0.06
FLE1	0.164	0.00, 0.00, 0.23, 0.51, 0.27		0.154	0.00, 0.20, 0.56, 0.21, 0.03	
FLE2	0.164	0.00, 0.00, 0.33, 0.45, 0.21		0.149	0.01, 0.19, 0.63, 0.16, 0.01	
FLE3	0.170	0.00, 0.00, 0.19, 0.45, 0.36		0.161	0.00, 0.13, 0.55, 0.29, 0.03	
FLE4	0.170	0.00, 0.00, 0.21, 0.44, 0.35		0.185	0.00, 0.03, 0.37, 0.49, 0.11	
FLE5	0.168	0.00, 0.01, 0.19, 0.57, 0.23		0.183	0.00, 0.01, 0.43, 0.47, 0.09	
FLE6	0.163	0.00, 0.01, 0.19, 0.57, 0.23		0.167	0.00, 0.05, 0.61, 0.28, 0.05	
Capacity (CAP)			0.00, 0.00, 0.17, 0.54, 0.29			0.01, 0.07, 0.45, 0.41, 0.06
CAP1	0.194	0.00, 0.00, 0.27, 0.47, 0.27		0.188	0.01, 0.15, 0.47, 0.36, 0.01	
CAP2	0.194	0.00, 0.01, 0.20, 0.56, 0.23		0.187	0.03, 0.11, 0.52, 0.33, 0.01	
CAP3	0.202	0.00, 0.00, 0.15, 0.56, 0.29		0.199	0.00, 0.08, 0.48, 0.39, 0.05	
CAP4	0.204	0.00, 0.00, 0.13, 0.55, 0.32		0.207	0.00, 0.03, 0.47, 0.44, 0.07	

CAP5	0.206	0.00, 0.00, 0.09, 0.57, 0.33		0.219	0.00, 0.01, 0.35, 0.52, 0.12	
Adaptability (ADA)			0.00, 0.00, 0.22, 0.49, 0.28			0.00, 0.04, 0.33, 0.44, 0.19
ADA1	0.200	0.00, 0.00, 0.16, 0.61, 0.23		0.213	0.00, 0.00, 0.23, 0.55, 0.23	
ADA2	0.196	0.00, 0.00, 0.29, 0.45, 0.25		0.188	0.00, 0.09, 0.41, 0.37, 0.12	
ADA3	0.200	0.00, 0.00, 0.17, 0.60, 0.23		0.206	0.00, 0.01, 0.36, 0.37, 0.25	
ADA4	0.206	0.00, 0.00, 0.24, 0.33, 0.43		0.213	0.00, 0.00, 0.25, 0.49, 0.25	
ADA5	0.198	0.00, 0.00, 0.25, 0.47, 0.28		0.179	0.01, 0.11, 0.44, 0.39, 0.05	
Efficiency (EFF)			0.00, 0.00, 0.18, 0.45, 0.37			0.00, 0.09, 0.37, 0.41, 0.12
EFF1	0.200	0.00, 0.00, 0.12, 0.57, 0.31		0.194	0.00, 0.12, 0.39, 0.43, 0.07	
EFF2	0.203	0.00, 0.00, 0.12, 0.51, 0.37		0.194	0.00, 0.05, 0.49, 0.41, 0.04	
EFF3	0.198	0.00, 0.00, 0.21, 0.43, 0.36		0.208	0.01, 0.05, 0.29, 0.52, 0.12	
EFF4	0.196	0.00, 0.01, 0.20, 0.45, 0.33		0.184	0.00, 0.16, 0.47, 0.33, 0.04	
EFF5	0.203	0.00, 0.00, 0.23, 0.31, 0.47		0.220	0.00, 0.08, 0.25, 0.36, 0.31	
Financial Strength (FIS)			0.01, 0.02, 0.17, 0.40, 0.40			0.01, 0.08, 0.34, 0.47, 0.09
FIS1	0.238	0.03, 0.01, 0.21, 0.47, 0.28		0.227	0.04, 0.16, 0.40, 0.36, 0.04	
FIS2	0.240	0.00, 0.03, 0.24, 0.44, 0.29		0.235	0.00, 0.09, 0.53, 0.33, 0.04	
FIS3	0.260	0.00, 0.01, 0.09, 0.43, 0.47		0.262	0.01, 0.04, 0.31, 0.52, 0.12	
FIS4	0.262	0.00, 0.01, 0.15, 0.29, 0.55		0.277	0.00, 0.04, 0.17, 0.63, 0.16	
Visibility (VIS)			0.00, 0.02, 0.20, 0.53, 0.25			0.00, 0.03, 0.44, 0.44, 0.09
VIS1	0.329	0.01, 0.03, 0.24, 0.52, 0.20		0.330	0.00, 0.03, 0.44, 0.51, 0.03	
VIS2	0.334	0.00, 0.01, 0.21, 0.49, 0.28		0.357	0.00, 0.01, 0.36, 0.41, 0.21	
VIS3	0.337	0.00, 0.03, 0.13, 0.57, 0.27		0.313	0.00, 0.07, 0.53, 0.39, 0.01	
Anticipation (ANT)			0.00, 0.00, 0.22, 0.47, 0.31			0.01, 0.07, 0.43, 0.40, 0.10
ANT1	0.198	0.00, 0.00, 0.24, 0.48, 0.28		0.205	0.00, 0.12, 0.32, 0.40, 0.16	
ANT2	0.198	0.00, 0.00, 0.24, 0.48, 0.28		0.190	0.00, 0.05, 0.60, 0.29, 0.05	
ANT3	0.194	0.00, 0.01, 0.24, 0.51, 0.24		0.197	0.00, 0.04, 0.53, 0.35, 0.08	
ANT4	0.216	0.00, 0.00, 0.09, 0.40, 0.51		0.216	0.00, 0.01, 0.35, 0.47, 0.17	
ANT5	0.195	0.00, 0.00, 0.28, 0.49, 0.23		0.191	0.03, 0.11, 0.37, 0.47, 0.03	
Dispersion (DIS)			0.00, 0.01, 0.17, 0.55, 0.27			0.00, 0.03, 0.29, 0.44, 0.24
DIS1	1.000	0.00, 0.01, 0.17, 0.55, 0.27		1.000	0.00, 0.03, 0.29, 0.44, 0.24	

Table 5.6: Membership functions for CSCC components

Code	CSCC Component	Level of importance		
		Weighting	MF at Level 2	MF at Level 1
RES	Resourcefulness	0.17	0.00, 0.03, 0.22, 0.41, 0.34	0.00, 0.02, 0.20, 0.47, 0.31
FLE	Flexibility	0.15	0.00, 0.00, 0.22, 0.51, 0.27	
CAP	Capacity	0.12	0.00, 0.00, 0.17, 0.54, 0.29	
ADA	Adaptability	0.12	0.00, 0.00, 0.22, 0.49, 0.28	
EFF	Efficiency	0.12	0.00, 0.00, 0.18, 0.45, 0.37	
FIS	Financial Strength	0.10	0.01, 0.02, 0.17, 0.40, 0.40	
VIS	Visibility	0.07	0.00, 0.02, 0.20, 0.53, 0.25	
ANT	Anticipation	0.12	0.00, 0.00, 0.22, 0.47, 0.31	
DIS	Dispersion	0.02	0.00, 0.01, 0.17, 0.55, 0.27	
Code	**CSCC Component**	**Level of current practice**		
		Weighting	**MF at Level 2**	**MF at Level 1**
RES	Resourcefulness	0.17	0.00, 0.07, 0.39, 0.45, 0.09	0.00, 0.07, 0.41, 0.42, 0.10
FLE	Flexibility	0.14	0.00, 0.10, 0.52, 0.33, 0.06	
CAP	Capacity	0.12	0.01, 0.07, 0.45, 0.41, 0.06	
ADA	Adaptability	0.13	0.00, 0.04, 0.33, 0.44, 0.19	
EFF	Efficiency	0.12	0.00, 0.09, 0.37, 0.41, 0.12	
FIS	Financial Strength	0.10	0.01, 0.08, 0.34, 0.47, 0.09	
VIS	Visibility	0.07	0.00, 0.03, 0.44, 0.44, 0.09	
ANT	Anticipation	0.12	0.01, 0.07, 0.43, 0.40, 0.10	
DIS	Dispersion	0.03	0.00, 0.03, 0.29, 0.44, 0.24	

For instance, if the component $FIS_{(im)}$ is considered, the component's importance level can be represented as follows in Equation (5.7.1).

$$R_{FIS_{(im)}} = \begin{vmatrix} MF_{FIS1} \\ MF_{FIS2} \\ MF_{FIS3} \\ MF_{FIS4} \end{vmatrix} = \begin{vmatrix} 0.03 & 0.01 & 0.21 & 0.47 & 0.28 \\ 0.00 & 0.03 & 0.24 & 0.44 & 0.29 \\ 0.00 & 0.01 & 0.09 & 0.43 & 0.47 \\ 0.00 & 0.01 & 0.15 & 0.29 & 0.55 \end{vmatrix} \tag{5.7.1}$$

The matrix D_i was then computed using the function R_i and WF set $[w_i = (w_1, w_2, w_3, \ldots, w_n)]$ of the measurement items within their respective capability components as follows.

$$D_i = R_i \bullet W_i = (d_{i1}, d_{i2}, d_{i3}, \ldots, d_{in}) \tag{5.8}$$

Hence,

$$D_i = (w_1, w_2, w_3, \dots, w_n) \bullet \begin{vmatrix} P_{1U_{i1}} & P_{2U_{i1}} & P_{3U_{i1}} & P_{4U_{i1}} & P_{5U_{i1}} \\ P_{1U_{i2}} & P_{2U_{i2}} & P_{3U_{i2}} & P_{4U_{i2}} & P_{5U_{i2}} \\ P_{1U_{i3}} & P_{2U_{i3}} & P_{3U_{i3}} & P_{4U_{i3}} & P_{5U_{i3}} \\ \dots & \dots & \dots & \dots & \dots \\ P_{1U_{in}} & P_{2U_{in}} & P_{3U_{in}} & P_{4U_{in}} & P_{5U_{in}} \end{vmatrix}$$

$$= (d_{i1}, d_{i2}, d_{i3}, \dots, d_{in}) \qquad (5.8.1)$$

In Equation (5.8.1), D_i denotes the membership degree of grading scale l_i, for a given component. Accordingly, the fuzzy evaluation matrix for the component $FIS_{(im)}$ was developed by integrating $R_{FIS_{(im)}}$ and $W_{FIS_{(im)}}$ measures as given in Equation (5.8.2). Moreover, $D_{FIS_{(im)}}$ indicates the fuzzy matrix for the importance indices of the identified financial strength capability. Similarly, D_i values for all the capability components (considering both the importance and level of current practice indices) were computed. These computed matrices are presented in Table 5.5 in the column 'MF at level 2'.

$$D_{FIS_{(im)}} = (0.238, 0.240, 0.260, 0.262) \begin{vmatrix} 0.03 & 0.01 & 0.21 & 0.47 & 0.28 \\ 0.00 & 0.03 & 0.24 & 0.44 & 0.29 \\ 0.00 & 0.01 & 0.09 & 0.43 & 0.47 \\ 0.00 & 0.01 & 0.15 & 0.29 & 0.55 \end{vmatrix} =$$

$$(0.01, 0.02, 0.17, 0.40, 0.40) \qquad (5.8.2)$$

The importance of each capability component (CI_i) can be then calculated using Equation (5.9), whereas l indicates the grading scale adopted in the questionnaire survey.

$$CI_i = \sum_{i=1}^{9} D_i \times l^t = (D_1, D_2, D_3, D_4, D_5, D_6, D_7, D_8, D_9) \times (1, 2, 3, 4, 5),$$

$$1 \leq CI_i \leq 5 \qquad (5.9)$$

For instance, the importance of FIS component ($FIS_{(im)}$) was assessed as follows.

$$CI_{FIS_{(im)}} = [(0.01 \times 1) + (0.02 \times 2) + (0.17 \times 3) + (0.40 \times 4) + (0.40 \times 5)]$$
$$= 4.18 \qquad (5.9.1)$$

Analogous to the calculation above, $FIS_{(cp)}$ which is the level of current practise of FIS component was calculated as in Equation (5.9.2).

$$CI_{FIS_{(cp)}} = [(0.01 \times 1) + (0.08 \times 2) + (0.34 \times 3) + (0.47 \times 4) + (0.09 \times 5)]$$
$$= 3.55 \qquad (5.9.2)$$

After calculating indices for both the importance and level of current practice, of the components, the FSE models for both the indices were computed separately.

5.4.5. Evaluating the Overall Capability Indices

During step 5, a fuzzy matrix $\bar{R}$ was developed to assess the overall level of importance of the CSCC towards achieving resilient supply chains in IC in HK and the level of current practice of the CSCC in the industry.

$$\bar{R} = \begin{vmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \\ D_6 \\ D_7 \\ D_8 \\ D_9 \end{vmatrix} = \begin{vmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} \\ d_{41} & d_{42} & d_{43} & d_{44} & d_{45} \\ d_{51} & d_{52} & d_{53} & d_{54} & d_{55} \\ d_{61} & d_{62} & d_{63} & d_{64} & d_{65} \\ d_{71} & d_{72} & d_{73} & d_{74} & d_{75} \\ d_{81} & d_{82} & d_{83} & d_{84} & d_{85} \\ d_{91} & d_{92} & d_{93} & d_{94} & d_{95} \end{vmatrix} \qquad (5.10)$$

In Equation (5.10), D_1- D_9 represent the nine components initiated after the factor analysis, namely, RES, FLE, CAP, ADA, EFF, FIS, VIS, ANT and DIS. Analogous to Equation (5.10), the overall importance level and level of current practice functions of SCC evaluation can be formulated as in Equation (5.10.1).

$$\overline{R_{(\iota m)}} = \begin{vmatrix} 0.00 & 0.03 & 0.22 & 0.41 & 0.34 \\ 0.00 & 0.00 & 0.22 & 0.51 & 0.27 \\ 0.00 & 0.00 & 0.17 & 0.54 & 0.29 \\ 0.00 & 0.00 & 0.22 & 0.49 & 0.28 \\ 0.00 & 0.00 & 0.18 & 0.45 & 0.37 \\ 0.01 & 0.02 & 0.17 & 0.40 & 0.40 \\ 0.00 & 0.02 & 0.20 & 0.53 & 0.25 \\ 0.00 & 0.00 & 0.22 & 0.47 & 0.31 \\ 0.00 & 0.01 & 0.17 & 0.55 & 0.27 \end{vmatrix} and$$

$$\overline{R_{(cp)}} = \begin{vmatrix} 0.00 & 0.07 & 0.39 & 0.45 & 0.09 \\ 0.00 & 0.10 & 0.52 & 0.33 & 0.06 \\ 0.01 & 0.07 & 0.45 & 0.41 & 0.06 \\ 0.00 & 0.04 & 0.33 & 0.44 & 0.19 \\ 0.00 & 0.09 & 0.37 & 0.41 & 0.12 \\ 0.01 & 0.08 & 0.34 & 0.47 & 0.09 \\ 0.00 & 0.03 & 0.44 & 0.44 & 0.09 \\ 0.01 & 0.07 & 0.43 & 0.40 & 0.10 \\ 0.00 & 0.03 & 0.29 & 0.44 & 0.24 \end{vmatrix} \tag{5.10.1}$$

Thereby, the matrix $\bar{R}$ was normalized using the appropriate WF set to arrive at $\bar{D}$.

$$\overline{D_\iota} = \overline{R_\iota} \bullet \overline{W_\iota} = (\acute{w}_1, \acute{w}_2, \acute{w}_3, \acute{w}_4, \acute{w}_5) \times \begin{vmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} \\ d_{41} & d_{42} & d_{43} & d_{44} & d_{45} \\ d_{51} & d_{52} & d_{53} & d_{54} & d_{55} \\ d_{61} & d_{62} & d_{63} & d_{64} & d_{65} \\ d_{71} & d_{72} & d_{73} & d_{74} & d_{75} \\ d_{81} & d_{82} & d_{83} & d_{84} & d_{85} \\ d_{91} & d_{92} & d_{93} & d_{94} & d_{95} \end{vmatrix}$$

$$= \left(\acute{D}_1, \acute{D}_2, \acute{D}_3, \acute{D}_4, \acute{D}_5\right) \tag{5.11}$$

It should be noted that $\overline{D_\iota}$ represents the fuzzy matrix for either 'importance' or 'current practice' indices of the SCC components. This fuzzy matrix can be formulated, as shown in Equation (5.12) using the grading scale (l=1,2,3,4,5) established in this study. C_i implies SCC evaluation index *i* (*i = importance or current practice indices*). This 'defuzzification approach' transforms fuzzy members into a 'crisp' output using a predefined grading scale which is vital in decision making (Osei-Kyei et al. 2019; Owusu et al. 2020).

$$C_i = \sum_{i=1}^{9} \overline{D}_i \times l^t = \left(\acute{D}_1, \acute{D}_2, \acute{D}_3, \acute{D}_4, \acute{D}_5\right) \times (1,2,3,4,5), 1 \leq C_i \leq 5 \tag{5.12}$$

Accordingly, the final fuzzy evaluation matrix was derived by normalizing the fuzzy matrix obtained for overall SCC indicators as follows.

$$\overline{D}_{(im)} = (0.169,0.146,0.122,0.121,0.125,0.099,0.072, 0.122,0.024)$$

$$\times \begin{vmatrix} 0.00 & 0.03 & 0.22 & 0.41 & 0.34 \\ 0.00 & 0.00 & 0.22 & 0.51 & 0.27 \\ 0.00 & 0.00 & 0.17 & 0.54 & 0.29 \\ 0.00 & 0.00 & 0.22 & 0.49 & 0.28 \\ 0.00 & 0.00 & 0.18 & 0.45 & 0.37 \\ 0.01 & 0.02 & 0.17 & 0.40 & 0.40 \\ 0.00 & 0.02 & 0.20 & 0.53 & 0.25 \\ 0.00 & 0.00 & 0.22 & 0.47 & 0.31 \\ 0.00 & 0.01 & 0.17 & 0.55 & 0.27 \end{vmatrix}$$

$$= (0.00, 0.02, 0.20, 0.47, 0.31) \tag{5.12.1}$$

$$\overline{D}_{(cp)} = (0.171,0.138,0.118,0.130,0.123, 0.098,0.074,0.122,0.027)$$

$$\times \begin{vmatrix} 0.00 & 0.07 & 0.39 & 0.45 & 0.09 \\ 0.00 & 0.10 & 0.52 & 0.33 & 0.06 \\ 0.01 & 0.07 & 0.45 & 0.41 & 0.06 \\ 0.00 & 0.04 & 0.33 & 0.44 & 0.19 \\ 0.00 & 0.09 & 0.37 & 0.41 & 0.12 \\ 0.01 & 0.08 & 0.34 & 0.47 & 0.09 \\ 0.00 & 0.03 & 0.44 & 0.44 & 0.09 \\ 0.01 & 0.07 & 0.43 & 0.40 & 0.10 \\ 0.00 & 0.03 & 0.29 & 0.44 & 0.24 \end{vmatrix}$$

$$= (0.00, 0.07, 0.41, 0.42, 0.10) \tag{5.12.2}$$

5.5 Discussion

Figure 5.2 presents an overall summary of CSCC with the level of criticality to IC in HK derived from relevant significance analysis. The first ranking measurement item is 'quality control' (C35) with an M value of 4.413. IC supply chains in HK are significantly susceptible to the tolerance issues allied with quality control. Hence, monitoring quality is essential to improve SCR. This could be why the respondents have ranked this SCC as the most critical measurement item. Alternative innovative technology development (C25) received the least score since the HK construction industry may be considered more innovative and thereby already injecting new technological advances into construction processes.

Being specific to the fuzzy synthetic evaluation of CSCV, the 'importance' index is 4.11 (high), reflecting the dire need for boosting SCC in achieving resilient supply chains in IC in HK. Comparatively, 3.54 is the 'current practice' index, spotlighting a long way to go before attaining resilient supply chains in IC in HK. According to the experts, all the CSCC components are highly important in achieving SCR. Although efficiency (index-4.19) may at the outset be arguably the most significant supply chain capability that the industry should pursue, dispersion (index-3.89) is one of the most implemented CSCC in 'practice'.

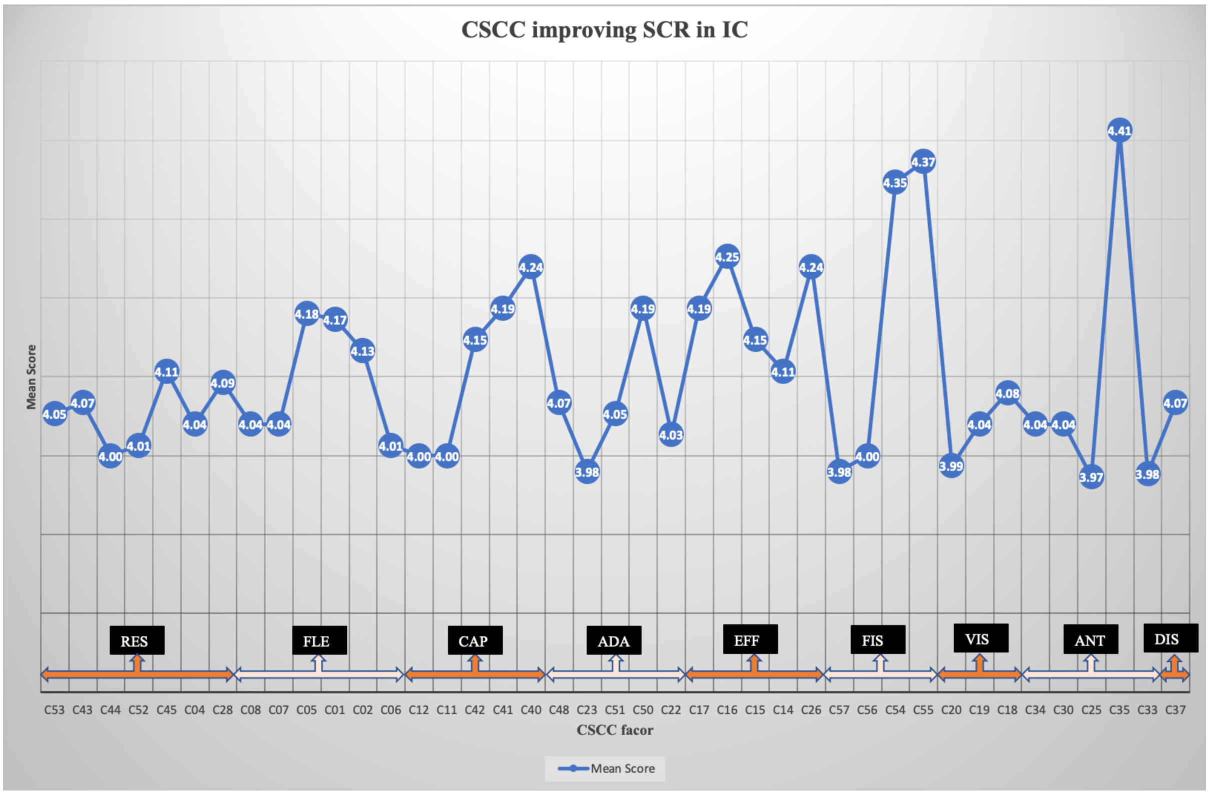


Figure 5.2: Critical Supply Chain Capabilities (CSCC) improving Supply Chain Resilience (SCR) in IC in HK

Efficiency (EFF)

Efficiency is the CSCC component with the highest mean score value; 4.187, highlighting its component significance. This component reflects the ability to produce construction outputs with minimum resources and without contributing to wasteful practices. In relation to IC, efficiency contributions are mainly from failure prevention, higher labor productivity, avoiding variations/rework, and waste elimination while productivity increases after moving up the 'learning curve' on tasks and more experience in general. Mean scores of all the measurement items of EFF are higher than 4.000, hence, vital for improved SCR in IC in HK. Failure prevention needs industry attention, since failures are possible at any node of IC supply chain operations beginning from manufacture to on-site assembly (Li et al., 2018a). Together with inadequate information sharing and technological breakdowns, these failures result in variations in IC in HK and, hence, call for resilient supply chains. This is clearly shown by receiving 4.25 mean score for the importance of 'avoid variations', and the current practice level of 3.44. Tolerance, assembly, logistics and manufacturing failures incur additional cost and time, contributing to non-value-added activities, i.e., so-called wastes (Ekanayake et al., 2019).

Although IC targets waste elimination (Jaillon et al., 2009), the focused application in current practice is considerably low (3.25). Also, non-value-added activities (waste) are still possible with the inadequate tolerance and assembly issues, logistics failures and manufacture failures (Ekanayake et al., 2019), hence, highlighting the need for SCR through waste elimination and lean supply chains (Yu et al., 2013). Therefore, it is encouraged to deploy the lessons learnt from previous projects to practice (Peck, 2005), though this is not easy due to the industry's fragmented nature and the temporary multi-organizational structure of the construction projects. According to the current practice, although the project appraisal or analysis reports were hard to observe, the experts suggested the importance of having records of the lessons learnt for future potentials.

On the other hand, Birkinshaw (2020) argues that there should be a shift from efficiency to reliability to improve resilience in the current global supply chains. Use of multiple suppliers and matching local demand on a local supply is further suggested to enhance reliability. Reeves and Varadarajan (2020) also argue that although having extra resources and buffers increase efficiency, it will amplify the interdependence and fragility of supply chains. Mobilizing and retaining multiple supply sources are not easy within one construction contract and could be costlier. For instance, maintaining equipment buffers such as with tower cranes may add significant wastes, and that is why back-up maintenance agreements are necessitated in IC in HK (Ekanayake, Shen, & Kumaraswamy, 2020). Although the above measures may incur extra costs, hence reduce 'efficiencies' on paper, this may be a useful price to pay for useful redundancies that increase resilience, which is also seen as more important after COVID-19.

Furthermore, setting up manufacturing factories in HK is inefficient compared to procuring prefabricated components or setting up or hiring plants in China due to labor and space constraints (Ekanayake et al., 2019). Therefore, matching supply to demand on a local basis is still difficult in IC in HK. In this regard, maintaining adequate buffer time is essential to absorb disruptions with the least impact. Even in IC, the experts neither expect nor recommend realizing 100% efficiencies since the importance level of this component is 4.19.

Financial Strength (FIS)

FIS was ranked with the second highest mean score; 4.18 by necessitating a good financial capacity in a competitive industry, specifically in the construction sector (Ekanayake et al., 2019). However, the current financial capacity (3.55) is lower, hence compelling portfolio diversification including self-manufacturing decisions (Han et al., 2017), having a good price margin, financial reserves and funds (Kadir et al., 2006) and good insurance coverage (Fateh & Mohammad, 2017). According to the findings of Han et al. (2017), higher profit levels of all IC supply chains are feasible with increased market size and any self-manufacturing decisions (portfolio diversification and vertical integration). Besides, it is mandatory to maintain healthy cash flows, including financial reserves, to pay prefabricated components manufacturers on time (Kadir et al., 2005) and to withstand all the financial vulnerabilities associated with supply chains (Ekanayake et al., 2019).

Given that the importance of having substantial financial reserves/funds, the measurement item was ranked as the third critical capability measure with 4.35 mean score. Indeed, IC supply chains need insurance coverage for the items in stores, and offsite during the logistics as a mechanism for timely and assured delivery of IC outputs while resisting disturbances (Fateh & Mohammad, 2017). Also, having insurance and contingency allocations is essential in IC as a safeguard to bear the uncertainties and losses since the construction sequence is standardized and fixed (Ekanayake et al., 2019). That is why the experts ranked having adequate insurance coverage as the second critical SCC with the mean value of 4.37. Although IC projects in HK are usually financially feasible, the respondents highlighted the importance of these FIS related CSCC measurement items for resilient supply chains.

Capacity (CAP)

As the third-highest ranked supply chain capability component, Capacity received an importance index of 4.12 with a current practice index of 3.44. Capacity implies the availability of adequate resources in the supply chain to enable continuous operation in IC (Ekanayake et al., 2019). This capability was highly researched within the SCR domain, as found, with justifications, in the related literature (Ekanayake et al., 2021). Although having backup equipment is beneficial in other supply chains, in IC, the primary equipment used are cranes. Hence, it is vital to have reliable backup maintenance agreements with the equipment suppliers or the maintenance companies as practiced in HK IC projects.

Since tower crane and material hoists breakdowns are common in IC in HK, 'redundancy' of the supply chain to bypass any such disruptions is required (Ekanayake et al., 2019). Redundancy increases SCR by facilitating quick recovery without leading to system failure (Sheffi & Rice, 2005). Redundancy depends upon the organizational capacities to manage uninterrupted workflow during disruption, and it should stop aggregating and aggravating the damages and losses. According to the experts, it is still questionable that the existing capacity of many firms can provide redundancies to overcome disruption and maintain continuity in IC supply chains in HK. This alerts practitioners to the need for capacity improvements.

Although traditional risk management is adopted as a crisis mitigation technique, it does not enable adequate protection over all possible threats (Van Der Vegt et al., 2015), positioning SCR as improved crisis management technique (Zavala et al., 2019). Irizarry et al. (2013) also proposed to deploy GIS and digital building information technologies in IC supply chains to enhance emergency response management, which can be considered as another initiative. Having a capable professional team to handle disruptions and effective communication strategy during a disruption is also very important for a speedy recovery (Zainal & Ingirige, 2018a). This should explain why the measurement item of ‘having a capable professional team to handle disruptions’ scored the fifth-highest mean value of 4.24. Also, having an effective communication strategy was ranked as the eighth critical of the measurement items of SCC. A few reputed construction companies have integrated the entire production system with BIM models by improving communication between the project professionals and enhancing their accountability in case of IC failures in HK. Moreover, the measurement items within this SCC component highlight the need for having reliable back-up maintenance agreements with the equipment suppliers or the maintenance companies (Ekanayake, Shen, & Kumaraswamy, 2020), redundancy of supply chains to bypass disruptions (Ekanayake et al., 2019), practicing an effective communication strategy during disruptive situations, having a professional response team to deal with disruptions (Zainal & Ingirige, 2018a), the development of effective crisis mitigation techniques instead of the traditional risk management practices (Zavala et al., 2019) with the use of BIM and GIS tools (Irizarry et al., 2013) by relating specifically to the IC practices in HK.

Dispersion (DIS)

DIS, includes just one measurement item, albeit with a significant (mean score=4.067) of the CSCC, namely, distributed decision making. This resembles the decentralization of decision-making power, which is substantial during onsite problem-solving. Besides, robust decision making is asserted as essential even in the advanced manufacturing of prefab components (Arashpour et al., 2017). Also, quick but sound decision-making is required in the materials flow control process to reach a balance between onsite buffers of components and just-in-time deliveries (Bataglin et al., 2017). Determining transportation batch sizes is another critical decision that should be taken for controlling the flow of prefabricated components and synchronizing these timings in both the prefabrication plant and assembly site (Bataglin et al., 2017). Therefore, these key decisions should be collaboratively taken by the relevant supply chain stakeholders involved in the flow of the prefabricated components (Zhang & Yu, 2020). Under these circumstances, distributed decision making is identified as a CSCC measurement item to enhance the ability to withstand SCV successfully. BIM is, therefore, introduced as a supplement to the SCR through decentralized decision-making (Bataglin et al., 2017).

Besides, 'distributed decision making' under the SCC component of 'dispersion' is one of the most widely practiced in the industry. However, the practice level of this measurement item (3.89) is still slightly less than the required level (4.07), highlighting the resilience gap of supply chains, even in a popularly pursued area/component. According to Ekanayake, Shen, & Kumaraswamy (2020), dispersion has received the least research interest over the years, whereas dispersion is essential in robust decision making. Since IC supply chains are highly fragmented, quick but sound decision making is only attainable through decentralized decision making. Recent relevant developments such as in RFID (Chen et al., 2020) and blockchain (Wang et al., 2020) integrated platforms will facilitate promising opportunities in such decision making.

Anticipation (ANT)

Anticipation includes five CSCC measurement items which provide the ability to detect potential future SCV. Considering the anticipation component, more importantly, quality control (with the highest mean score of 4.41) is essential for the IC to avoid tolerance issues in assembly (Ekanayake et al., 2019). This is why contractors pay for additional quality checkers assigned to oversee component manufacturing factories. However, the contractors who use their own manufacturing plants can control their quality better through BIM-enabled systems (Ekanayake, Shen, & Kumaraswamy, 2020) whereas IoT, BIM, and RFID enabled tools are proposed to enhance the real-time visibility together with promising traceability in the supply chain process (Li et al. 2018b). Further, blockchain encrypted software packages may add the expected traceability and accountability to the supply chain information sharing process (Wang et al., 2020). These developments are vital in avoiding transport disruptions, excess storage demands, and prefabricated component queues in HK.

BIM integrated project management tools can help to trigger early warning signals before any disruptions, as model simulations are possible with the techniques. Also, intensive training is very important during the onsite assembly process as the assembly of prefabricated components require skilled labor (Ekanayake et al., 2019), especially since they are related to risky operations (Fard et al., 2017) and hence, to avoid safety disruptions, tolerance issues and delays (Ekanayake et al., 2019). Conducting simulations and mock-ups before the assembly process would be beneficial in this regard. Moreover, developing and employing innovative technologies improve the anticipation and also eases adaptation during a disruption. Innovative tools such as BIM and other IoT based techniques and tools have already been adopted in IC in HK, thereby reaping associated benefits and calling for new initiatives to enhance supply chain performance.

Resourcefulness (RES)

RES consists of seven underlying SCC measurement items and, all these measurement items facilitate a collaborative, secure and resourceful approach to enhance SCR, hence named as 'resourcefulness'. This component manifests the highest percentage of variance, which is 44% with the highest content. Personal security is the highest loaded measurement item within the SCC component-(0.768), highlighting the dire need for improved safety at site. Although IC facilitates improved safety (Wong et al., 2003), personal security is essential during the installation of prefabricated components as there are fracture and fall-related hazards (Li et al., 2011). The experts highlighted that, if there is a severe safety disruption, the sites are closed until all the safety inquiries are completed, posing other problems from disruptions. All projects which are under the public housing authority need to undergo quarterly safety audits, where any failures may trigger blacklisting of the contractors from future projects, thereby safeguarding safety at IC sites.

Collaborative forecasting, decision making, and information exchange are vital (Ekanayake et al., 2019) since these facilitate effective and successful decision making. That is why these two measurement items received relatively high factor loadings of 0.702 and 0.656. To address existing shortfalls in these areas, Li et al. (2011) proposed virtual prototyping and Zhong et al. (2017) introduced an Internet of Things (IoT) enabled BIM platform in their studies to improve the collaborative data interoperability in the IC supply chains. Cybersecurity is another main challenge faced (Ghaffarianhoseini et al., 2017) and it is imperative to provide appropriate cybersecurity to the supply chain information, data sharing and use to avoid unauthorized data access and copyright infringement even in IC supply chains. Obtaining more competitive price from suppliers reduces the price risks associated with supply chains (Lim et al., 2011). Having multiple-supplier sources enable consistent production of IC since most of the prefabricated units are outsourced or imported from Mainland China to HK. This outsourcing can lead to acute logistics disruptions and cause onsite assembly delays as experienced already. Hence, having supplier backups, including transportation supplier backups, are very important. Maintaining adequate buffer time between supply chain operations reduces the vulnerabilities due to tardiness in site deliveries (Zhai et al., 2018). Even in HK, the IC supply chains have faced delays due to tardy delivery of prefabricated components, so maintaining an adequate buffer time was helpful (Ekanayake et al., 2019).

Flexibility (FLE)

FLE component exhibit 7.4% of the variance, including six measurement items. These FLE measurement items reflect the ability of quicker resource mobilization in response to a disruption. As the highest loaded measurement item, vertical integration is beneficial since there are vulnerabilities due to outsourcing. However, outsourcing facilitates increased sustainability in the supply chains because the third-party logistics providers practice improved resource utilization and efficient processes. As most of the contractors do not have their in-house prefabrication plants, they are denied higher profit level under the decision of self-manufacturing (Han et al., 2017), necessitating vertical integration of the supply chain manufacture and assembly. For example, postponement of the production of prefabricated units could be required if there are onsite disruptions such as tower crane breakdowns and safety hazards (Ekanayake et al., 2019).

Besides, most of the construction sites in HK are very congested and early, or excess delivery of materials can cause intolerable queuing problems. These demand flexible production of prefabricated components where the production postponement is required. Since IC supply chains are highly susceptible to logistics disruptions (Z. Wang et al., 2018) due to the transportation of imported oversized/overweight prefabricated units, the availability of alternative transportation channels is encouraged to avoid delays in IC in HK (Ekanayake et al., 2019) [with this ranking as the tenth critical of the SCC measurement items with the mean value of 4.18]. In this circumstance, having flexible agreements with transportation suppliers is practiced by HK companies.

As the latest initiative, MiC is introduced as it offers more opportunities to improve project performance, and the industry is appreciating the associated benefits (Choi et al., 2017). Also, modular designs enable multiple/repeat uses of the materials and equipment, including metal formwork systems. Besides, appropriate production planning by utilizing optimum outsourcing quantities add more value to modular product design (Hsu et al., 2017). By identifying the need for risk-sharing/pooling, even IC utilizes risk-sharing techniques to help withstand SCV. For instance, sharing inventory holding costs (Zhai et al., 2018) can help in this respect. Also, the experts identified the necessity of private-public collaboration as a proper risk-sharing mechanism in IC supply chains, where joint ventures or partnerships are not too familiar.

Adaptability (ADA)

ADA includes five measurement items, providing supply chains with an ability to adapt in response to SCV with a variance percentage of 5.28. Having a strong reputation for the quality of the construction output and maintaining close and healthy relationships with clients is highly beneficial to recover from a dip in the market position of an organization. Hong Kong public clients conduct quality audits quarterly on IC contractors, and their future work eligibility is decided based on their past performance. With the increase of market size, even the profit levels may increase (Han et al., 2017) and improve the resilience capabilities in IC.

Further, lead time reduction including production lead time hedging, operational lead time hedging, and transportation lead-time hedging are also suggested as effective ways to raise adaptability in IC (Zhai et al., 2017, 2018; Zhai & Huang, 2017). This avoids unnecessary storage throughout the entire supply chain process. Faster delivery of construction output also improves the resilience capacity, which is manifested in MiC methods. Therefore, IC supply chains should encourage adopting MiC for improved adaptability of supply chains in the context of the HK construction industry. Fast re-routing of requirements is another of the CSCC measurement items (Peck, 2005) which enhances the adaptability of supply chains by provoking steady and immediate reinstatement of the processes after a disruption. Therefore, capable, resourceful and flexible supply chains are necessitated in this context, highlighting the useful integration of SCC categories.

Visibility (VIS)

VIS refers to having sound knowledge of ongoing supply chain operations and the environment. This component includes three measurement items, accounting for 4.036 mean score and 1.297 variance percentage of importance. According to the findings of Li et al. (2019), there is a gap of efficiency and collaboration in decision-making systems in IC since the relevant information is stored and handled in diverse systems of various stakeholders, who are geographically isolated. Collaboration is identified as the soft aspect of supply chain management, which enhances team learning and team performance in construction supply chains (Koolwijk et al., 2018). A Building Information Modeling (BIM) integrated IC was proposed by the above-cited authors to improve the supply chain visibility. An Internet of Things (IoT) enabled BIM platform is another initiative to enhance real-time data visibility and traceability of IC supply chains in HK (Li et al., 2018a). BIM and virtual prototyping technologies provide robust avenues for different supply chain stakeholders to improve their daily operations, collaboration, decision making, and supervision throughout the construction. Also, RFID and barcode detecting methods add to supply chain visibility through real-time data capture, enhanced speed and accuracy of data entry (Li et al., 2011). Also, BIM and Geo-Information Systems integrated methods improve logistical visibility of IC supply chains (Irizarry et al., 2013).

All of these five SCC components, namely, resourcefulness (collaborative, secure and resourceful approaches to enhance SCR), flexibility (the ability of quicker resource mobilization following a disruption), adaptability (ability to adapt in response to supply chain vulnerabilities), visibility (having sound knowledge of ongoing supply chain operations and the environment) and anticipation (ability to detect potential future supply chain disruptions) also received lower values for the level of current practice indices compared to their levels of importance. Therefore, it is essential to move a step further in mobilizing SCC to avoid turbulence over the supply chain vulnerabilities in IC in HK.

Table 5.7: Overall impact calculations of SCC improving SCR in IC in HK

Capability	Level of importance			Level of current practice			
	Index	Coefficient	Ranking	Index	Coefficient	Ranking	Coefficient Symbols
RES	4.05	0.17	7	3.54	0.17	6	C_{RES}
FLE	4.05	0.15	8	3.34	0.14	9	C_{FLE}

CAP	4.12	0.12	3	3.44	0.12	8	C_{CAP}
ADA	4.06	0.12	6	3.77	0.13	2	C_{ADA}
EFF	4.19	0.12	1	3.56	0.12	4	C_{EFF}
FIS	4.18	0.10	2	3.55	0.10	5	C_{FIS}
VIS	4.00	0.07	9	3.58	0.07	3	C_{VIS}
ANT	4.09	0.12	4	3.52	0.12	7	C_{ANT}
DIS	4.07	0.02	5	3.89	0.03	1	C_{DIS}
Total		1.00			1.00		
OI	**4.11**			**3.14**			

Finally, analogous to the FSE analysis results, mathematical models for evaluating the importance levels and current practices in SCC improving SCR in IC in HK were developed as presented in Equation 5.13. The coefficients assigned to CSCC components correspond with the respective normalized values are shown in Table 5.7.

$$
\begin{aligned}
&Overall\ Capability\ Evaluation\ Index \\
&\quad = [C_{RES}|CV_{RES}|] + [C_{FLE}|CV_{FLE}|] + [C_{CAP}|CV_{CAP}|] + [C_{ADA}|CV_{ADA}|] \\
&\quad + [C_{EFF}|CV_{EFF}|] + [C_{FIS}|CV_{FIS}|] + [C_{VIS}|CV_{VIS}|] + [C_{ANT}|CV_{ANT}|] \\
&\quad + [C_{DIS}|CV_{DIS}|] \qquad (5.13)
\end{aligned}
$$

5.6 Chapter Summary

To promote SCR practice in IC, this chapter enabled the useful mathematical modeling of SCC improving SCR in IC in HK by applying statistical analysis and fuzzy set theory to the data that was collected for this purpose. Further, this chapter presented the importance and the current practice levels of each of the SCC and the overall impact of each on IC. Forty-one SCC measurement items were identified as the critical measures associated with IC in HK through the factor analysis of collected data. Factor analysis also enabled a well-justified grouping of these measurement items into five underlying CSCC components, namely, resourcefulness, flexibility, capacity, adaptability, efficiency, financial strength, visibility, anticipation and dispersion as explicated clearly in this chapter.

Then, the soft computing approach-FSE was facilitated in developing the multi-level-multi-criteria fuzzy mathematical model to assess the criticality and the current practice of SCC in IC in HK. An importance index of 4.11 showed that the identified capabilities are critical in achieving resilient supply chains. In contrast, a current practice index of 3.54 indicated that there is a wide gap to be bridged in realizing the benefits associated with SCR in IC in HK. Efficiency component (importance index: 4.19) has the highest impact among all the SCC, while dispersion is the highest in practice (3.89). However, there was a gap between the current practice and importance levels in each of the supply chain capability components.

Findings presented in this chapter contribute to this important body of knowledge by evaluating the perceived importance *vs* current practice levels of SCC in IC projects in HK, thereby empowering practitioners to plan and utilize suitable strategies at appropriate levels to boost SCR in IC in HK. These evaluation models are, to the knowledge of the researcher, the first set of structured models designed to assess SCC of IC, also providing useful insights to practitioners for well-informed decision making in formulating strategies to initiate and nurture resilient supply chains in IC in HK. Indeed, findings of Chapter 5 partially fulfil the further related research requirements proposed in Chapter 4 by identifying and assessing critical supply chain capabilities.

Chapter 6 Capabilities to Withstand Vulnerabilities and Boost Resilience in Industrialized Construction Supply Chains [4]

6.1 Introduction

Given the significance of injecting SCR into IC practices highlighted in the previous chapters and by fully satisfying the research Objective 2, Chapter 6 examines and models the impact of SCC on withstanding SCV using Partial Least Squares Structural Equation Modeling (PLS-SEM) approach. Building on the previous chapters along with precursor findings, this chapter documents the detailed investigation of the causal relationships between SCC and SCV and the effectiveness of the capability measurement items. This dimension added considerable value to this research work and optimized the significance of the outputs since the study transcends the analysis of the criticality of the SCC and SCV by themselves and identifies the relative impacts of one on the other. To move forward from previous work done, it was based on a perceived need for empirical and quantitative assessment of the already developed SCC and SCV constructs; and also after providing clear elucidations and justifications of these constructs. On the other hand, to this researcher's knowledge, no known research has yet identified the significant correlational impacts of SCC and SCV, even for conventional (non-IC) construction supply chains.

However, the findings are in this case, skewed towards IC in HK since the constructs were assessed, hypotheses were tested, and the model was developed in the specific context of HK. Finally, the findings of this chapter contribute to the deepened understanding of the impact of

[4] The core research and findings in this chapter have been peer-reviewed before publication in:

Ekanayake, E.M.A.C., Shen, G.Q., Kumaraswamy, M.M., Owusu, E.K. and Xue, J., 2021. Capabilities to Withstand Vulnerabilities and Boost Resilience in Industrialized Construction Supply Chains: A Hong Kong Study. *Engineering, Construction and Architectural Management*. DOI: 10.1108/ECAM-05-2021-0399.

SCC on SCR and assist professional practitioners in making better decisions by selecting appropriate capabilities to counteract specific vulnerabilities in a given scenario, hence enabling more resilient and sustainable IC practices in HK. Further, the developed research framework and methodology described in this chapter lay a foundation for extensive worldwide studies in this research domain. Although the data collection and analysis for this study were just before the COVID 19 outbreak, the recent worldwide upheavals in general, including supply chain disruptions from the pandemic, will surely increase the relevance and significance of the methodology and findings illustrated in this chapter. Moreover, the forthcoming sections of this chapter describe the steps in developing the research framework, the study hypotheses, and research design in brief. The discussion of the developed models is then followed by chapter summary.

6.2 Research Framework and Hypotheses

6.2.1. Research Framework

A research framework can be either established based on theory or logic, or both, and it is beneficial in creating new knowledge of a specific research domain (Darko et al., 2018). The research framework developed in this chapter has both theoretical and logical underpinnings. According to Pettit et al. (2010), SCR entails two constructs: (i) vulnerabilities – the key factors which make supply chains susceptible to disruptions and (ii) capabilities – the attributes, which enable supply chains to perform better, anticipate and withstand disruptions. Expanding on these, Pettit et al. (2013) showed how creating a capability portfolio can counteract the inherent SCV, which could lead to a balanced resilience as hypothesized to improved supply chain performance. The 'Contingency Theory' is considered to be an appropriate framework for discussing proactive management strategies of supply chains, mitigating uncertain disruptions (Birkie et al., 2017; Grötsch et al., 2013).

Further, a contingent resource-based view posits that sustained competitive advantage can be gained through resource generation and regeneration of existing capabilities (Brandon-Jones et al., 2014). Besides, a 'Dynamic Capability View' provides deep insights into the delineation of capabilities during dynamic and uncertain environments and enables the determination of appropriate resources and capabilities to respond to dynamic changes by focusing on the idiosyncrasies of contingencies (Chowdhury & Quaddus, 2017; Teece et al., 1997). In line with the principles and propositions of 'dynamic capability', this study postulates that organizational supply chains need to create dynamic capabilities to withstand vulnerabilities under a tumultuous supply chain environment, necessitating SCR capabilities as value-creating strategies in the long run.

Therefore, dynamic capabilities can be considered as the sources of SCR (Ambulkar et al., 2015), which empower organizations with adaptive capacities. These resilience capacities are two-fold: (a) proactive capabilities [provide withstanding abilities to the supply chains (Wieland & Wallenburg, 2013)] and (b) reactive capabilities [provide abilities of supply chains to respond to change by adapting their initial stable configurations (Wieland & Wallenburg, 2012). In this regard, agility and robustness enhance resilience capability (Wieland & Wallenburg, 2013). Visibility, dual-sourcing, transshipping (Christopher & Peck, 2004), flexibility (Tomlin, 2006), and leanness (Purvis et al., 2016) also protect against supply chain threats. Pettit et al. (2013) established a 13-factor capability assessment tool for manufacturing and service firms by advancing the SCR theory. In an example from practice, the findings on SCC by Chowdhury and Quaddus (2015) were significant for the Bangladesh garment industry. Based on these developments and probing specific supply chain dynamics in another scenario, Zainal and Ingirige (2018a) identified and suggested 12 capabilities for improving Malaysian public construction projects. Inspired by these useful contributions to SCR theory, this researcher established a nine CSCC constructs model with forty-one capability measurement items concerning IC in HK as described in Chapter 5. Figure 6.1 presents all these identified supply chain capability measurement items with their codes. It was postulated that the IC firms should reconfigure resources and processes by building strengths aligning with these capabilities to weather, withstand and mitigate supply chain dynamics and turbulences.

Supply chain dynamics and turbulences are triggered by SCV, leading to supply chain deficiencies. Since industrialized construction supply chains are relatively unchangeable and fixed once established, disruptions affecting or triggered by one SC member may exacerbate its impact on the whole network (Zhai et al., 2017). These vulnerabilities can be the outcomes of a chain of events generating cascading effects contributing to each vulnerability (Zainal & Ingirige, 2018b), requiring careful assessment and proactive remedies as explained in Chapter 4. Natural disasters, labor shortages and disputes, supply shortages, and quality problems (Chopra & Sodhi, 2004) are common attributes shared in the cluster of SCV. Besides, the Japanese triple disaster in 2011 triggered by a tsunami, leading to floods and a nuclear disaster too, the European migration crisis in 2015, SARS in 2003, and most recently, the Covid19 type of global disruptions have adversely affected global supply chains to significant extents.

After identifying the research lacuna in IC given its special conditions, constraints and context, that militate against applying such a general classification based on manufacturing practices, to IC, the researcher grouped twenty-four CSCV into five underlying constructs through results generated from an empirical study focused on IC practices in HK as described in Chapter 4. Figure 6.1 further explicates the constructs and the vulnerability measurement items created. Based on these theoretical underpinnings, the rationale is based on the premise that SCC act as counter-balancers of SCV in achieving resilient supply chains in IC in HK, as shown in Figure 6.1, the research framework proposed for PLS-SEM analysis. This proposed framework is quite beneficial in developing a better understanding of the dynamic supply chain culture underlying IC processes, myriad disruptions, their consequential impacts, and the related capabilities that could effectively withstand these impacts. Further, this research framework is useful in analyzing the impact of capabilities on confronting vulnerabilities in the pursuit of SCR of IC in HK, as hypothesized and illustrated in the next section.

Supply Chain Capabilities (SCC)

SCC Construct	Code	Measurement Items
Resourcefulness	RES1	Personnel security
	RES2	Collaborative information exchange & decision making
	RES3	Collaborative forecasting
	RES4	Cyber-security
	RES5	Obtain more competitive price from suppliers and subcontractors
	RES6	Multiple sources/suppliers
	RES7	Maintaining buffer time
Flexibility	FLE1	Vertical integration
	FLE2	Production postponement
	FLE3	Alternate distribution channels/multimodal transportation
	FLE4	Modular product design
	FLE5	Multiple uses
	FLE6	Risk pooling/sharing
Capacity	CAP1	Backup equipment facilities
	CAP2	Redundancy
	CAP3	Consequence mitigation
	CAP4	Effective communications strategy
	CAP5	Professional response team
Adaptability	ADA1	Strong reputation for quality
	ADA2	Lead time reduction
	ADA3	Faster delivery
	ADA4	Close and healthy client-contractor relationships
	ADA5	Fast rerouting of requirements
Efficiency	EFF1	Failure prevention
	EFF2	Avoid variations/rework
	EFF3	Higher labour productivity
	EFF4	Waste elimination
	EFF5	Learning from experience
Financial Strength	FIS1	Good price margin
	FIS2	Portfolio diversification
	FIS3	Financial reserves and funds
	FIS4	Good insurance coverage
Visibility	VIS1	Efficient IT system & information exchange
	VIS2	Business intelligence gathering
	VIS3	Products, assets, people visibility
Anticipation	ANT1	Deploying tracking and tracing tools
	ANT2	Monitoring early warning signals
	ANT3	Alternative innovative technology development
	ANT4	Quality control
	ANT5	Cross training/intensive training
Dispersion	DIS1	Distributed decision making

Supply Chain Vulnerabilities (SCV)

SCV Construct	Code	Measurement Items
Economic SCV	ESCV1	Exchange rate fluctuations
	ESCV2	Price fluctuations
	ESCV3	Liability claims
	ESCV4	Cost overrun
	ESCV5	Industry/market pressures
	ESCV6	Information misuse
	ESCV7	Economic policy changes
Technological SCV	TSCV1	Technology failure
	TSCV2	IT system failure
	TSCV3	Inadequate IT systems
	TSCV4	Information loss
	TSCV5	Variations/rework
Procedural SCV	PSCV1	Safety issues
	PSCV2	Implication of new laws/regulation
	PSCV3	Systems/machines breakdown
	PSCV4	Transport disruptions including port stoppages
	PSCV5	Physical damage to the buildings/accidents
Organizational SCV	OSCV1	Communication breakdown/issues
	OSCV2	Loss of skilled workforce
	OSCV3	Disruptions due to outsourcing
	OSCV4	Inadequate supplier selection
Production-based SCV	PBSCV1	Quality loss
	PBSCV2	Supply-demand mismatch/shortages
	PBSCV3	Labour strikes/disputes

Figure 6.1: The research framework developed for PLS-SEM analysis

6.2.2. Hypotheses Development

This chapter focuses on the two research thrusts mentioned above and described in previous chapters: capabilities and vulnerabilities allied with SCR in IC. Resilient supply chains are essential for achieving performance-enhanced, more sustainable supply chains in IC.

Therefore, a comprehensive research exercise was conducted to facilitate the adoption of SCR capabilities in construction organizations and to help develop smoother and more resilient and sustainable construction processes. During the initial stages of this research project, first, a set of SCV and SCC targeting SCR were determined through a systematic and comprehensive literature search, and thereby critical SCV and critical SCC were extracted and grouped according to their underlying themes through a Hong Kong-based case study of IC. Details of these preliminary stages are presented in detail in the previous chapters of this thesis.

CSCV constructs included Economic (ESCV), Technological (TSCV), Procedural (PSCV), Organizational (OSCV), and Production-based (PBSCV). CSCC constructs are namely, Resourcefulness (RES), Flexibility (FLE), Anticipation (ANT), Dispersion (DIS), Capacity (CAP), Adaptability (ADA), Efficiency (EFF), Financial Strength (FIS), and Visibility (VIS). These SCC are the precursors to the SCR implementation so that when better understood and appropriately adopted in projects, they can help generate the envisaged resilient supply chains as explicated above. Further, the five SCV constructs and nine SCC constructs that were developed, were used to assess the SCR in this study. Insights from the literature confirm that SCC helps withstand relevant SCV (Pettit et al., 2013). Hence targeting resilient supply chains, it can be postulated that SCC counteract or negatively influence SCV.

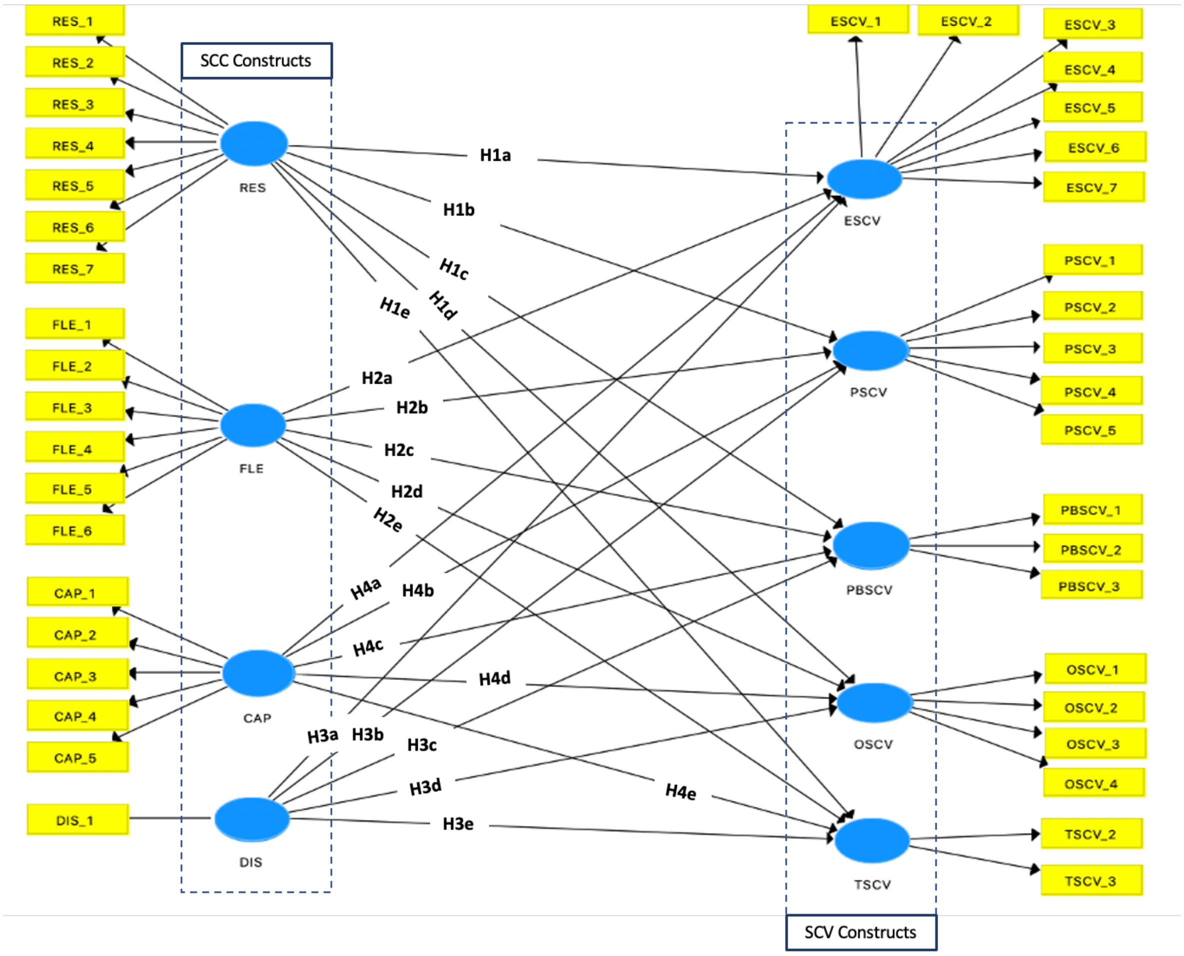
All these nine SCC constructs were tested for their impact on the five SCV constructs. However, from the 1st path-correlation of PLS-SEM analysis, only four of the SCC components, namely, capacity, dispersion, flexibility and resourcefulness, showed significant results. Therefore, based on the above results, the insights mentioned above, and the research framework (Figure 6.1), the following key research hypotheses were postulated.

H1. Resourcefulness-related SCC have a negative influence on all five SCV constructs

H2. Flexibility-related SCC have a negative influence on all five SCV constructs

H3. Dispersion-related SCC have a negative influence on all five SCV constructs

H4. Capacity-related SCC have a negative influence on all five SCV



SCC– Supply Chain Capabilities, SCV – Supply Chain Vulnerabilities, RES – Resourcefulness, FLE – Flexibility, CAP– Capacity, DIS – Dispersion, ESCV – Economic SCV, PSCV – Procedural SCV, PBSCV – Production-based SCV, OSCV – Organizational SCV, TSCV – Technological SCV

Figure 6.2: Model of Research Hypotheses

Five sub hypotheses were developed under each hypothesis by extending each capability construct's influence on all the five SCV constructs; hence a total of 20 sub-hypotheses were postulated as shown in Figure 6.2. Moreover, it is assumed that all the constructs captured in SCC have a potentially significant influence on all SCV to avoid any subjective skewing of hypotheses that could compromise this study. Accordingly, a model to visualize the study hypotheses was developed by including all the 20 sub-hypotheses, as in Figure 6.2.

6.3 Research Design

As described in Chapter 2, following the questionnaire survey, PLS-SEM analysis was conducted using SmartPLS 3.3.2 software and helped in testing the research hypotheses and validating the developed hypothetical models. The analysis was conducted under three stages of (I) model specification, (II) outer model evaluation, and (III) reflective indicators. Figure 6.2 presents the hypothetical model developed, including exogenous (SCC measures) and endogenous (SCV measures) constructs. Each SCC construct comprises formative indicators (supply chain capability measurement items), whereas each SCV construct comprises reflective indicators (supply chain vulnerability measurement items). These supply chain capability and supply chain vulnerability measurement items are the observable variables in this model and referred to as the 'measurement items' hereafter. Further, the developed constructs are the latent variables that cannot be directly measured. The PLS-SEM algorithm was run during the outer model evaluation, and the reliability and the validity of the outer model constructs were evaluated using the construct's convergent validity and discriminant validity as explicated in Chapter 2.

6.4 Results

6.4.1. Evaluation of Measurement Model

Table 6.1 and Table 6.2 present the final evaluation results of the SCC measurement model's influence in withstanding SCV targeting SCR in IC in HK. Since the factor loadings of TSCV1, TSCV4, and TSCV5 measurement items were less than 0.50, the researcher deleted them from the model to come up with the best-fit model. Besides, measurement items loaded with low figures should be avoided since their contribution is insignificant to the model's explanatory power (Nunnally, 1978). Accordingly, the PLS algorithm was re-run until a valid and reliable measurement model was achieved.

According to Table 6.1, Cronbach's alpha coefficients of all the constructs were above 0.70 and similarly, the composite reliability scores were higher than 0.70. The results indicate that the measurement model is internally consistent and reliable. Further, all factor loadings and AVE values were above 0.50. The AVE value ≥ 0.50 denotes a sufficient degree of convergent validity when a latent variable explains greater than 50% of its indicators' variance (Hair et al., 2011). Therefore, the results of this study support and provide evidence of the convergent validity of the constructs. As presented in Table 6.3, each latent construct's AVE value is greater than the respective construct's highest squared correlation with another construct by fulfilling the Fornell–Larcker criterion. Similarly, each measurement item's loading on the parent construct was higher than the other cross-loadings, justifying the discriminant validity of the constructs. Therefore, these results cleared the way forward for the structural path modeling by providing evidence to support the measurement model's reliability and validity.

Table 6.1: Measurement validity of constructs

Latent Variables	Code	CA	rho_A	CR	AVE
Supply Chain Vulnerability Constructs					
Economic Supply Chain Vulnerabilities	ESCV	0.892	0.912	0.915	0.606
Organizational Supply Chain Vulnerabilities	OSCV	0.712	0.710	0.821	0.535
Production-based Supply Chain Vulnerabilities	PBSCV	0.804	0.846	0.883	0.717
Procedural Supply Chain Vulnerabilities	PSCV	0.869	0.886	0.905	0.657
Technological Supply Chain Vulnerabilities	TSCV	0.906	0.908	0.955	0.914
Supply Chain Capability Constructs					
Capacity	CAP	0.879	0.888	0.911	0.673
Dispersion	DIS	1.000	1.000	1.000	1.000
Flexibility	FLE	0.919	0.931	0.936	0.711
Resourcefulness	RES	0.918	0.924	0.934	0.670

Note: CA represents Cronbach's Alpha; AVE represents Alpha Average Variance Extracted; CR represents Composite Reliability.

Table 6.2: Discriminant validity of constructs

	CAP	DIS	ESCV	FLE	OSCV	PBSCV	PSCV	RES	TSCV
CAP	**0.820**								
DIS	0.439	**1.000**							
ESCV	0.134	0.304	**0.778**						
FLE	0.744	0.360	0.217	**0.843**					
OSCV	0.409	0.104	0.272	0.430	**0.731**				
PBSCV	0.133	0.055	0.037	0.255	0.620	**0.847**			
PSCV	0.402	0.345	0.408	0.414	0.558	0.412	**0.811**		
RES	0.649	0.345	0.070	0.694	0.484	0.594	0.494	**0.818**	
TSCV	0.195	0.151	0.386	0.103	0.165	0.186	0.046	0.131	**0.956**

The bold diagonal values are the square root of average variance extracted of each construct, while the other values are the correlations amongst constructs.

6.4.2. Evaluation of Structural Model

Table 6.3 indicates the bootstrapping results of the PLS-SEM structural model developed in this study. According to the results, paths linking CAP-PBSCV, FLE-ESCV, RES-OSCV, and RES-PSCV had a *t*-value above 1.96, indicating that these paths are statistically significant at the level of 0.05. Therefore, H4, H1, and H2 hypotheses were partially and suitably supported. The paths linking DIS-ESCV, RES-ESCV and RES-PBSCV have *t*-value greater than 2.56, indicating that these paths are statistically significant at the 0.01 level. Hence, hypotheses H3 and H1 are also suitably supported. Besides, the higher path coefficient implies a more substantial influence on the variables (Aibinu & Al-Lawati, 2010). Figure 6.3 clearly shows each path coefficient's strength in the PLS-SEM model of the impact of SCC on withstanding SCV in achieving SCR of IC in HK. The thicker the path lines, the stronger the path influence. Therefore, the most robust path is between RES and PBSCV, implying the most substantial influence in achieving resilient supply chains in IC. The coefficients of determination (R^2) value of the dependent variables are greater than 0.3. On the most substantial path of PBSCV, it is 0.518. Therefore, it further confirms the quality and the predictive accuracy of the model (Hair et al., 2014).

Table 6.3: Evaluation of structural model

Paths	(O)	(M)	(STDEV)	(|O/STDEV|)	P values	Inference
CAP→ESCV	0.043	0.046	0.195	0.218	0.827	Not Supported
CAP →OSCV	0.145	0.158	0.178	0.818	0.413	Not Supported
CAP →PBSCV	**0.372**	**0.365**	**0.154**	**2.420**	**0.016***	**Supported**
CAP →PSCV	0.035	0.051	0.184	0.193	0.847	Not Supported
CAP →TSCV	0.221	0.185	0.230	0.964	0.335	Not Supported
DIS→ESCV	**0.319**	**0.317**	**0.101**	**3.170**	**0.002****	**Supported**
DIS →OSCV	0.125	0.143	0.129	0.972	0.331	Not Supported
DIS →PBSCV	0.068	0.079	0.095	0.716	0.474	Not Supported
DIS →PSCV	0.179	0.180	0.124	1.447	0.148	Not Supported
DIS →TSCV	0.083	0.097	0.138	0.602	0.547	Not Supported
FLE →ESCV	**0.460**	**0.477**	**0.192**	**2.403**	**0.016***	**Supported**
FLE →OSCV	0.127	0.134	0.210	0.607	0.544	Not Supported
FLE →PBSCV	0.076	0.077	0.168	0.450	0.652	Not Supported
FLE →PSCV	0.074	0.051	0.209	0.355	0.722	Not Supported
FLE →TSCV	0.122	0.092	0.254	0.479	0.632	Not Supported
RES→ESCV	**0.472**	**0.483**	**0.176**	**2.680**	**0.007****	**Supported**
RES →OSCV	**0.345**	**0.348**	**0.174**	**1.988**	**0.047***	**Supported**
RES →PBSCV	**0.911**	**0.921**	**0.099**	**9.226**	**0.000****	**Supported**
RES →PSCV	**0.358**	**0.374**	**0.141**	**2.547**	**0.011***	**Supported**
RES →TSCV	0.043	0.044	0.194	0.221	0.825	Not Supported

Note:
(O) = Original Sample; (M) = Sample Mean; (STDEV) =Standard Deviation;
(|O/STDEV|) = t statistics
The bold texts represent the significant paths.
*The path coefficient is significant at $p < 0.05$
** The path coefficient is significant at $p < 0.01$

6.5 Discussion

The proposed model is based on the IC supply chains in Hong Kong as supply chain dynamics are jurisdiction-specific. Therefore, these findings are validated specifically for the Hong Kong context. Indeed, this chapter identified the critical SCC constructs with the allied significant paths and essential components of SCV, where the industry professionals would need to pay their particular attention. To facilitate this, this section discusses the results generated from the PLS-SEM analysis from a good practice enhancement perspective. Therefore, the significance of each path is explicated further, considering the measurement items included in the appropriate supply chain vulnerability and capability constructs as follows.

6.5.1. Resourcefulness (RES) → Production-based SCV (PBSCV)

The PLS-SEM model supported a significantly negative influence of resourcefulness towards production-based SCV. These results identified this path as the most significant path, demarcating resourcefulness as the most critical capability that the IC in HK needs. The results also suggested PBSCV as the most critical SCV where greater attention is required. The results can be further interpreted as: the higher the resourcefulness, the lesser the supply chain disruptions due to PBSCV, and the higher the withstanding capacity of IC supply chains. Since PBSCV are allied with the production process of IC supply chains, a collaborative and resourceful approach seems very important for withstanding PBSCV; hence, collaborative resourcefulness is suggested to be effective. In line with Ekanayake et al. (2019) findings, quality loss, supply-demand mismatch/shortages and labor disputes are the most significant supply chain disruptions in IC in HK, grouped in PBSCV construct. Unless an appropriate tolerance is ensured in the factory, quality issues could disrupt the assembly process (Ekanayake et al., 2019).

On the other hand, a supply-demand mismatch is also highlighted by these failed or 'sub-prime' production processes. Although labor disputes are highly visible in the manufacturing process, the loss of skilled labor has become one of the biggest challenges that the IC industry faces in HK (Ekanayake et al., 2019). In order to withstand PBSCV, RES is suggested to be the solution (with the path significance of 9.181). Collaborative decision making is vital in this regard, where it is possible to generate accurate prefabricated components exclusive of errors. Zhong et al. (2017) suggested deploying the internet of things enabled BIM platforms in the IC supply chains to improve the collaborative data interoperability. Similarly, the industry is currently utilizing BIM-enabled platforms in their projects, targeting improved professional collaboration from manufacturing to assembly. These tools facilitate early design freeze and supply chain visibility, which cause error-free designs. In addition, the systems, including enterprise resource planning, provide timely alerts to project stakeholders on resource shortages and buffers, which may reduce unnecessary queuing of resources or the prefabricated units themselves. This can have a high impact on compact sites in the city of HK.

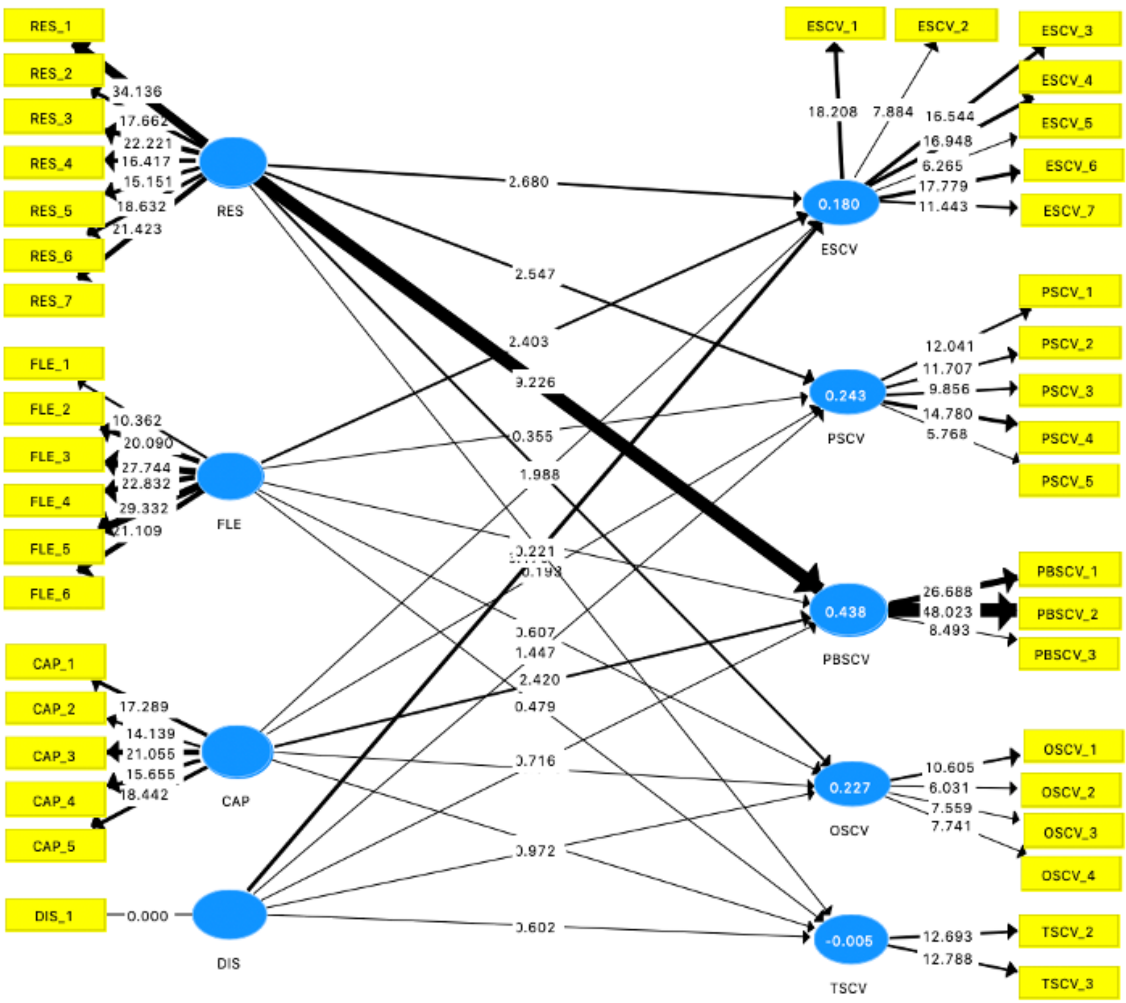


Figure 6.3: PLS-SEM model of the impact of SCC on withstanding SCV in achieving SCR in IC in HK

Obtaining competitive prices from suppliers is critical (Lim et al., 2011) since the process enables selecting appropriate prefabrication manufacturers as most of the units are outsourced to HK from mainland China. Nevertheless, outsourcing is beneficial, given the higher cost of skilled labor and the skilled labor scarcity in the industry. The quality assembly of IC units depends upon the caliber of the skilled labor and their motivation. Therefore, facilitating adequate site safety to avoid labor-related disputes is worth pursuing. The current practice in public housing projects in HK provides a good example, in that they conduct quarterly safety audits of the contractors of IC projects and blacklist those who are non-compliant against certain criteria. Therefore, the developed supply chain capability of improved safety is also essential in this respect in IC projects in HK. As a result, resourcefulness enables effective withstanding of PBSCV in IC.

6.5.2. Dispersion (DIS) → Economic SCV (ESCV)

As the second steady path shown in Figure 6.3, dispersion (DIS) with just one measurement item, namely distributed decision-making substantially impacts retarding economic SCV with the path significance of 3.222. Decentralization of critical decision-making power is very helpful in providing fast and appropriate recovery from disruption. Since IC supply chains are highly fragmented, on-site decision making should be undertaken by the site experts, as in a manufacturing factory. Therefore, economically feasible decisions on outsourcing and favorable decisions under industry/market pressure could be made and would adequately respond to the economic SCV. Risks of escalating project costs may be substantially reduced due to quick, but better-informed; hence sound decision-making in the materials flow control process (Bataglin et al., 2017).

6.5.3. Resourcefulness (RES)→ Economic SCV (ESCV), Organizational SCV (OSCV) and Procedural SCV (PSCV)

Resourcefulness is also effective in counteracting economic SCV (with the third-highest path significance of 2.733). This path is closely related to the disruptions due to the economic changes and affected even by economic policy changes. A special feature of these disruptions is that their disruptive impact is acute although they are not frequent. Price fluctuations impact resource scarcity, and outsourcing decisions are affected by exchange rate fluctuations in IC supply chains. Collaborative decision making is influential in this respect. Prefabricated components are almost impossible to modify after producing them, leading to rework and cost overruns in the event of mistakes. Not being an exception, IC projects in HK also face disruptions due to design, manufacture, and assembly problems (Li et al., 2011). As suggested by Wong et al. (2003), having better control over manufacturing substantially reduces the chances of cost overruns. Tardiness in supply chain deliveries hampers the associated IC benefits (Mok et al., 2015), while 'buffer space hedging' is suggested to be an effective counter-measure (Zhai et al., 2019b). This would also be included under the resourcefulness construct.

Cybersecurity as a RES capacity is influential in avoiding information misuse through information systems and software to prevent rework from unsuitable supply chain configurations. Therefore, this should be considered as well, despite having an excellent information sharing platform to enhance supply chain collaboration. That is why a resourceful, collaborative approach is required in making all the supply chain decisions to avoid these disruptions due to ESCV. Further, resourcefulness supports the other two SCV constructs of organizational and procedural. These constructs especially cover the specific SCV associated with IC in HK such as transport disruptions and also the safety issues due to the handling of over-weight and over-sized prefabricated components and transporting them from China to HK. Therefore, resourcefulness is highly influential in overcoming these significant vulnerabilities to a greater extent.

6.5.4. Capacity (CAP) → Production-based SCV (PBSCV)

The development of CAP (capacity) towards PBSCV received the fifth-highest importance with a path significance of 2.452. The CAP construct awards supply chain resources for continuous supply chain operation. Having backup supply chain equipment, including machinery at the factory and on-site equipment such as cranes and hoists, are beneficial in avoiding supply-demand mismatch and shortages over time (Ekanayake et al., 2019). Redundancy as a capacity measurement item, facilitates quick recovery after disruption despite the failure of the entire system (Sheffi & Rice, 2005), hence being quite useful in any significant disruption, especially in supply chain breakdowns due to quality issues, supply shortages, and labor disputes. However, it is still questionable whether the existing capacity of many firms allows for providing redundancies to overcome disruptions and maintain continuity in IC supply chains in HK, hence alerting practitioners to the need for capacity improvements.

Emergency response management (Irizarry et al., 2013) is another capacity measurement item that guarantees a speedy recovery from disruptions and is very important in the continuity of the supply chain flow. Having a capable professional team for disruption management is important since all these production-based disruptions are critical and depend upon human factors. Maintaining an effective communication strategy is highly influential in mitigating SCV (Ekanayake et al., 2019) since IC supply chains in HK are fragmented in nature (Li, 2017). That is why several reputed construction companies in HK have integrated their supply chains using BIM platforms to enhance effective communication and accountability between the supply chain stakeholders. However, there is a way forward to realize resilient supply chains by inculcating these practices even in 'modular integrated construction' (MiC) or in design for manufacture and assembly which are specific approaches in the IC sector.

6.5.5. Flexibility (FLE) → Economic SCV (ESCV)

Flexibility negatively impacts the economic SCV, targeting resilient supply chains in IC in HK with the path significance of 2.390. Under the FLE construct, vertical integration is significantly advantageous and economically feasible over outsourcing prefabricated components. Since most IC contractors do not maintain their in-house prefabrication plants, the contractors are denied higher profit levels under a self-manufacturing decision (Han et al., 2017), based on the vertical integration of the supply chain manufacture and assembly. Production postponement is also an economic decision that could be taken, if useful to deal with economic and financial policy changes (Ekanayake et al., 2019). Risk pooling and sharing is another substantial flexibility measurement item, necessitating effective private-public collaboration as a proper risk-sharing mechanism in withstanding ESCV in IC in HK, but is yet to be realized.

Accordingly, the findings of this chapter highlight the need to reinforce the SCC constructs of resourcefulness, capacity, dispersion, and flexibility by paying specific attention to production-based and economic SCV in realizing resilient IC supply chains in HK. Industry practitioners and professionals may benefit from paying more attention to appropriate application of the findings of this chapter in their key decision making for developing implementation programs for effective disruption management. The computed PLS-SEM model in Figure 6.3 is based on HK industrialized construction practices but could also be used as a basis for other countries where IC is well-practiced.

6.6 Chapter Summary

To further promote SCR practices appropriately in IC and given the potential value of linking SCC to related SCV, this chapter enabled developing a statistical PLS-SEM model to evaluate the correlational impact of SCC on SCV in achieving resilient supply chains in IC in the dense urban setting of HK. The chapter identified that resourcefulness has the highest significant impact on withstanding production-based SCV and also, found six other significant paths; resourcefulness related SCC can help to withstand economic, organizational and procedural SCV; capacity-related SCC can help to withstand production-based SCV; dispersion related

SCC can help to withstand economic SCV; and flexibility related SCC can help to withstand economic SCV, in particular. Hence, RES, CAP, DIS and FLE were determined as the highly influential SCC in developing resilient IC supply chains in HK. The key contribution of this chapter to the SCR knowledge domain is in developing a mathematical model that explicates how various types of SCC help in achieving SCR by effective withstanding of strong SCV in the IC sector in HK. Indeed, findings of Chapter 6 satisfy the further research directions proposed in Chapter 4 and fulfil Objective 2 of this research.

Chapter 7 Dynamic Modeling of SCR in IC with Proposed Improvement Strategies[5]

7.1 Introduction

This chapter presents the outcomes generated by examining the impacts of SCV on each supply chain phase and by evaluating the influence of SCV and SCC which are two fundamental concerns of SCR from the industrialized construction perspective in Hong Kong. Further, this chapter proposes useful strategies to enhance the resilient capabilities in IC practices in HK. To generate all these outcomes presented in Chapter 7, the research data was collected through the questionnaire survey, interviews and two comparative case studies, and analyzed using Social Network Analysis and System Dynamics Modeling (SDM).

The findings generated from Chapter 7 provide evidence-based pointers to project professionals to initiate well-focused performance-enhancing measures to achieve SCR in IC, being the first known initiative to explore the potential use of SDM to assess dynamics of IC supply chains in the pursuit of resilience. Besides, this chapter satisfies the research Objective 3 and Objective 4 of this overall thesis. The forthcoming sections of this chapter 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 SCR in IC, and finally, the chapter summary.

---

[5] The core research and findings in this chapter have been peer-reviewed before publication in:

Ekanayake, E.M.A.C., Shen, G.Q., Kumaraswamy, M.M., Owusu, E.K. and Abdullahi, S., 2021. Modelling Supply Chain Resilience in Industrialized Construction: A Hong Kong Case. *Journal of Construction Management and Engineering.* 147(11). 10.1061/(ASCE)CO.1943-7862.0002188.

7.2 Theoretical Foundations and the Conceptual Framework

IC supply chains span a much longer process and timeframe than in conventional in-situ construction since they straddle across two production environments. Further, IC supply chains require longer periods for potential error reduction for achieving the often-critical 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, specializations 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, Shen, Kumaraswamy, et al., 2020). 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 faces during on-site assembly (Li et al., 2018a). Coupled with the inherent complexity and the fragmented nature of the IC supply chains, these further multiply and amplify vulnerabilities across the supply chain network as described in detail in the previous chapters of this thesis.

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, SCR can only be enhanced by improving the appropriate SCC (Pettit et al., 2013) and elaborated in Chapter 5, 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 realize these technological capacities, connecting the entire value chain with a seamless data flow (McKinsey Global Institute, 2020).

Delving deeper, SCR aligns with the ‘Dynamic Capability View’ which supports the explanation of SCC in dynamic and uncertain environments by utilizing appropriate resources and capabilities to respond to dynamic changes (Chowdhury & Quaddus, 2017) and clearly explicated in Chapter 6. Hence, this study postulates that supply chains need to create dynamic capabilities to withstand SCV under tumultuous supply chain environments, to boost the performance of IC in HK.

Building on these theoretical assumptions, this study employed SDM to investigate the dynamics of SCC, targeting resilient IC supply chains in HK. SDM provides an effective mechanism to discover, elucidate, and measure interrelationships and dynamics among the elements of a model (Wang et al., 2018). Besides, SDM 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 SCR and SCC initiation. Studies by

Olivares-Aguila and ElMaraghy (2020), Kochan et al. (2018), Bueno-Solano and Cedillo-Campos (2014) used the same SDM in evaluating dynamic supply chain disruptions. Therefore, the focus of previous studies was on assessing the dynamic impact of one or more SCV and hence, lacks the 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 modeling the SCR impact, Chapter 7 of this research study investigates the effect of SCC in strategies to boost SCR in IC with the help of relevant modeling techniques such as system dynamics and social network analysis, depending on the material being probed. After specific detailed precursor studies, in Chapter 4, the researcher previously identified five SCV constructs, i.e., economic, technological, procedural, organizational, production-based components incorporating 24 critical SCV; and also, nine SCC components (in Chapter 5), i.e. resourcefulness, flexibility, anticipation, dispersion, capability, adaptability, efficiency, financial strength and visibility, incorporating 41 critical SCC measurement items, in respect of IC supply chains in HK. These were built upon for further data collection and model development as appropriate to this chapter findings and explicated further in the forthcoming sections. Since fortification of resilience requires new initiatives, these findings led to the formulation of strategies to enhance SCR in IC in HK based on two comparative case studies, and the results generated from the dynamic modeling of IC supply chains.

A theoretical framework (Figure 7.1) was developed for the above purpose, including SCV constructs and SCC components which are the two main categorical measures established in the literature, highlighting that SCR could be realized 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 chain, hence shown as a positive link. On the other hand, SCC are the counter balancers of SCV, hence indicated by a negative link to SCV. Figure 7.1, thus, represents a generic overview of how the individual supply chain vulnerabilities and supply chain capabilities categorical measures (which are the indicators of SCR) affect the entire supply chain process of IC. The theoretical relationships depicted in Figure 7.1 are examined later in this chapter to establish how these supply chain vulnerabilities and supply chain capabilities indicators collectively impact each supply chain phase and the entire supply chain of IC and how the negative impacts can be strategically extirpated or minimized.

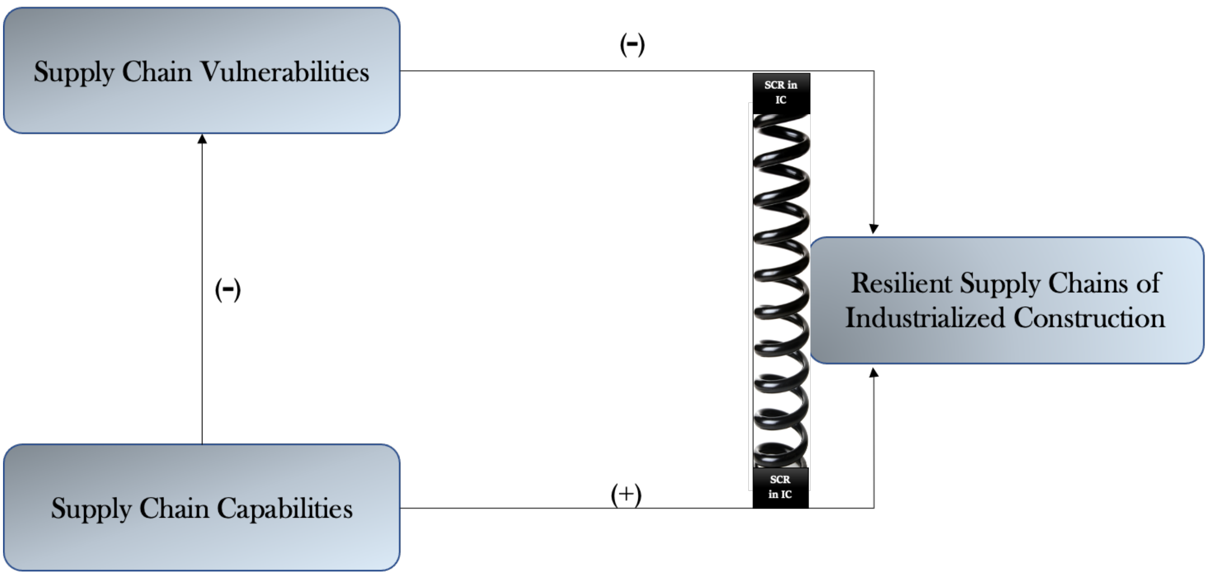
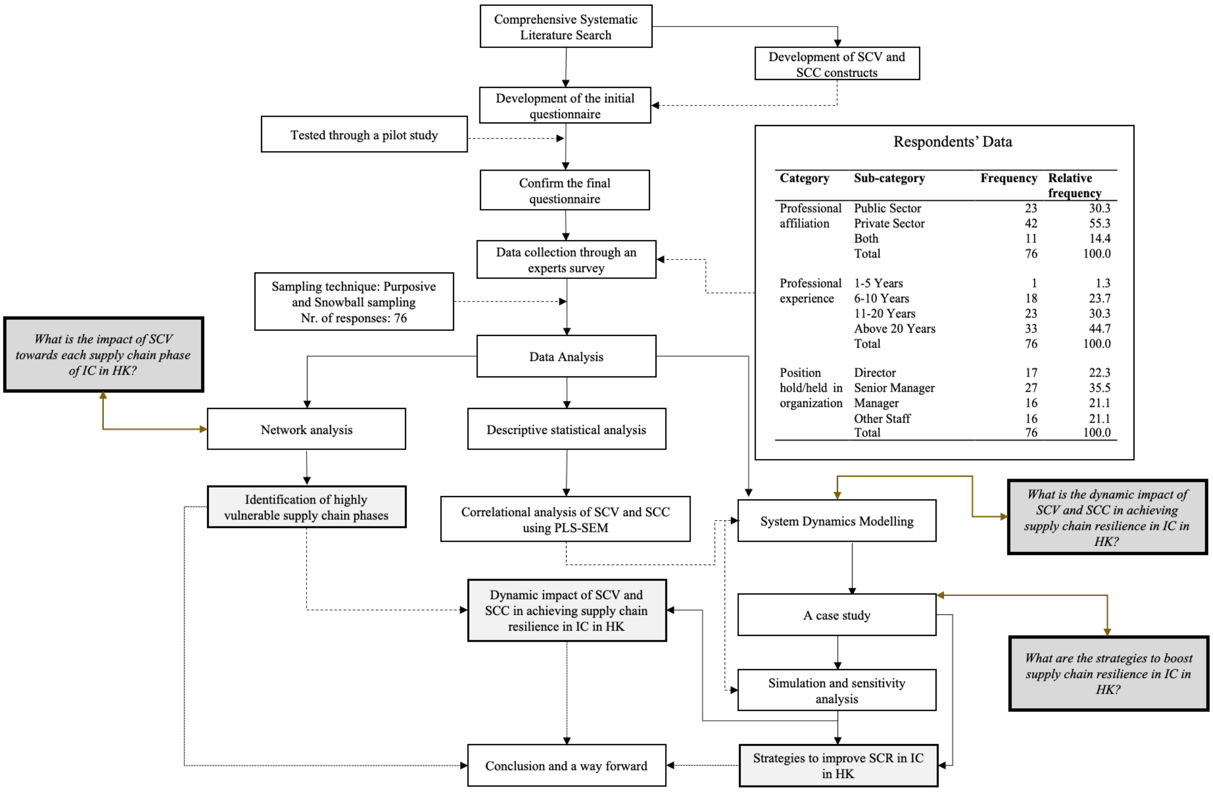


Figure 7.1: Theoretical relationships among the constructs

7.3 Research design

A comprehesive and robust research methdology 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, over-arching priciples and current best practices, along with their strengths and weaknesses. Figure 7.2 depicts the research methods used and the flow, and research outcome in line with each research activity of this chapter to improve readers' understanding. As stated in the chapter introduction, a mixed method approach was adopted to derrive chapter findings by deploying an expert opinion survey and case study being the main data collection techniques used. All these techniques are described in detail in this thesis Chapter 2.



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

Figure 7.2: Research methods used and the flow of Chapter 7

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 supply chain capability measurement items and the criticality of each supply chain vulnerability (based on probability of occurrence and the level of severity) [see Chapter 4 and Chapter 5 for more details]. All these data covered all the IC supply chain phases, and the experts separately identified the SCV associated with each supply chain phase during the semi-structured interviews.

Owing to the nature of the anticipated outcomes, which were of course linked to the accomplishment of research objectives, three main tools were employed. The mean ranking approach was first employed to conduct a descriptive analysis to determine the criticalities of supply chain vulnerability and supply chain capability measures 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 Social Network Analysis (SNA) approach. Thereafter, simulation of the accumulated impacts of SCV and the appropriate SCC measures was conducted using the SDM approach to help instigate appropriate measures to achieve resilient supply chains in IC in HK. All these analysis tools are further explained in detail in Chapter 2, also justifying their suitability for this research.

The descriptive statistics of the expert survey of all the underlying components of this study are given in Table 7.1. These components include all the variables considered in the SNA and SDM. Supply chain vulnerability constructs include all the negative variables that hamper, and retard SCR. SCC constructs include all the positive variables which encourage and enable SCR. 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 the resilience of IC supply chains. Before the SDM, 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, SNA was conducted, and the process is described further as follows.

Table 7.1:Descriptive statistics of the determinants of SCR

No	Code	Construct	Mean	NV-Mean	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: NV-Mean – Normalized values of construct means; SNA-Social Network Aanalysis

7.3.1. SNA 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. The vulnerability level of each phase 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 Figure 7.3. 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.

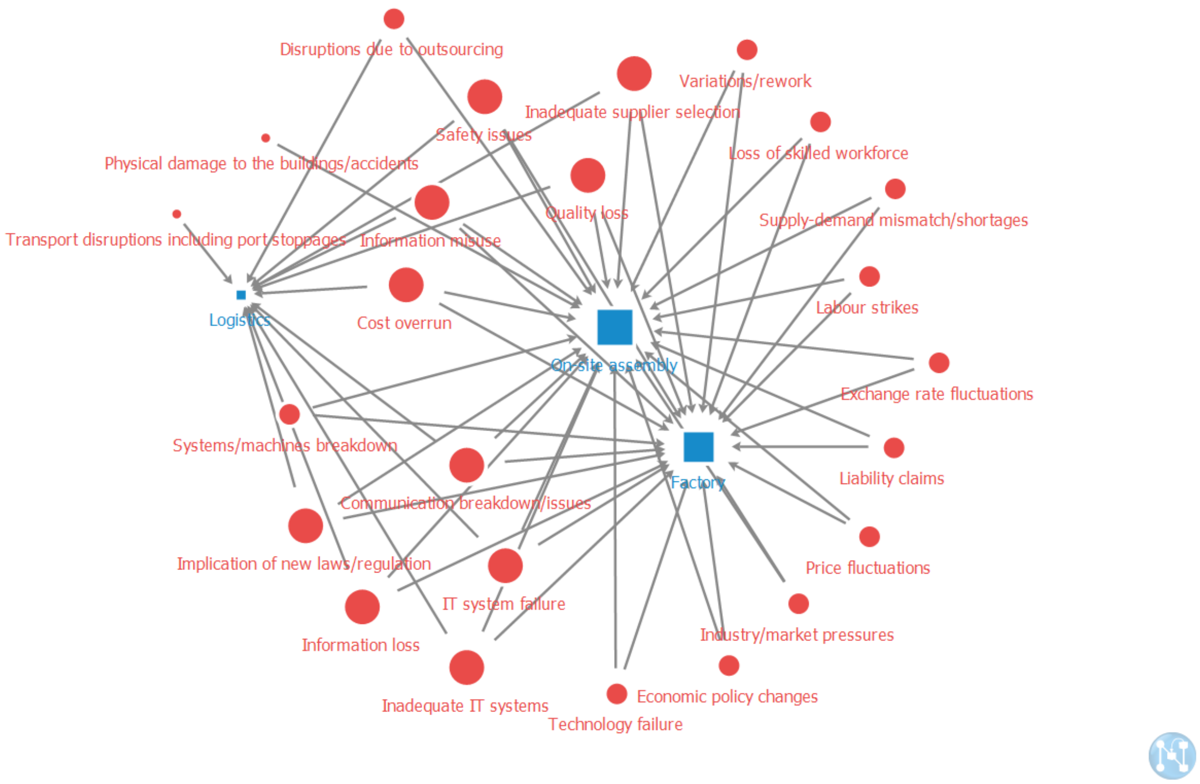


Figure 7.3: Two-mode network analysis of SCV in IC

The node size reflects the level of vulnerability of each supply chain phase. Further, 'degree' as one of the key measures in SNA 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 SNA are further elaborated in the discussion section.

7.3.2. SD Model

Model development

The application of the SDM 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 behavior of the supply chain system 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 SCR. 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 SCR performance in IC. Also, the SCC can be grouped under nine constructs representing the relevant underlying factors in each construct. Therefore, the relationships between each underlying factor and the appropriate constructs were first established using the Partial Least Squares Structural Equation Modeling (PLS-SEM) (Ajayi, 2016). Thereby, the relationships between the factors were modelled through the use of Vensim 8.1.0 software.

Causal loop diagram (CLD)

A causal loop diagram visualizes the cause-and-effect relationships between the variables in a model by articulating the interrelationships of various elements which create a system (Ajayi, 2016). This diagram includes nodes and links where nodes refer to the variables and links represent the variables' relationships. SCR 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 SCR 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 Hong Kong.

Therefore, the positive loops are the nine SCC components which 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 Figure 7.4. 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 (SFD) is another possible method of presenting causal relationships between variables in SDM (Coyle, 1997). According to Ajayi (2016), SFD is an algebraic representation that can be run on a computer since it is written in equations and computer coding. Hence, SFD facilitates quantitative analysis and mathematical simulation of a model without just limiting to evaluation through tracing of the causal and use trees (T. Wang et al., 2018). The CLD was converted to a SFD thereafter using Vensim software to simulate dynamic relationships of various strategies in achieving resilient supply chains in IC. The SFD is presented in Figure 7.5, and all the notations used are described in Table 7.2.

As shown in Figure 7.5, the variables in the stock and flow diagram, include stocks, flows, auxiliary variables, and constant indicators. The SFD 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 SFD, two comparable 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 Modeling (BIM) platform. Table 7.3 presents further details about these two projects.

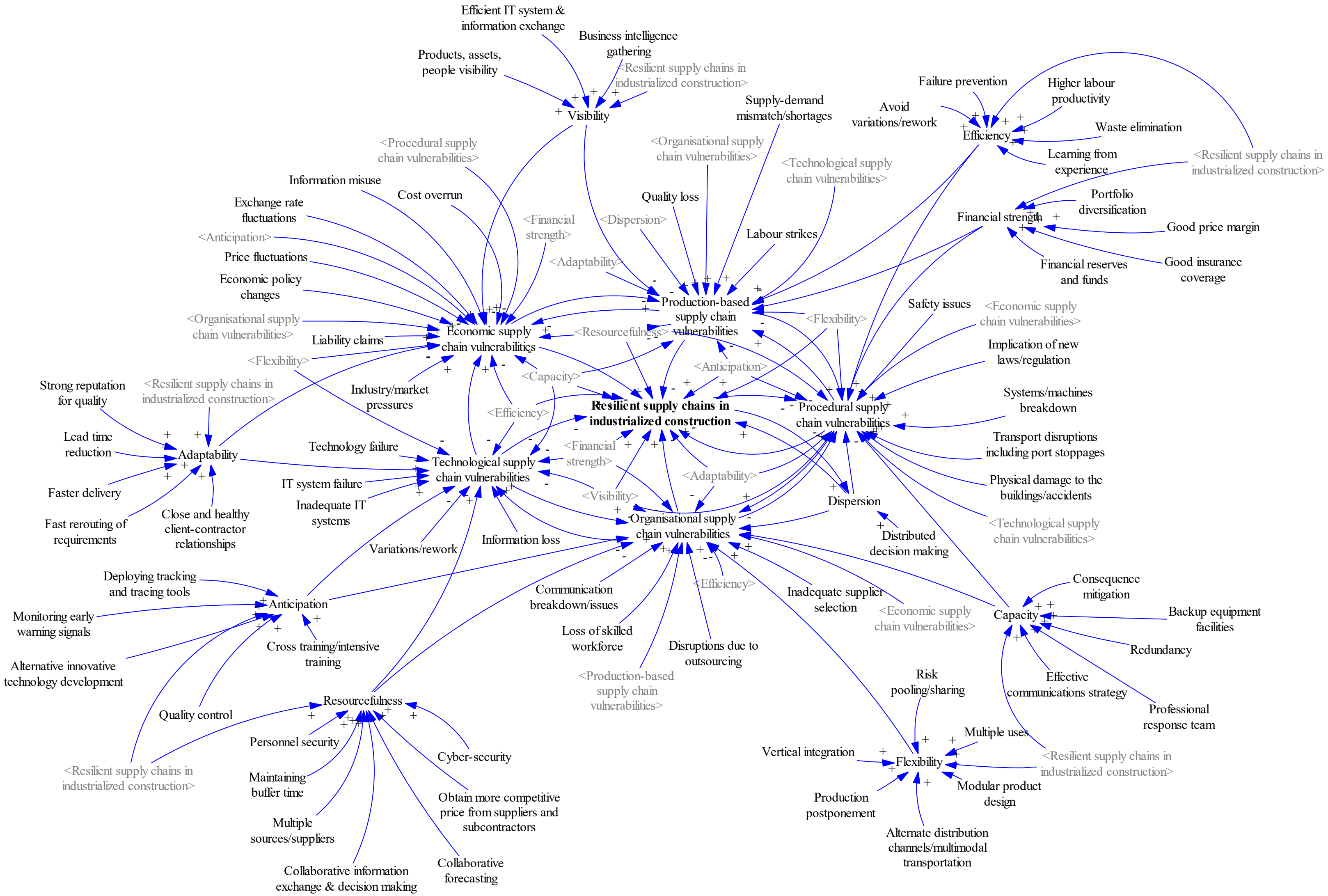


Figure 7.4: Causal Loop Diagram of the constructs of SCR in IC in Hong Kong

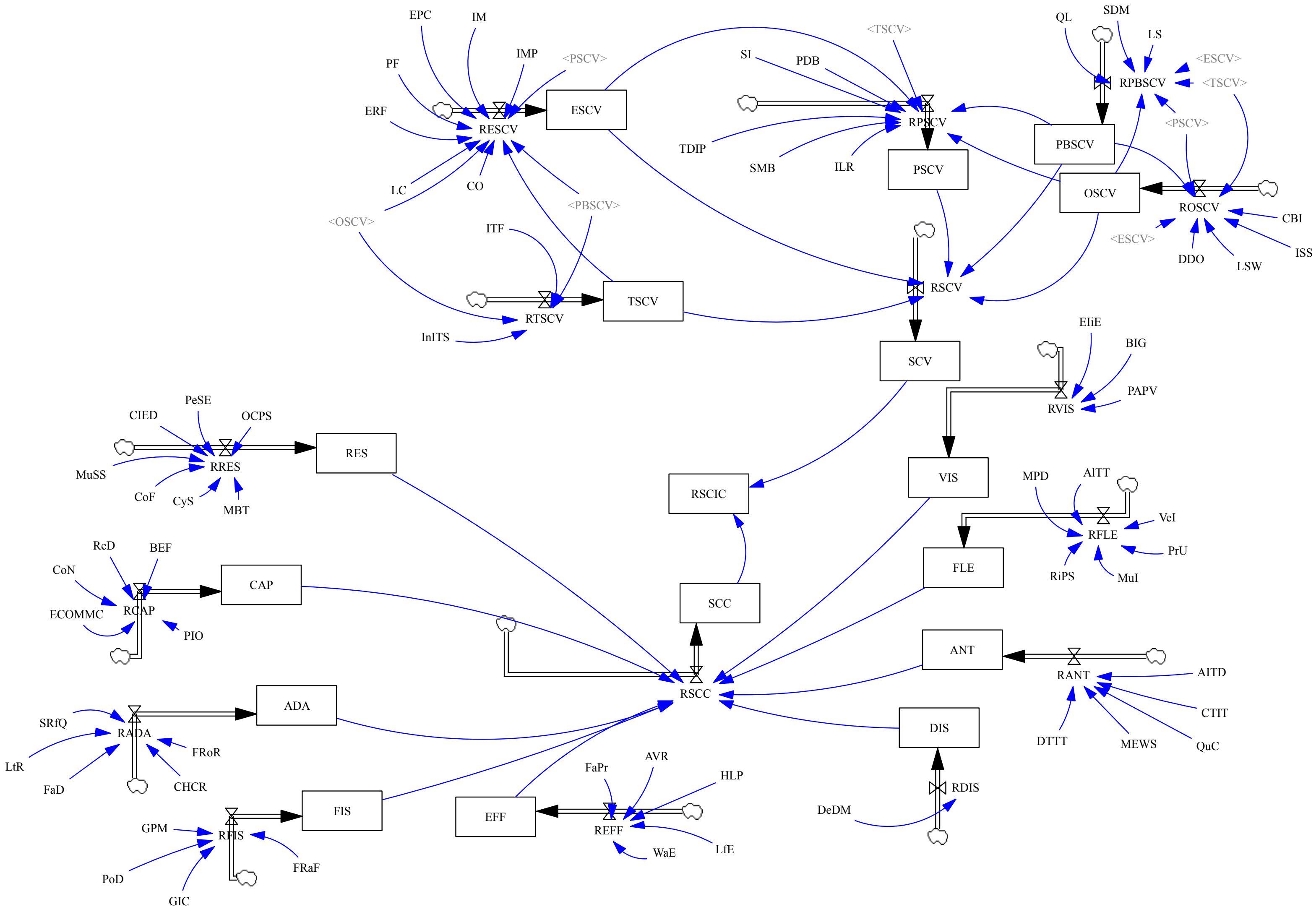


Figure 7.5: Stock and Flow Diagram of the constructs of SCR in IC in Hong Kong

Table 7.2: Descriptions of the model variables with assigned values

Variable Name and Abbreviation		(w_{x_i})	$AL(A)$	$AL(B)$
Resourcefulness	RES			
Personnel security	PeSe	0.892	0.80	0.90
Collaborative information exchange & decision making	CIED	0.794	0.90	0.95
Collaborative forecasting	CoF	0.812	0.90	0.90
Cyber-security	CyS	0.789	0.80	0.90
Obtain more competitive price from suppliers and subcontractors	OCPS	0.813	0.60	0.90
Multiple sources/suppliers	MuSS	0.829	0.80	0.90
Maintaining buffer time	MBT	0.794	0.95	0.95
Flexibility	FLE			
Vertical integration	VeI	0.755	0.50	0.95
Production postponement	PrU	0.847	0.70	0.80
Alternate distribution channels/multimodal transportation	AlTT	0.870	0.80	0.80
Modular product design	MPD	0.851	0.80	0.95
Multiple uses	MuI	0.886	0.90	0.90
Risk pooling/sharing	RiPS	0.843	0.80	0.70
Capacity	CAP			
Back-up equipment facilities	BEF	0.831	0.70	0.80
Redundancy	ReD	0.802	0.80	0.70
Consequence mitigation	CoN	0.851	0.95	0.90
Effective communications strategy	ECOMMC	0.798	0.95	0.80
Professional response team	PIO	0.819	0.95	0.95
Adaptability	ADA			
Strong reputation for quality	SRfQ	0.851	0.99	0.99
Lead time reduction	LtR	0.797	0.95	0.95
Faster delivery	FaD	0.893	0.99	0.99
Close and healthy client-contractor relationships	CHCR	0.764	0.99	0.99
Fast rerouting of requirements	FRoR	0.800	0.90	0.95

Variable Name and Abbreviation		(w_{x_i})	$AL(A)$	$AL(B)$
Financial Strength	FIS			
Good price margin	GPM	0.792	0.25	0.70
Portfolio diversification	PoD	0.848	0.50	0.90
Financial reserves and funds	FRaF	0.853	0.90	0.90
Good insurance coverage	GIC	0.832	0.99	0.90
Anticipation	ANT			
Deploying tracking and tracing tools	DTTT	0.744	0.40	0.40
Monitoring early warning signals	MEWS	0.861	0.60	0.60
Alternative innovative technology development	AITD	0.820	0.70	0.90
Quality control	QuC	0.795	0.95	0.90
Cross training/intensive training	CTIT	0.774	0.80	0.90

Variable Name and Abbreviation		(w_{x_i})
Economic SCV	ESCV	
Exchange rate fluctuations	ERF	0.842
Price fluctuations	PF	0.789
Liability claims	LC	0.796
Cost overrun	CO	0.789
Industry/market pressures	IMP	0.640
Information misuse	IM	0.817
Economic policy changes	EPC	0.759
Technological SCV	TSCV	
IT system failure	ITF	0.953
Inadequate IT systems	InITS	0.960
Procedural SCV	PSCV	
Safety issues	SI	0.839
Implication of new laws/regulation	ILR	0.847
Systems/machines breakdown	SMB	0.841

Efficiency	EFF				Transport disruptions including port stoppages	TDIP	0.840
Failure prevention	FaPr	0.787	0.70	0.85	Physical damage to the buildings/accidents	PDB	0.666
Avoid variations/rework	AVR	0.888	0.80	0.95	Organisational SCV	OSCV	
Higher labor productivity	HLP	0.900	0.99	0.99	Communication breakdown/issues	CBI	0.815
Waste elimination	WaE	0.893	0.60	0.90	Loss of skilled workforce	LSW	0.636
Learning from experience	LfE	0.641	0.95	0.99	Disruptions due to outsourcing	DDO	0.700
Visibility	VIS				Inadequate supplier selection	ISS	0.779
Efficient IT system & information exchange	EIiE	0.766	0.60	0.80	Production-based SCV	PBSCV	
Business intelligence gathering	BIG	0.615	0.99	0.99	Quality loss	QL	0.892
Products, assets, people visibility	PAPV	0.921	0.40	0.60	Supply-demand mismatch/shortages	SDM	0.887
Dispersion	DIS				Labor strikes	LS	0.754
Distributed decision making	DeDM	1.000	0.95	0.95	Resilient supply chains in IC	RSCIC	

Table 7.3: 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

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 supply chain capability measures and the level of vulnerability due to supply chain disruptions. The data related to level of SCC application and the level of vulnerability (on a range of 0% to 100%, which indicates 0% as the least to 100% as the highest) of these two projects were collected during the case study [$AL(X)$ values presented in Table 7.2]. Besides, all the project-specific details, lessons learnt, and the individual arrangements by the firms 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. PLS-SEM has computed a weighting score for each link (relationships) within the constructs [(w_{x_i}) values presented in Table 7.2]. 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 7.1.

$$R_{x_i} = \frac{w_{x_i}}{\sum_{j=1}^{n} w_{x_j}} \qquad (7.1)$$

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 7.2.

$$AL(X) = \sum_{i=1}^{n} L_{x_i} \times R_{x_i} \qquad (7.2)$$

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 7.1.

(III) Then, this study computed the significance index of all the latent variables using the following Equation 7.3, in order to understand each construct's significance towards achieving the resilient IC supply chains.

$$R_{X_i} = \frac{w_{X_i}}{\sum_{j=1}^{n} w_{X_j}} \qquad (7.3)$$

In Equation 7.3, 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 7.4 and Equation 7.5, considering their relative impacts on the contributing factors and their level of application.

$$SCV = AL_{ESCV} \times R_{ESCV} + AL_{TSCV} \times R_{TSCV} + AL_{PSCV} \times R_{PSCV} + AL_{OSCV} \times R_{OSCV} + AL_{PBSCV} \times R_{PBSCV} \tag{7.4}$$

$$SCC = AL_{FLE} \times R_{FLE} + AL_{RES} \times R_{RES} + AL_{CAP} \times R_{CAP} + AL_{ADA} \times R_{ADA} + AL_{FIS} \times R_{FIS} + AL_{DIS} \times R_{DIS} + AL_{VIS} \times R_{VIS} + AL_{EFF} \times R_{EFF} + AL_{ANT} \times R_{ANT} \tag{7.5}$$

SCV is the combined impact of all the vulnerabilities, whereas SCC denotes the combined impact of all the capability measures. Relevant AL and R values were calculated using Equation 7.2 and Equation 7.3.

(V) Finally, the balancing impact of SCC and SCV towards achieving SCR 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 & Pugh, 1981) and model validation is essential in SDM (Stearman, 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 (Stearman, 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 this chapter results. The results are further elaborated in the forthcoming sections.

7.4 Vulnerability Analysis of Supply Chain Phases

This section presents the outcomes generated and consequential discussions based on SNA of the IC supply chains. Figure 7.6 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 Figure 7.3 and Figure 7.6, 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.

The manufacturing and the on-site assembly phases are highly susceptible to the labor-related issues, which are very significant in IC. Loss of skilled labor is a highly influential vulnerability that reduces the performance of 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.

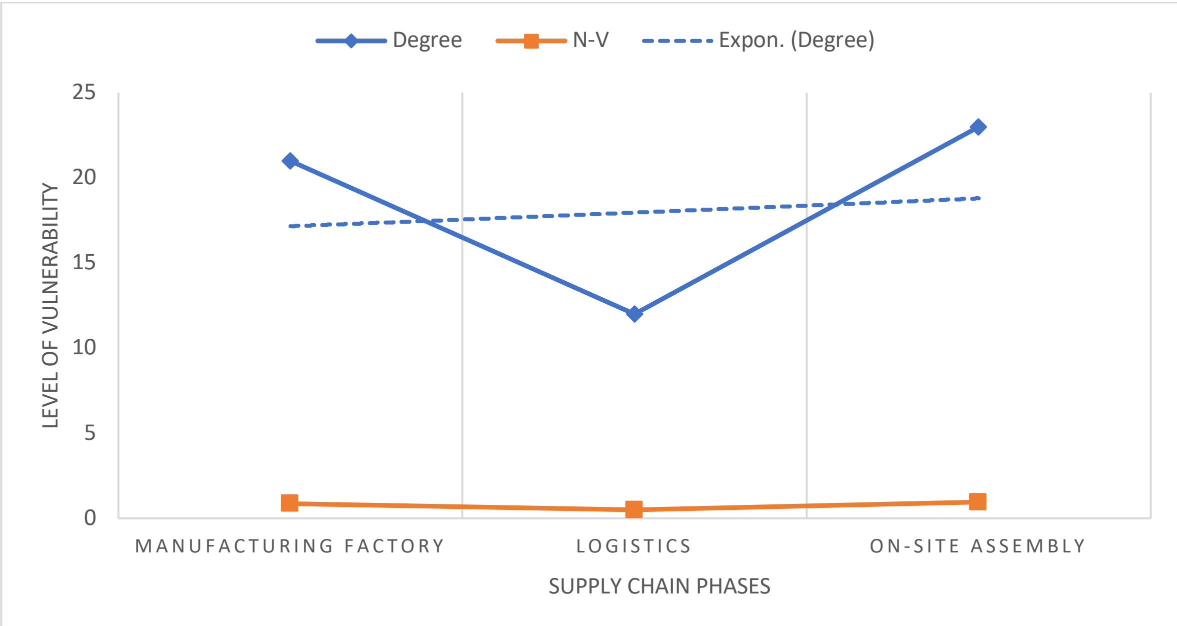


Figure 7.6: Vulnerability impact on each supply chain phase

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 Figure 7.3, the 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. 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.

7.5 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 SDM approach as explicated above. This modeling 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 (I) models were performed using the SyntheSim Simulate function of the Vensim software. Figure 7.7 shows the output generated for SCR levels in Case A and Case B. As shown in Figure 7.7, 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 SCR values.

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 Modeling (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.

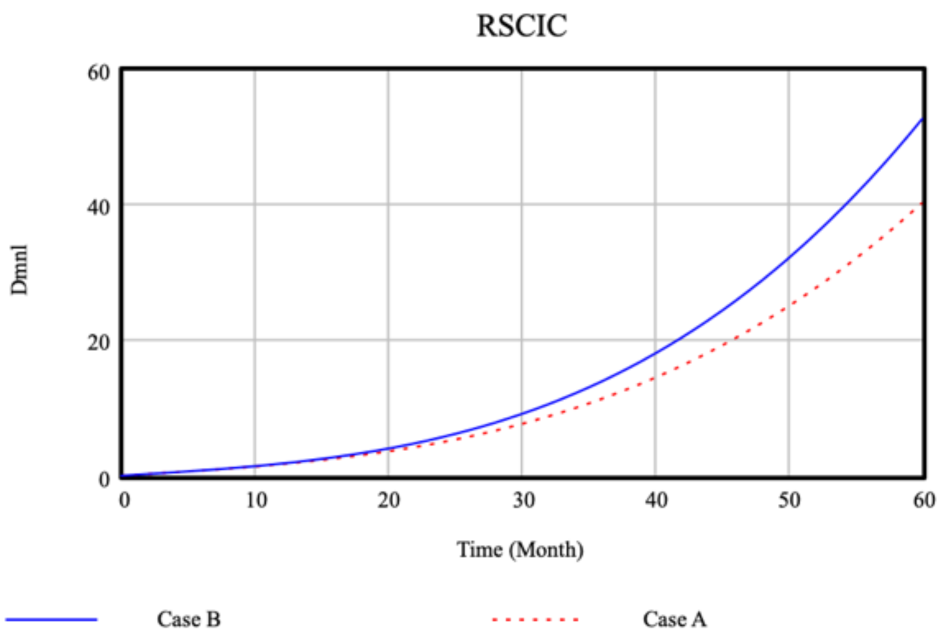


Figure 7.7: Comparison of SCR levels between Case A and Case B

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, Shen, & Kumaraswamy, 2020). Finally, more or less, all these capabilities and vulnerabilities contributed to achieving resilient supply chains in both Case A and B, where Case B seems to have a more resilient supply chain with its significant withstanding ability of SCV. However, both the projects need to initiate robust strategies to reach the 100% level of SCR, as suggested in the next section of this study.

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 SCR while maintaining all the other strategies at the baseline levels (graph of project A) as presented in Figure 7.8. The baseline scenario of this study yielded approximately 40% of SCR, as shown in Figure 7.8. However, all the strategies contributed to increased resilience. At the same time, the results suggested that anticipation can make the highest impact on SCR implementation by providing the valuable ability to detect potential supply chain disruptions in advance. In this construct, therefore, there should be adequate provisions for the deployment of tracking and tracing tools (Li et al., 2018c), quality control and intensive training (Ekanayake, Shen, & Kumaraswamy, 2020).

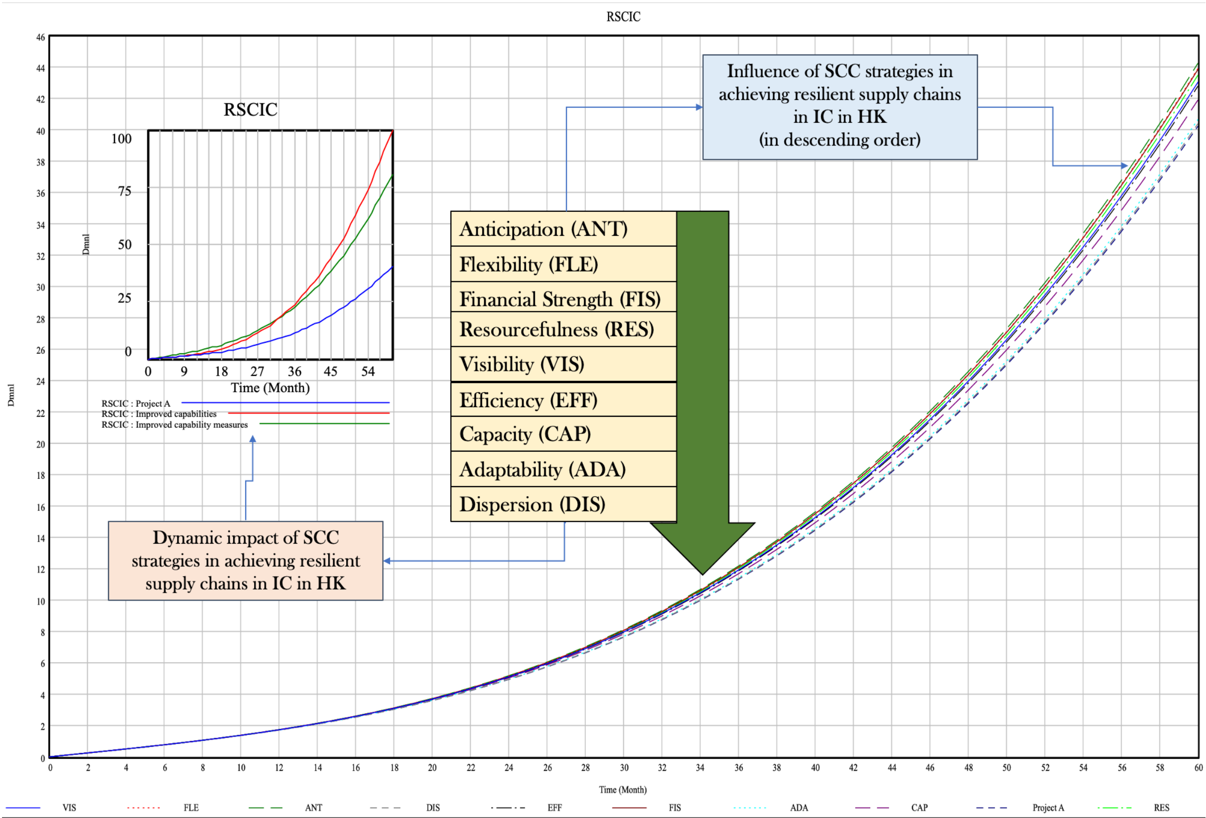


Figure 7.8: Influence of SCC components in achieving resilient supply chains in IC in HK

Further, as separate strategies, all the supply chain capability constructs contribute to increasing SCR 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, the dynamic impact of all the SCC strategies contributes to reaching SCR up to 90% with the dynamic impacts of SCV as depicted in Figure 7.8. 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, the outcomes of this study lead to suggesting the following strategies to install and/or upgrade supply chain resilience practices in IC in HK as explicated in the forthcoming section.

7.6 Strategies to Uptake SCR 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 in terms of 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.

7.6.1. Development of a Smart Software Package

Building information modeling (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 which is 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 and excessive resource waste, while enabling component quality certification and tracking of certified components. Precise selection of prefabricated units and knowing the right quantity to transport is essential to avoid disruptive stock management and to maintain appropriate production lead times. This is smoothly facilitated by 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 logistical processes. 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 realizing 'just in time delivery' of prefabricated components. Complex IC site logistics are likely to trigger acute disruptions due to limited space, safety 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 empower 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 optimal task allocation to vehicle drivers are among other associated merits. Most importantly, real-time traceability of vehicles facilitates accurate and frequent vehicle tracking, identifying and assessing of 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 SCR.

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 data security of the IC supply chain process 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 off-site, work done, and materials on-site through the system and can provide healthy cash flows for contractors without payment delays.

Therefore, introducing of a BIM+RFID+GIS+Blockchain integrated software package would be highly beneficial for enhancing SCR in IC while offering promising avenues to improve SCC of participating 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 support system, which could also withstand associated vulnerabilities more effectively. Further, remote inspection and record-keeping will also be advantageous since this reduces liability issues and provides for timely 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 and a potential strategy to enhance IC supply chains' resilient capacity in HK.

7.6.2. Enhance Interoperability of Software Used

While the aforementioned smart software package is vital in achieving SCR 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 fully developed, leave alone tried and tested 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 to integrate all these useful software with the existing enterprise resource planning systems of the organizations. Therefore, there is a need to enhance the interoperability of the software used, encouraging SCR in IC.

7.6.3. Extensive Use of Appropriate Technology

As a result of higher labor cost and loss of skilled labor in HK, the manufacturing of IC components is done in Mainland China. In these circumstances, the use of automated production lines will make the supply chain process more resourceful and efficient (by satisfying two major SCC components). 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 safeguards 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 minimize 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.

7.6.4. Maintaining In-house Prefabrication Yard and Increasing the Use of Modular Units

According to the findings of SDM, and as explicated above, the organization with its own prefabrication yard is more resilient to SCV than the other. In the case studies, the higher the vertical integration, the lower the cost implication, the lower the outsourcing and the 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 MIC 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.

7.6.5. 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 SCR in different industries (Liu et al., 2018; Mancheri et al., 2019). Further, it is clear that promotional policies should be influential in achieving SCR in IC in HK. Although policy support for modular integrated construction was announced in the Chief Executive's 2017 Policy Address (Hong Kong Special Administrative Region

Government, 2017), the policies regarding SCR implementation are not yet elaborated 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; standardized 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 relevant public policy drivers and related potential contributions from IC are expected to encourage and promote SCR uptake and improvements in IC in HK.

7.7 Chapter Summary

Chapter 7 was designed to investigate the dynamic impact of SCV and SCC in achieving SCR in IC in HK. First, this chapter determined the on-site assembly phase as the most vulnerable to the associated SCV. It was also identified that the logistics phase faces identical SCV compared to the other two supply chain phases, through SNA of data collected for this purpose. Thereafter, this study developed a causal loop diagram, stock and flow diagram and ran the simulation using SDM to investigate the dynamics of SCC 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 highly influential in fulfilling resilience requirements. Visibility, efficiency, capacity and adaptability show their moderate influence in targeting SCR, while dispersion was at the lowest point since the industry is already practicing dispersion measures to a greater extent in current practice, so there is no need to add this to fresh strategic initiatives.

Besides, effective strategies to uptake SCR practice in IC in HK were proposed, based on the two comparative case study findings and simulation results. These strategies consisted of: (i) develop a smart software package, (ii) enhance interoperability of software used, (iii) extensive use of appropriate technology, (iv) establish and maintain in-house prefabrication yard and increase use of modular units, and (v) uptake policy support. The primary contribution of this chapter to the SCR knowledge domain and industry is from modeling the dynamic impact of SCR and proposing strategies to uptake SCR in IC in HK, thereby also targeting the associated benefits of value-enhanced supply chain performance in IC. Indeed, the findings of Chapter 7 fulfil Objective 3 and Objective 4 of this research.

Chapter 8 Conclusion

8.1 Introduction

Chapter 8 concludes this research by revisiting the research aim and objectives and the outcomes in this context. While the topic of SCR is noted to be a horizontal concept since it straddles multiple disciplines and needs continuing close attention to meet many ‘moving targets’, this research targeted to explore SCR as specific to IC supply chains since the industry is increasingly seeking innovative solutions to enhance supply chain performance by withstanding the pressure of prolonged and tumultuous disruptions. Accordingly, the aim of this study and the research objectives were developed, and a systematic research approach was followed as detailed in the previous thesis chapters. Chapter 8 was designed in this regard to revisit and review the research aim and objectives; and to check whether they have been satisfied. Further, the key research outcomes are summarized in this chapter by highlighting the research contribution towards the body of knowledge and the construction industry. Finally, the limitations faced are discussed while revealing future research directions.

8.2 Review of Research Objectives and Summary of Research Findings

Organizations are presently experiencing and envisaging prolonged supply chain disruptions, arising from COVID-19. This recent pandemic further reminds organizations of the need to rethink their plans and decision making to survive these tumultuous vulnerabilities. These SCV can persist for prolonged periods and can propagate to other supply chain tiers and links, in a ripple or cascading effect. Furthermore, due to extensive outsourcing, most supply chains are now also vulnerable to weaknesses and complexities in their ancillary supply chains.

Therefore, the attention of many leading economies worldwide, including in HK has been re-focused on strategies and methodologies to reduce the vulnerability levels of supply chains, while also safeguarding these supply chains from exploitation. Being a pivotal contributor to HK's economy, the construction industry has been targeting value-enhanced performance. In this context, IC has emerged as an attractive construction approach, providing an environment-friendly, better quality, cleaner, and safer working environment. IC requires resilient and robust supply chains, since employing on-site assembly of prefabricated components produced in factories outside HK. The recent progression to Modular integrated Construction (MiC) enables the assembly of volumetric units or models onsite with the advantages of reduced construction time, reduced labor usage, better quality, enhanced safety and productivity, and reduced exposure to external services with greater sustainability as identified in the literature and practice. However, the inherent complexity and fragmented nature of IC supply chains often lead to disruptions and reduced performance levels.

Stepping back to the general context, 'supply chain resilience' has been introduced as a game-changing supply chain management goal and approach, which is a better alternative to traditional risk management practices, opening up robust pathways to withstand common SCV. Such resilience targets become viable if deploying adequate and appropriate SCC, which are critical measures of SCR. In addition, supply chain networks vary according to their geographical context in different ways that can shape their types and levels of vulnerability in general. This research addresses the need for a specific study to investigate IC supply chain behavior in HK. The construction industry is unique, and the supply chain configuration of the construction projects is distinctive. Since IC is developed by incorporating advances in offsite manufacturing practices, IC supply chains are more complicated than in traditional construction practices, for instance, as they extend to encompass the supply chain phases of factory-manufacturing, logistics and on-site assembly. Also, the type of manufactured unit, corresponding supply chain configurations and levels of 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. The types and levels of vulnerabilities in supply chains, and manufacturing and delivering such different unit types would thereby differ. In the HK context, all the prefabricated units are presently transported from Mainland China; hence supply chains are also commonly affected by transportation and cross-border logistics-related vulnerabilities compared to the other jurisdictions as discussed in detail in the previous chapters. Therefore, suitably focused jurisdiction-specific studies are critical in detecting appropriate supply chain capability imperatives to ameliorate jurisdiction-specific supply chain vulnerabilities.

Moreover, it is essential to clear pathways to enhance the resilience capability of IC supply chains to address the current performance conundrum faced by the industry in general. Given this background and rapidly changing conditions, this study aimed to develop and propose strategies to enhance supply chain resilience in IC through developing a dynamic model to assess SCR in IC in HK. Further, four research objectives were established to attain the research aim and stated in Chapter 1 as follows.

1. Identify supply chain vulnerabilities and capabilities as critical measures of supply chain resilience in industrialized construction
2. Develop mathematical models to assess supply chain vulnerabilities, supply chain capabilities and their correlational impacts
3. Develop a dynamic SCR evaluation model for industrialized construction in Hong Kong via probing and assessing relevant supply chain vulnerabilities and capabilities
4. Propose strategies to enhance supply chain resilience in industrialized construction in Hong Kong

The main aim, including all the individual objectives, were achieved using appropriate research methods and techniques explained in Chapter 2. The research methods included but were not limited to, a systematic review of literature, expert surveys and interviews, comparative case studies, site visits and several advanced data analysis techniques. The succeeding sections present the primary research outcomes and conclusions for each research objective. More importantly, this study is the first known empirical study that explored the SCR concept in the IC context. Also, this research contributes significantly not only to the SCR knowledge domain but also to improve the industry practice and outcomes of IC and benefits therefrom. Notably, the findings of each of the stipulated objectives offer very useful and practical implications towards withstanding of SCV while improving SCR in IC, specifically targeting a high-density, dynamic and highly developed jurisdiction of Hong Kong.

Objective 1: Identify supply chain vulnerabilities and capabilities as critical measures of supply chain resilience in industrialized construction

Two comprehensive and systematic reviews of literature through meta-analysis were conducted to identify the vulnerabilities and capabilities (separately) as critical measures of supply chain resilience in IC. At first, this study reviewed the various identified SCV over the past 20 years. Thirty-seven vulnerabilities were identified after rigorous screening in this systematic review. These publications were also, examined and analyzed in terms of annual publication trend, the trend of publications by the country, methodological approaches adopted in previous research exercises, and thematic categorization of the vulnerabilities to receive a deep understanding on the knowledge development in this domain.

The results revealed that 2017-2018 was the year with the highest number of supply chain vulnerability related publications, and the USA was the country that had the highest publication frequency. Following the thematic analysis process, an appropriate action framework was developed for addressing the identified SCV in IC consisting of six constructs, namely, Project Organizational; Procedural; Supplier/customer; Technological; External Environmental; and Financial Vulnerabilities and suggesting the requirement of appropriate capabilities to withstand them.

Similarly, the second planned review was conducted to draw on relevant examples of SCC that have been previously pursued in different industries to withstand numerous SCV. Fifty-eight SCC measurement items were identified by analyzing 44 selected articles during this review. These articles were comprehensively analyzed to determine the number of publications annually, publications by country, methodological approaches followed in the previous research studies, and thematic categorization of SCC. The results unveiled 2018 as the year with the highest relevant publications, while the USA was the country that contributed to the highest number of such publications.

Following the thematic categorization process, a proposed framework for targeting SCR in IC was developed, including 12 supply chain capability constructs, namely, flexibility, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, market position, security, and financial strength. Both the identified SCC and the developed constructs facilitated an overview of SCC to enhance possible future developments of SCR in IC and provided a platform for further empirical studies to realize other research objectives. Indeed, these two review processes are described in detail in thesis Chapter 3 and satisfied the research Objective 1, which was to identify the vulnerabilities and capabilities which are the critical measures of supply chain resilience in IC.

Objective 2: Develop mathematical models to assess supply chain vulnerabilities, supply chain capabilities and their correlational impacts

To satisfy Objective 2 of this research, first, a supply chain vulnerability assessment model was developed as elaborated in Chapter 4 by applying statistical analysis and fuzzy set theory to in-depth data that was collected for this purpose. To this end, empirical research was conducted, leading to 76 questionnaire responses and interview findings from industry experts and experienced practitioners who worked/ are working in IC projects in HK. The results revealed

26 CSCV as appropriate to the IC supply chains, while 'loss of skilled labor' was identified as the most influential supply chain vulnerability. Variations/rework and communication issues were identified as the second and third CSCV.

Based on these extracted 26 SCV, this study further analyzed the professional judgements of experienced IC experts to evaluate the probability and the severity of SCV using the useful and established methodology of factor analysis. Twenty-four factors emerged as especially critical in IC in HK. Factor analysis enabled a well-justified grouping of these CSCV into five underlying components, namely, economic, technological, procedural, organizational and production-based. Next deploying a soft computing approach for FSE, a multi-level-multi-criteria fuzzy mathematical model was developed to assess the overall impact of vulnerabilities. The model showed that the overall impact is 3.36 (on a scale from 1 to 5), indicating the IC supply chains are considerably vulnerable to the disruptions. Production-based vulnerabilities (impact-3.52) had the highest impact among the components. Although the economic component showed a higher variance percentage, the highest influential component was the organizational SCV with the highest mean score value, highlighting its significance in IC in HK.

Second, a supply chain capability assessment model was developed as elaborated in Chapter 5 by applying statistical analysis and fuzzy set theory to in-depth data that was collected for this purpose. Using a list of 57-measurement items extracted from an exhaustive literature review (Chapter 3), this study solicited the professional judgements of experienced IC experts to evaluate the level of importance and the current practice level of SCC in improving the SCR of IC in HK. Forty-one measurement items remained critical and were, therefore, considered in the factor analysis after the data normalization and the necessary statistical analysis process. Thereby, the factor analysis resulted in the well-justified grouping of these measurement items into nine CSCC components of resourcefulness, flexibility, capacity, adaptability, efficiency, financial strength, visibility, anticipation and dispersion. Although the component 'flexibility' received the highest variance percentage, 'efficiency' was the component with the highest mean score.

A soft computing approach- Fuzzy Synthetic Evaluation (FSE) was then conducted, and multi-stage fuzzy mathematical models were separately developed to assess the criticality and the current practice of SCC in IC in HK. An importance index of 4.11 showed that the identified capabilities are critical in achieving resilient supply chains. In contrast, a current practice index of 3.54 indicated that there is a wide gap to be bridged in realizing the benefits associated with SCR in IC in HK. Efficiency component (importance index: 4.19) has the highest impact among all the SCC, while dispersion is the most in practice (3.89). However, there is a gap between the current practice and importance levels in each of the SCC components, as was revealed in the research outcomes.

Third, it was attempted to investigate the impact of supply chain capabilities to withstand supply chain vulnerabilities targeting resilience IC supply chains. Therefore, this study developed a statistical PLS-SEM model to evaluate the impact of SCC on SCV in achieving resilient supply chains in IC in the dense urban setting of HK. Relevant data were gathered through an expert survey involving seventy-six industry professionals who possess the required experience and knowledge on IC practices in HK. The results indicated that the SCC construct of resourcefulness has the highest significant impact on withstanding production-based SCV, which are very critical in this context. Also, there were six other significant paths; resourcefulness related SCC can help to withstand economic, organizational and procedural SCV; capacity-related SCC can help to withstand production-based SCV; dispersion related SCC can help to withstand economic SCV; and flexibility related SCC can help to withstand economic SCV. Hence, resourcefulness, capacity, dispersion and flexibility were determined as the highly influential SCC in developing resilient supply chains in IC in HK.

Indeed, these three assessment models developed under this research are described in thesis Chapter 4, Chapter 5 and Chapter 6, respectively. Specifically, the research outcomes generated in thesis chapters 4, 5 and 6 fulfilled the research Objective 2, which was to develop models to assess supply chain vulnerabilities and supply chain capabilities and investigate the impact of supply chain capabilities to withstand supply chain vulnerabilities in IC in HK.

Objective 3: Develop a dynamic SCR evaluation model for industrialized construction in Hong Kong via probing and assessing relevant supply chain vulnerabilities and capabilities

Given that resilience is a strategic imperative in IC supply chains in HK and noting the research lacuna in modeling the SCR impact, this study investigated the effect of SCC in strategies to boost SCR in IC with the help of modeling techniques such as system dynamics and social network analysis, depending on the material being probed. First, under this research objective, the level of vulnerability of each supply chain phase of IC was identified through SNA modeling. Accordingly, it was found that the onsite assembly phase is the most vulnerable to the associated SCV, and the logistics phase faces identical SCV compared to the other supply chain phases.

This led to the development of a causal loop diagram, a stock and flow diagram and then to running the simulation using SDM to investigate the dynamics of SCC in realizing resilient supply chains in IC. It was 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 showed their moderate influence targeting SCR. 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. These findings significantly contribute to the SCR knowledge domain and towards the industry practice as described in the succeeding sections of this chapter. Besides, the research outcome generated in thesis Chapter 7 satisfied the research Objective 3, which was to develop a dynamic SCR evaluation model for industrialized construction in Hong Kong via probing and assessing relevant supply chain vulnerabilities and capabilities.

Objective 4: Propose strategies to enhance supply chain resilience in industrialized construction in Hong Kong

With respective to thesis Objective 4, two comparative case studies were conducted using two real-time IC projects in HK. These case studies enabled the identification of the real-life practice of SCC in IC supply chains in HK, vulnerability levels of IC supply chains towards disruptions, as well as the verification of the dynamic model developed under Objective 3. The findings suggested that Case B is more resilient than Case A because of the inherent capabilities of the supply chain 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 based on the case study findings. 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. Hence, this research finally satisfied the research Objective 4, which was to propose strategies to enhance supply chain resilience in industrialized construction in Hong Kong with the outcomes made in thesis Chapter 7. All these research outcomes taken together, thus successfully fulfilled the research aim derived in this thesis: to develop and propose strategies to enhance supply chain resilience in IC through developing a dynamic model to assess SCR in IC in HK.

8.3 Contributions of the Research

This study makes significant theoretical and practical contributions to the knowledge domains of SCR and IC in several aspects as follows. First, this study identified and presented a set of SCV and SCC as specific to the IC under the umbrella of SCR. The envisaged action framework developed in Chapter 3 based on the identified SCV and SCC should prove vital to the stakeholders of IC supply chains and other industry practitioners in formulating appropriate and adequate capability measures needed by resilient supply chains. Also, the identified IC-specific SCV and SCC would deliver a package of useful information and add basic new knowledge for academia and industry to instigate more profound research and focused development (R&D) of capacity development initiatives for SCR in IC. Given the increasing use of IC worldwide, e.g., the surge of 'modular' construction in many countries, this study set out to cross-refer relevant identified general SCC with IC supply chains and SCV, and hence, provide both academic researchers and industry practitioners with a comprehensive list of potentially useful SCC to be incorporated into their future studies and practices that target enhanced SCR.

Second, the research findings of Chapter 4 contribute substantially to both practice and theory by providing pointers to determine the level of criticality of the vulnerabilities, drawing the attention of industry professionals to suitably address critical SCV by developing value-enhanced, resilient supply chains in IC in HK. Besides, the identified five SCV components unveil the underlying groupings of critical SCV that can be addressed together to increase the SCR. The originality and significance of the present findings are heightened by more severe constraints encountered in the particularly high-density/high-rise urban setting in HK; and where cross-border logistics are also necessitated in IC projects.

Further, advanced supply chain management strategies, including the recent advances in SCR, are widely adopted in today's competitive economy. Their successful implementation has proved effective in handling unpredictable supply chain disruptions. Hence, achieving resilient, sustainable supply chains is seen to be important from the organizational level. From this viewpoint, it has become necessary for the professionals involved in IC in HK, to evaluate, check and compare SCV affecting overall supply chain performance before initiating appropriate measures to withstand them. This further includes investigating poorly performing areas of the supply chain network, so as to target better management, and future improvements, even major reforms. In these circumstances, industry stakeholders, especially the managerial level professionals can adopt the proposed FSE based soft computing approach (presented in Chapter 4) in which vulnerability assessment is developed, based on the linguistic judgement of industry experts. This was appropriately generalized for the IC context in HK using fuzzy triangular numbers via a predefined fuzzy scale in determining vulnerability levels of the industry.

Moreover, this multi-criteria-multi-level framework would facilitate effective planning and decision making by the project managers, starting with sufficient identification of SCV with their respective levels of probabilities and severities; leading to successful decision making on developing appropriate organizational capacities to withstand them. Therefore, this can be considered to be a momentous milestone along the road to achieving SCR in IC in HK that is by establishing an FSE model to evaluate the overall impact of the SCV. This fuzzy model could be helpful to industry professionals whenever they plan to assess their supply chain uncertainties further, in order to uplift the overall performance of IC in HK. Indeed, this fuzzy

SCV assessment model developed for IC contributes to the related theory by being the first known evaluation model under this IC context and utilizing fuzzy synthetic evaluation to assess SCV in the construction research domain.

Third, the findings of Chapter 5 on SCC are beneficial in the following aspects. The contribution of critical SCC findings can be taken as twofold. On the one hand, they provide an in-depth understanding of critical SCC related to IC in HK, and on the other hand, they enable assessment of the relative levels of the criticality of the grouped critical supply chain capability measurement items. All identified nine components could be focused upon, for improving practice as specific components under common themes and influence different stages of supply chain processes. Besides, it is essential to the professionals involved in IC in HK to evaluate, check and compare SCC for improving the overall supply chain performance, highlighting an evaluation model for SCC. This also needs supply chain capability initiatives targeting organizational reforms and better management, along with necessary future improvements. Under these circumstances, the industry practitioners, especially the managerial level professionals, could be motivated to use the proposed FSE based soft computing approach in which capability assessment is established based on the linguistic judgement of industry experts. Furthermore, this approach was appropriately generalized for the IC context in HK using fuzzy triangular numbers with the use of a predefined fuzzy scale in determining the levels of importance and of current practice indices of SCC of the industry.

Moreover, the developed multi-stage fuzzy assessment models would facilitate successful decision-making and problem-solving tools not only by identifying the appropriate level of SCC practices but also by determining the current practice gap. The performance indices are mostly subjective, bearing some sort of ambiguity and vagueness in the decision-making. However, fuzzy set theory helps to overcome such subjectivity and uncertainty in decision-making. Hence, this study proposed the aforesaid hierarchical evaluation models with multiple performance indices to estimate the extent of the SCR. These evaluation models will further point industry practitioners towards implementing appropriate strategies to remain adaptive in the turbulent IC supply chains by improving the overall performance of the supply chain network. Also, evaluating the perceived importance *vs* current practice levels of SCC in IC projects in HK empowers practitioners to plan and utilize suitable strategies at appropriate levels to boost SCR.

On the other hand, academic and industry researchers and practitioners are encouraged to explore more comprehensive SCR evaluation models based on their specific regional or industry contexts based on the research exercise done in Chapter 5. Hence, Chapter 5 fulfils its original purpose of developing and demonstrating an evidence-based and viable methodology for decision-makers in assessing and improving SCC in IC in HK. Therefore, it is emphasized that Chapter 5 constitutes a significant milestone in the journey to establish FSE models to evaluate the overall performance of SCC in achieving SCR in IC in HK also, by creating considerable theoretical knowledge in SCR knowledge domain.

Fourth, the results and the PLS-SEM model generated in Chapter 6 could be of great value for industry professionals, researchers, and policymakers who are seeking evidence-based quantitative justifications and explanations regarding the influence of SCC towards SCR in IC in HK. A sound awareness of significant SCC and SCV, and their correlation can be critical in making decisions in adopting SCC appropriately to the practice. The key contribution of Chapter 6 to the SCR knowledge domain is in developing a quantitative model that illustrates how various types of SCC help achieve SCR by effective withstanding of strong SCV in the IC sector. Industry practitioners could thereby map these capabilities with the corresponding SCV and deploy SCC at suitable levels and appropriate doses to withstand those corresponding

SCV. This unsurprisingly benefits from drawing upon lessons learned, hence being enriched by the combination of relevant best practices from both traditional construction and manufacturing. Theoretically, Chapter 6 findings also contribute to the SCR and IC knowledge domains by initiating novel research approaches and proposing a model that explains how various SCV and SCC influence in achieving resilient supply chains in IC. This further expands the existing SCR research domain by extending its potential applications in the construction sector. In addition, the research methods employed in Chapter 6 and the model developed there can be used as useful references and platforms for other jurisdictions where IC is widely practiced. Thereby, industry professionals may develop such impact analysis models as appropriate to their industry contexts by considering jurisdiction-specific supply chain dynamics.

Fifth, the major research findings generated in Chapter 7 provide evidence-based pointers to project professionals based on a validated system dynamics model to initiate well-focused performance-enhancing measures to achieve SCR in IC. Theoretically, the findings depicted the conceptual relationship between SCC and SCV under the phenomena of resilience. The relationship between SCC and SCV were examined later in this study and established how these supply chain 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 or minimized. Revealing of SCV associated with each supply chain phase together with their vulnerabilities is highly beneficial to the industry professionals to enhance appropriate protection in each supply chain phase. Also, analysis of supply chain dynamics through SDM spotlighted to industry professionals that there is a huge room for improvement under the SCC of anticipation, flexibility, financial strength, and resourcefulness, indicating that their practice should be improved and highly influential in fulfilling resilience requirements in IC in HK. Furthermore, the capabilities of visibility, efficiency, capacity and adaptability should be moderately improved in practice, given that their moderate influence towards SCR in IC in HK.

Finally, and most importantly, this research contributed useful strategies, namely, the use of a smart software package, enhanced interoperability of software used, extensive use of appropriate technology, maintaining an in-house prefabrication yard and increasing use of modular units, and policy support to enhance the resilient capabilities and boost SCR in IC in HK based on real-life case study findings.

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 known study which was 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 modeling in supply chain resilience analysis. Indeed, this study contributes significantly to research in prefabricated construction by proposing the first known 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 known application of social network analysis in the supply chain resilience knowledge domain in vulnerability analysis. Furthermore, this is the first known attempt to assess the vulnerability level of each IC supply chain phase as well. Besides, proposing the first set of useful strategies to uptake and improve resilience in IC supply chain practices, is highly beneficial as a starting point 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.

8.4 Limitations of the Research

Although this study offers a significant contribution to the IC knowledge domain, some perceived limitations of this study are worth noting. The research findings and conclusions should, of course, be viewed in the light of the research assumptions and limitations faced and how the latter were addressed. The sample size of the respondents was relatively small in this study. The researcher attempted to counteract, if not overcome this constraint by conducting interviews with the respondents without limiting to only a questionnaire survey. This boosted the interpretation and reliability of the results. However, subsequent studies may increase the response rate for enhanced generalization of the results and case study based real-time justifications would facilitate verification of the results. In addition, although the sample size used here was fully justified in the research method section and was representative of the relatively small 'population' of experts on IC in HK, the use of big data from a bigger sample of a larger future population, could enable the development of more precise SCR models. Further, this study established the FSE theory and protocols for SCV and SCC analysis by demonstrating a successful and useful application. It is also observed that FSE has been critiqued for a possible limitation of obtaining a crisp priority vector from a triangular fuzzy comparison matrix. In addition, the fuzzy mathematical models and the PLS-SEM model developed in this research are not verified through case study justifications. Hence, future studies may seek more rigorous computational methods to derive impact indices with the use of big data and to develop verified models in this regard as a 'Research and Development'(R&D) exercise.

The SDM results were verified and discussed based on two comparative case studies in HK due to time resource and access constraints. More projects can be included in an extended sensitivity analysis exercise to generate better and widely applicable results. Non-generalization of the results may be another limitation associated with this study. The nature of supply chains and their dynamics differ in different 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, and given HK's specific socio-economic background, the parameters and calibration of these models 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, used and proposed in this research to ascertain the generalized results while drawing lessons to be learned from different country contexts. The associated vulnerabilities, capabilities and their levels of criticality would necessarily differ, although some exciting core commonalities may hopefully emerge. Hence, country-specific case-studies would enable more relevant and robust results while helping to verify the findings generated in this study. Also, the factors studied in this study may not be the only factors that affect the dependent variable. Still, there could be other potential factors, and their omission may potentially lead to unobserved heterogeneity and biases of the estimates in the models.

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, the researcher 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 modeling can be undertaken to determine the impact of Covid-19 towards IC supply chains in HK itself as well, noting that resilience imperatives may increase while conditions may also change.

8.5 Future Research Directions

The identified vulnerabilities and capabilities can be evaluated and validated for IC using subject matter expert surveys and case studies covering different cultural dimensions. Industry practitioners from different jurisdictions can consider this research as a basic guideline for enhancing SCR measures in their organizational capacities. Further, the commercial relationships between supply chain partners/members could be investigated since a deep understanding of these, and the underlying economic exchange and transactional profiles may be needed before addressing specific vulnerabilities arising from typical (e.g., skewed/

asymmetric, even seemingly unfairly weighted or 'unbalanced') commercial relationships that have developed from standardized contracts and/or standard practices.

Future studies may also give greater weightage to the type of special vulnerabilities that surfaced with the rapid spread of the COVID-19 virus at the time of completing this study, and drastically affected global supply chains in most industries. Besides, a factor-wise impact evaluation model of SCC could be computed, which will generate a robust and even more comprehensive output. It is also encouraged to update the developed models by incorporating upcoming, e.g., post-COVID19 industrial innovations and initiatives to feed into timely recommendations.

In addition, the models developed here are generic to the IC supply chains in HK, rather than focusing on any specific types, such as modular integrated construction. Hence, future studies may especially focus on specific IC types. Also, reliability testing of the decision-support models is encouraged as a further study direction while deploying more rigorous computational methods to generate indices with the use of big data.

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 the support from policymakers and industry leaders. Besides, SCR aspects can be linked with 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 generate 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.

Finally, this study confirms SCR to be a well-timed strategy to boost supply chain performance in IC in HK since the industry is now facing acute challenges due to unforeseen disruptions and an aggravated performance conundrum. Meanwhile, the results from this study, being rigorous and pragmatic, while grounded on proven principles, can help upgrade current IC practices to a level of reasonable resilience, thereby realizing the main target of cleaner and sustainable construction. In conclusion, the unprecedented supply chain disruptions caused by the global COVID19 pandemic, albeit after the data collection and analysis for this study, showed how crucial it is to develop a suite of capabilities that can cope with even previously unimagined specifics, even if within the scope of identified general vulnerabilities.

Annexure A
Research Questionnaire

To whom it may concern

Dear Sir/Madam

Invitation to participate in a research on 'Supply Chain Resilience in Industrialised Construction'

As a respected practitioner with knowledge of supply chain management in general, and in prefabricated construction, you are cordially invited to complete the attached questionnaire for a Ph.D. research entitled "Supply Chain Resilience in Industrialised Construction." This research is sponsored by The Research Grants Council (RGC) of Hong Kong through the Hong Kong Ph.D. Fellowship Scheme and The Hong Kong Polytechnic University's Postgraduate Studentship Scholarship. This research is supervised by Professor Geoffrey Qiping Shen and co-supervised by Professor Mohan Kumaraswamy.

The overall research aims to explore the vulnerabilities and capabilities as the measures of supply chain resilience in industrialised construction and to develop a model to enhance the supply chain resilience in industrialised construction, thus, improving the industrial performance. The questionnaire is simple and takes approximately 25 minutes to complete**. Of course, there are no wrong or correct answers, only your much-needed opinions.** All your responses will be treated with strict confidentiality and used only for academic purpose.

We understand that this survey will consume some of your precious time, but this research will not be successful without your expert opinions. **Lastly, we would be grateful if you can forward the questionnaire to other professionals, who you know have a wealth of experience or knowledge of this topic.** Many thanks for your kind consideration. For any inquiries, please contact Miss Anushika (Tel.: +852-6765 ; and email: anushika.ce.ekanayakemudiyanselage@) or Professor Geoffrey Qiping Shen (email: bsqpshen@). Your views are valuable to the success of this research. After the research, we are willing to share a summary of the outcomes with practitioners and anyone who shows interest.

We would be grateful if you could complete and return the questionnaire to the researchers within **one week**. Thank you again for your kind consideration.

Yours sincerely,

…………………………………

Ekanayake Mudiyanselage, Anushika CE, Ph.D. Student
Professor Geoffrey Qiping Shen, Interim Vice President (Student Affairs)
Chair Professor of Construction Management
Academic Discipline Leader of Construction & Real Estate Management
The Hong Kong Polytechnic University, Hong Kong

Supply Chain Resilience in Industrialized Construction - Questionnaire Survey

Please tick ("√") to indicate your opinions.
<u>Information of Participants (Subject matter experts)</u>

1. Your current professional affiliation: ☐ Public sector ☐ Private sector ☐ Both

2. Work Organisation: ☐ Contractor ☐ Manufacturer ☐ Client ☐ Designer ☐ Transporter
   ☐ Other please specify____

3. Your working experience in the construction industry:
   ☐ 1-5 years ☐ 6-10 years ☐ 11-20 years ☐ Above 20 years

4. Current position in organization: ☐ Director ☐ Senior Manager ☐ Manager ☐ Other staff

Question:
1. To what extent is the industrialised construction supply chain vulnerable to the following events?
2. What is the probability of occurrence of the event?

	Vulnerabilities	**1. Level of vulnerability** 1= Not vulnerable to 5= Highly vulnerable	**2. Probability of occurrence** 1= Improbable to 5= Highly probable
1	**Project Organisational Vulnerabilities**		
	Labor strikes/disputes	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Communication breakdown/issues	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Loss of skilled workforce	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Closing/selling off the organisations	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Loss of trust/fraud	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Disruptions due to outsourcing	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Poor project definition	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
2	**Procedural Vulnerabilities**		
	Transport disruptions including port stoppages	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Quality loss	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Variations and/or rework	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Utility disruptions i.e. electricity, water	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Systems/machines breakdown	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Safety issues	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Site inventory losses/theft	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Energy scarcity	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
3	**Supplier/Customer Vulnerabilities**		
	Supply-demand mismatch/shortages	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Inadequate supplier selection	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Forced take over by the client	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
4	**Technological Vulnerabilities**		
	Information loss	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Technology failure	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Information misuse	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Inadequate IT systems	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	IT system failure	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5

Question:
1. To what extent is the industrialised construction supply chain vulnerable to the following events?
2. What is the probability of occurrence of the event?

	Vulnerabilities	1. Level of vulnerability 1= Not vulnerable to 5= Highly vulnerable	2. Probability of occurrence 1= Improbable to 5= Highly probable
5	**External Environmental Vulnerabilities**		
	Natural disasters	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Terrorism/war	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Political economy changes	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Adverse weather	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Implication of new laws/regulation	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Industry/market pressures	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Epidemics/viruses/bacteria	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Physical damage to the buildings/accidents (eg: fire, boiler explosion)	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
6	**Financial Vulnerabilities**		
	Financial loss in the supply chain	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Price fluctuations	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Exchange rate fluctuations	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Liability claims	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Cost overrun	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Economic crises	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5

Question:
3. How important are the following supply chain capabilities for industrialised construction?
4. What is the CURRENT level of application of these capabilities?
"We" is pointed to the organization that you belong

	Capabilities	3. Level of importance 1= Not Important to 5= Very Important	4. Level of application 1= Strongly Disagree to 5= Strongly Agree
1	**Flexibility**		
	Our products include modular product design	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Our resources can be used for multiple times	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Our supply contracts can be easily modified to change specifications, quantities and the terms	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have many alternative suppliers/sources	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have alternate distribution channels/transportation	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have mechanisms to share our risks	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have the flexibility to stop or postpone the prefabricated units' production	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We control more than one stage of the supply chain	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have integrated inventory management with SCM	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
2	**Capacity**		
	We have excess capacity of materials, equipment & labor	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Disruption happens at one stage may not breakdown the entire system	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have alternative equipment for backup	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have reliable back-up utilities (electricity, water)	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5

Question:

3. How important are the following supply chain capabilities for industrialised construction?
4. What is the CURRENT level of application of these capabilities?
   "We" is pointed to the organization that you belong

	Capabilities	3. Level of importance 1= Not Important to 5= Very Important	4. Level of application 1= Strongly Disagree to 5= Strongly Agree
3	**Efficiency**		
	We have effective methods to reduce waste	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Our labor productivity is very high	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We take preventative measures to avoid variations and rework	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Our product is reliable and not prone to failures	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
4	**Visibility**		
	We have real-time data on location and status of supplies, finished goods, equipment and employees	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We are highly aware of future trends in the industry and the behavior of our competitors, technologies & markets	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have efficient IT system & information exchange	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We adapt transparent e-procurement system	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
5	**Adaptability**		
	We have fast rerouting of requirements when disruptions occurred	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We take actions to leadtime reduction of the operations	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We conduct process simulation to facilitate adaptability	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We develop innovative technologies to improve our operations	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We learn from experience	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We use IT based reporting tools	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We maintain buffer time in between the operations	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We conduct parallel operations	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
6	**Anticipation**		
	We use early warning signals	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We employ demand forecasting methods	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We adhere a formal risk management process	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We conduct trainings to deal with disruptions	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We deploy tracking and tracing tools such as RFID/QR code/Bar code	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We monitor quality control	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We conduct disruption management research	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
7	**Dispersion**		
	Our organisation empowers on-site experts to make key decisions	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Our production facilities are at various locations	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Our inputs are from a network of suppliers	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
8	**Recovery**		
	We have a professional response team to handle disruptions	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have an effective communication strategy to deal with unexpected situations	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We adopt prompt consequence mitigation strategies	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5

Question:

3. How important are the following supply chain capabilities for industrialised construction?
4. What is the CURRENT level of application of these capabilities?
   "We" is pointed to the organization that you belong

	Capabilities	3. Level of importance 1= Not Important to 5= Very Important	4. Level of application 1= Strongly Disagree to 5= Strongly Agree
9	**Collaboration**		
	We encourage collaborative decision making	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We encourage collaborative forecasting	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We obtain competitive price from suppliers/ subcontractors	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We procure materials globally	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have public-private collaboration in doing projects	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
10	**Market position**		
	Our products/services have a strong reputation for quality	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have a very good market share	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Our firm has healthy long-term relationships with each of our clients	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Our projects provide faster delivery of the construction	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
11	**Security**		
	We have adequate cyber-security/information security	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have adequate personnel/resources security	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
12	**Financial strength**		
	We have strong financial reserves/funds	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We have a good insurance coverage	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	Our financial portfolio is very diverse	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5
	We maintain a good price margin to deal with uncertainties	☐1 ☐2 ☐3 ☐4 ☐5	☐1 ☐2 ☐3 ☐4 ☐5

Please, if you would like to receive a summary of the research findings, kindly provide your NAME and the EMAIL address

***Name:* _________ *Email Address:*_**

-The end-

Please, thank you for participation

Annexure B
Interview Questions

1. Most common vulnerabilities faced.
2. Impact of them.
3. Mitigation Strategies adhered.
4. A. how do you prepare for the disruptions?
   b. What security measures that you take to protect against treats?
   c. How do you predict them?
   d. How do you decide the possible response plan?
5. Please provide some examples for the disruptions.
   a. When?
   b. Did you have any warning?
   c. How was the disruption first identified?
   d. Who identified?
   e. Who affected?
   f. Did you prepare?
6. Impact
   a. What was the immediate impact?
   b. Is this happen very often?
7. Response
   a. Initial response?
   b. Was that successful?
   c. Any action made it worse?
   d. When it totally solved?
8. Recovery
   a. Key roles you played?
   b. Did you inform this to your client?
   c. Did you modify the early response plan?
   d. Did you identify the root cause of the problem?
9. Any long term impacts?
10. Learning
    a. Did you create a report?
    b. Did you communicate the lessons learn to the others?
    c. How the firm changed after the event?
    d. How other SC members helped you to tackle?
    e. Do they provide future insights?

References

Abdul-Karim, J. (2008). Strategies of effective project delivery system. *School of Professional and Continuing Education, University Technology Malaysia*.

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

Ahmad, S. B. S., Mazhar, M. U., Bruland, A., Andersen, B. S., Langlo, J. A., & Torp, O. (2020). Labour productivity statistics: a reality check for the Norwegian construction industry. *International Journal of Construction Management, 20*(1), 39–52.

Aibinu, A. A., & Al-Lawati, A. M. (2010). Using PLS-SEM technique to model construction organizations' willingness to participate in e-bidding. *Automation in Construction, 19*(6), 714–724.

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

Akintoye, A., McIntosh, G., & Fitzgerald, E. (2000). A survey of supply chain collaboration and management in the UK construction industry. *European Journal of Purchasing & Supply Management, 6*(3–4), 159–168.

Ali, A., Mahfouz, A., & Arisha, A. (2017). Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review. *Supply Chain Management, 22*(1), 16–39.

Ali, I., Nagalingam, S., & Gurd, B. (2017). Building resilience in SMEs of perishable product supply chains: enablers, barriers and risks. *Production Planning and Control, 28*(15), 1236–1250.

Aloini, D., Dulmin, R., Mininno, V., & Ponticelli, S. (2012). Supply chain management: A review of implementation risks in the construction industry. *Business Process Management Journal, 18*(5), 735–761.

Alshenqeeti, H. (2014). Interviewing as a data collection method: A critical review. *English Linguistics Research, 3*(1), 39–45.

Amaratunga, D., Baldry, D., Sarshar, M., & Newton, R. (2002). Quantitative and qualitative research in the built environment: application of "mixed" research approach. *Work Study, 51*(1), 17–31.

Ambulkar, S., Blackhurst, J., & Grawe, S. (2015). Firm's resilience to supply chain disruptions: Scale development and empirical examination. *Journal of Operations Management, 33–34*, 111–122.

Ameyaw, E.E., Chan, A. P. C., Owusu-Manu, D. G., & Coleman, E. (2015). A fuzzy model for evaluating risk impacts on variability between contract sum and final account in government-funded construction projects. *Journal of Facilities Management, 13*(1), 45–69.

Ameyaw, E.E., Pärn, E., Chan, A. P. C., Owusu-Manu, D. G., Edwards, D. J., & Darko, A. (2017). Corrupt practices in the construction industry: Survey of Ghanaian experience. *Journal of Management in Engineering, 33*(6), 5017006.

Ameyaw, Effah Ernest, & Chan, A. P. C. (2015). Evaluation and ranking of risk factors in public–private partnership water supply projects in developing countries using fuzzy synthetic evaluation approach. *Expert Systems with Applications, 42*(12), 5102–5116.

Ameyaw, Ernest Effah, & Chan, A. P. C. (2016). A fuzzy approach for the allocation of risks in public–private partnership water-infrastructure projects in developing countries. *Journal of Infrastructure Systems, 22*(3), 4016016.

Annarelli, A., & Nonino, F. (2016). Strategic and operational management of organizational resilience: Current state of research and future directions. *Omega (United Kingdom), 62*, 1–18.

Arashpour, M., Bai, Y., Aranda-mena, G., Bab-Hadiashar, A., Hosseini, R., & Kalutara, P. (2017). Optimizing decisions in advanced manufacturing of prefabricated products: Theorizing supply chain configurations in off-site construction. *Automation in Construction, 84*, 146–153.

Arif, M., Blismas, N., & Wakefield, R. (2009). Drivers, constraints and the future of offsite manufacture in Australia. *Construction Innovation, 9*(1), 72–83.

Arif, M., & Egbu, C. (2010). Making a case for offsite construction in China. *Engineering, Construction and Architectural Management, 17*(6), 536–548.

Arif, M., Goulding, J., & Rahimian, F. P. (2012). Promoting Off-Site Construction: Future Challenges and Opportunities. *Journal of Architectural Engineering, 18*(2), 75–78.

Arnheiter, E. D., & Harren, H. (2005). A typology to unleash the potential of modularity. *Journal of Manufacturing Technology Management, 16*(7), 699–711.

Badir, Y. F., Kadir, M. R. A., & Hashim, A. H. (2002). Industrialized building systems construction in Malaysia. *Journal of Architectural Engineering, 8*(1), 19–23.

Bao, Z., Lee, W. M. W., & Lu, W. (2020). Implementing on-site construction waste recycling in Hong Kong: Barriers and facilitators. *Science of The Total Environment, 747*, 141091. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.141091.

Barlow, J., Childerhouse, P., Gann, D., Hong-Minh, S., Naim, M., & Ozaki, R. (2003). Choice and delivery in housebuilding: lessons from Japan for UK housebuilders. *Building Research & Information, 31*(2), 134–145.

Bataglin, F. S., Viana, D. D., Formoso, C. T., & Bulhões, I. R. (2017). Application of Bim for Supporting Decisionmaking Related to Logistics in Prefabricated Building Systems. In proceedings of the *25th Annual Conference of the International Group for Lean Construction*, 9-12 July 2017. Heraklion, Greece, pp. 71–78.

Batista, L., Bourlakis, M., Smart, P., & Maull, R. (2018). In search of a circular supply chain archetype–a content-analysis-based literature review. *Production Planning & Control, 29*(6), 438–451.

Begum, R. A., Satari, S. K., & Pereira, J. J. (2010). Waste generation and recycling: Comparison of conventional and industrialized building systems. *American Journal of Environmental Sciences, 6*(4), 383.

Bellisario, A., & Pavlov, A. (2018). Performance management practices in lean manufacturing organizations: a systematic review of research evidence. *Production Planning & Control, 29*(5), 367–385.

Bernard, H. R. (2017). *Research methods in anthropology: Qualitative and quantitative approaches*. Lanham: Rowman & Littlefield.

Berry, A. J., & Collier, P. M. (2007). Risk in supply chains: Exploratory case studies in the automotive industry. *International Journal of Risk Assessment and Management, 7*(8), 1005–1026.

Bertrand, C., & Bourdeau, L. (2010). Research interviews by Skype: A new data collection method. In proceedings of the *9th European Conference on Research Methodology for Business and Management Studies*, 24-25 June 2010. Madrid, Spain. pp. 1-12.

Bevilacqua, M., Ciarapica, F. E., & Marcucci, G. (2018). A modular analysis for the supply chain resilience triangle. *IFAC-PapersOnLine, 51*(11), 1528–1535.

Birkie, S. E., Trucco, P., & Campos, P. F. (2017). Effectiveness of resilience capabilities in mitigating disruptions: leveraging on supply chain structural complexity. *Supply Chain Management: An International Journal, 22*(6), 506–521.

Birkinshaw, J. M. (2020). The new boadroom imperative: from agility to resilience. *Forbes*, 28, 2020. [Accessed 10 March 2020].

Birkmann, J. (2007). Risk and vulnerability indicators at different scales: Applicability, usefulness and policy implications. *Environmental Hazards, 7*(1), 20–31.

Boin, A., Kelle, P., & Clay Whybark, D. (2010). Resilient supply chains for extreme situations: Outlining a new field of study. *International Journal of Production Economics, 126*(1), 1–6.

Bonnefous, S., Massuelle, M. H., & Richard, V. (1997). *Aspects sémantiques du risque. Vocabulaire Lié Au Risque à Travers Une Analyse Bibliographique*: IPSN. Pp.35.

Borkenau, P., & Ostendorf, F. (1990). Comparing exploratory and confirmatory factor analysis: A study on the 5-factor model of personality. *Personality and Individual Differences, 11*(5), 515–524.

Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal, 9*(2), 27.

Brandon-Jones, E., Squire, B., Autry, C. W., & Petersen, K. J. (2014). A Contingent Resource-Based Perspective of Supply Chain Resilience and Robustness. *Journal of Supply Chain Management, 50*(3), 55–73.

Briscoe, G., & Dainty, A. (2005). Construction supply chain integration: an elusive goal? *Supply Chain Management: An International Journal, 10*(4), 319–326.

Brown, J. D. (2002). The Cronbach alpha reliability estimate. *JALT Testing & Evaluation SIG Newsletter, 6*(1), 17–19.

Bruno, M., & Clegg, R. (2015). A foresight review of resilience engineering. *In Lloyd's Register Foundation Report Series*, no. 2015.2. Lloyds Register.

Brusset, X., & Teller, C. (2017). Supply chain capabilities, risks, and resilience. *International Journal of Production Economics, 184*, 59–68.

Bueno-Solano, A., & 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.

C21. (1999). *Reinventing Construction, Construction 21 Review Committee*, Ministry of Manpower and Ministry of National Development, Sigapore. [Accessed 10 March 2020].

Cedillo-Campos, M. G., Pérez-Salas, G., Bueno-Solano, A., González-Ramírez, R. G., & Jímenez-Sánchez, E. (2014). Supply chain disruptions propagation caused by criminal acts. *Journal of Applied Research and Technology, 12*(4), 684–694.

Chaghooshi, A., Momeni, M., Abdollahi, B., Safari, H., & Kamalabadi, I. (2018). Planning for disruptions in supply chain networks. *Uncertain Supply Chain Management, 6*(2), 135–148.

Chan, A. P. C. (2001). Time–cost relationship of public sector projects in Malaysia. *International Journal of Project Management, 19*(4), 223–229.

Chan, A. P. C., Darko, A., Olanipekun, A. O., & 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.

Chan, A. P. C., & Owusu, E. K. (2017). Corruption forms in the construction industry: Literature review. *Journal of Construction Engineering and Management, 143*(8), 4017057.

Chan, W. T., & Hu, H. (2002). Constraint programming approach to precast production scheduling. *Journal of Construction Engineering and Management, 128*(6), 513–521.

Chang, N.-B., Chen, H.-W., & Ning, S.-K. (2001). Identification of river water quality using the fuzzy synthetic evaluation approach. *Journal of Environmental Management, 63*(3), 293–305.

Chauhan, P., Kumar, S., & Sharma, R. K. (2015). Modeling drivers of political risk in offshore outsourcing. *European Journal of Business and Management, 7*(9), 34–44.

Chen, Q., Adey, B. T., Haas, C., & 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.

Cheng, C.-H. (1997). Evaluating naval tactical missile systems by fuzzy AHP based on the grade value of membership function. *European Journal of Operational Research, 96*(2), 343–350.

Cheng, G., & Zhu, X. (2010). Research on resilient supply chain on the basis of Hooke's law. In proceedings of the *2010 International Conference on E-Product E-Service and E-Entertainment-IEEE2010,* 7-9 November 2010. Henan, China, pp. 1–3.

Chiang, Y.H., Chan, E. H.-W., & Lok, L. K.-L. (2006). Prefabrication and barriers to entry—a case study of public housing and institutional buildings in Hong Kong. *Habitat International, 30*(3), 482–499.

Chinowsky, P., Diekmann, J., & Galotti, V. (2008). Social network model of construction. *Journal of Construction Engineering and Management, 134*(10), 804–812.

Chinowsky, P., Diekmann, J., & O'Brien, J. (2010). Project organizations as social networks. *Journal of Construction Engineering and Management, 136*(4), 452–458.

Choi, J. O., Chen, X. Bin, & Kim, T. W. (2017). Opportunities and challenges of modular methods in dense urban environment. *International Journal of Construction Management, 19*(2), 93–105.

Chopra, S., & Sodhi, M. S. (2004). Supply-chain breakdown. *MIT Sloan Management Review, 46*(1), 53–61.

Chowdhury, M. M. H., Dewan, M. N. A., & Quaddus, M. A. (2012). Supply chain resilience to mitigate disruptions: A QFD approach. In proceedings of the *Pacific Asia Conference on Information Systems-PACIS 2012*, 11-15 July 2012. Ho Chi Minh City – Vietnam, pp. 66.

Chowdhury, M. M. H., & Quaddus, M. A. (2015). A multiple objective optimization based QFD approach for efficient resilient strategies to mitigate supply chain vulnerabilities: The case of garment industry of Bangladesh. *Omega (United Kingdom), 57*, 5–21.

Chowdhury, M. M. H., & Quaddus, M. A. (2016). Supply chain readiness, response and recovery for resilience. *Supply Chain Management: An International Journal, 21*(6), 709–731.

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

Chowdhury, M. M. H., Quaddus, M. A., & Agarwal, R. (2019). Supply chain resilience for performance: role of relational practices and network complexities. *Supply Chain Management: An International Journal, 24*(5), 659–676.

Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *International Journal of Logistics Management, 15*(2), 1–13.

CICID. (2011). *Summary Report, Symposium: Construction Industry Development – Comparison and Acceleration*. 18 Jan. 2011, Centre for Innovation in Construction and Infrastructure Development, The University of Hong Kong, 14p. http://www.civil.hku.hk/cicid/3_events/102/10. [Accessed 10 March 2020].

CIRC. (2001). *Construct for Excellence*. Construction Industry Review Committee (CIRC), HKSAR Government, Hong Kong. [Accessed 10 March 2020].

Colicchia, C., Creazza, A., Noè, C., & 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), 5–21.

Colicchia, C., Dallari, F., & Melacini, M. (2010). Increasing supply chain resilience in a global sourcing context. *Production Planning and Control, 21*(7), 680–694.

Comes, T., & Van de Walle, B. (2014). Measuring disaster resilience: The impact of hurricane sandy on critical infrastructure systems. *ISCRAM, 11*, 195–204.

Coyle, R. G. (1997). System dynamics modelling: a practical approach. *Journal of the Operational Research Society, 48*(5), 541–545.

Creswell, J. W. (2014). *A concise introduction to mixed methods research*. NY: SAGE publications.

Cui, Y. (2018). Knowledge-based system for improving supply chain resilience. In proceedings of the *13th International Conference on Natural Computation, Fuzzy Systems and Knowledge Discovery*, 29-31 July 2017. Guilin, China, pp. 1752–1756.

Čuš-Babič, N., Rebolj, D., Nekrep-Perc, M., & Podbreznik, P. (2014). Supply-chain transparency within industrialized construction projects. *Computers in Industry, 65*(2), 345–353.

Cutter, S. L., Burton, C. G., & Emrich, C. T. (2010). Disaster resilience indicators for benchmarking baseline conditions. *Journal of Homeland Security and Emergency Management, 7*(1), Artical 51.

Dainty, A. R. J., Millett, S. J., & Briscoe, G. H. (2001). New perspectives on construction supply chain integration. *Supply Chain Management: An International Journal, 6*(4), 163–173.

Darko, A., & 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.

Darko, A., Chan, A. P. C., Yang, Y., Shan, M., He, B.-J., & Gou, Z. (2018). Influences of barriers, drivers, and promotion strategies on green building technologies adoption in developing countries: The Ghanaian case. *Journal of Cleaner Production, 200*, 687–703.

Demiralp, G., Guven, G., & Ergen, E. (2012). Analyzing the benefits of RFID technology for cost sharing in construction supply chains: A case study on prefabricated precast components. *Automation in Construction, 24*, 120–129.

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

Dong, L., & Tomlin, B. (2012). Managing disruption risk: The interplay between operations and insurance. *Management Science, 58*(10), 1898–1915.

Du, J., Jing, H., Castro-Lacouture, D., & Sugumaran, V. (2019). Multi-agent simulation for managing design changes in prefabricated construction projects. *Engineering, Construction and Architectural Management, 27*(1), 270–295.

Dulaimi, M., Akintoye, A., & Main, J. (2007). Collaborative relationships in construction: the UK contractors' perception. *Engineering, Construction and Architectural Management, 14*(6), 597–617.

Durach, C. F., Kembro, J., & Wieland, A. (2017). A new paradigm for systematic literature reviews in supply chain management. *Journal of Supply Chain Management, 53*(4), 67–85.

Dziuban, C. D., & Shirkey, E. C. (1974). When is a correlation matrix appropriate for factor analysis? Some decision rules. *Psychological Bulletin, 81*(6), 358.

Easterby-Smith, M., Thorpe, R., & Jackson, P. R. (2012). *Management research*. NY: SAGE publications.

Egan, J. (1998). *Rethinking construction : the report of the Construction Task Force to the Deputy Prime Minister*, John Prescott, on the scope for improving the quality and efficiency of UK construction. [Accessed 10 March 2020].

Einarsson, S., & Rausand, M. (1998). An approach to vulnerability analysis of complex industrial systems. *Risk Analysis, 18*(5), 535–546.

Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review, 14*(4), 532–550.

Ekanayake, E. M. A. C., Shen, G., & Kumaraswamy, M. M. (2021). Identifying supply chain capabilities of construction firms in industrialized construction. *Production Planning and Control, 32*(4), 303–321.

Ekanayake, E. M. A. C., Shen, G., & Kumaraswamy, M. M. (2019). Managing Vulnerabilities and Capabilities for Supply Chain Resilience in Industrialised Construction. In proceedings of the *ARCOM2019 Conference*, 2-4 September 2019. Leeds, United Kingdom. pp. 811–820.

Ekanayake, E. M. A. C., Shen, G., & Kumaraswamy, M. M. (2020). Resilient Supply Chains in Industrialised Construction: A Hong Kong Case Study. In proceedings of the *Construction Research Congress 2020: Project Management and Controls, Materials, and Contracts*, 8-10 March 2020. Tempe, Arizona. pp. 311–319.

Ekanayake, E. M. A. C., Shen, G., Kumaraswamy, M. M., & Owusu, E. K. (2020). Identifying supply chain vulnerabilities in industrialized construction: an overview. *International Journal of Construction Management.* https://doi.org/10.1080/15623599.2020.1728487

Elleuch, H., Dafaoui, E., Elmhamedi, A., & Chabchoub, H. (2016). Resilience and Vulnerability in Supply Chain: Literature review. *IFAC-PapersOnLine, 49*(12), 1448–1453.

Enshassi, M. S. A., Walbridge, S., West, J. S., & Haas, C. T. (2019). Integrated risk management framework for tolerance-based mitigation strategy decision support in modular construction projects. *Journal of Management in Engineering, 35*(4), 5019004:1-5019004:16.

Eriksson, P. E., & Laan, A. (2007). Procurement effects on trust and control in client‐contractor relationships. *Engineering, Construction and Architectural Management, 14*(4), 387‐399.

Eysenck, H. J. (1994). Systematic reviews: Meta-analysis and its problems. *BMJ, 309*(6957), 789–792.

Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, Scopus, web of science, and Google scholar: strengths and weaknesses. *The FASEB Journal, 22*(2), 338–342.

Fard, M. M., Terouhid, S. A., Kibert, C. J., & Hakim, H. (2017). Safety concerns related to modular/prefabricated building construction. *International Journal of Injury Control and Safety Promotion, 24*(1), 10–23.

Fateh, M. A. M., & Mohammad, M. F. (2017). Industrialized Building System (IBS) Provision in Local and International Standard Form of Contracts. *Journal of Construction in Developing Countries, 22*(2), 67–80.

Fiksel, J. (2003). Designing resilient, sustainable systems. *Environmental Science & Technology, 37*(23), 5330–5339.

Fiksel, J. (2006). Sustainability and resilience: toward a systems approach. *Sustainability: Science, Practice and Policy, 2*(2), 14–21.

Fiksel, J. (2015). *From risk to resilience*. *In Resilient by design* (pp. 19–34). NY: Springer.

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of Marketing Research, 18*(1), 39–50.

Gadde, L.E., & Dubois, A. (2010). Partnering in the construction industry—Problems and opportunities. *Journal of Purchasing and Supply Management, 16*(4), 254–263.

Gann, D. M. (1996). Construction as a manufacturing process? Similarities and differences between industrialized housing and car production in Japan. *Construction Management & Economics, 14*(5), 437–450.

Gel, Y. R., Miao, W., & Gastwirth, J. L. (2007). Robust directed tests of normality against heavy-tailed alternatives. *Computational Statistics & Data Analysis, 51*(5), 2734–2746.

Ghaffarianhoseini, A., Tookey, J., Ghaffarianhoseini, A., Naismith, N., Azhar, S., Efimova, O., & Raahemifar, K. (2017). Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges. *Renewable and Sustainable Energy Reviews, 75*, 1046–1053.

Gibb, A. G. F. (1999). *Off-site fabrication: prefabrication, pre-assembly and modularisation*. NJ: John Wiley & Sons.

Gibb, A. G. F., & Isack, F. (2003). Re-engineering through pre-assembly: client expectations and drivers. *Building Research & Information, 31*(2), 146–160.

Gibb, A. G. F., & Neale, R. H. (1997). Management of prefabrication for complex cladding: Case study. *Journal of Architectural Engineering, 3*(2), 60–69.

Goddard, W., & Melville, S. (2004). *Research methodology: An introduction*. SA: Juta and Company Ltd.

Gondard-Delcroix, C., & Rousseau, S. (2004). Vulnerability and Sustainable Risk Management Strategies: A Study Applied to Rural Households in Madagascar. *The human and social dimensions of Sustainable Development*. File 3 (2004), doi: 10.4000/developpementdurable.1185.

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

Goodier, C., Gibb, A. G. F., Mancini, M., Turck, C., Gjepali, O., & Daniels, E. (2019). Modularisation and offsite in engineering construction: an early decision-support tool. *Proceedings of the Institution of Civil Engineers - Civil Engineering, 172*(6), 3–14.

Gopalakrishnan, S., & Ganeshkumar, P. (2013). Systematic reviews and meta-analysis: understanding the best evidence in primary healthcare. *Journal of Family Medicine and Primary Care, 2*(1), 9.

Gosling, J., Naim, M., & Towill, D. (2013). A supply chain flexibility framework for engineer-to-order systems. *Production Planning & Control, 24*(7), 552–566.

Goulding, J. S., Pour Rahimian, F., Arif, M., & Sharp, M. D. (2015). New offsite production and business models in construction: priorities for the future research agenda. *Architectural Engineering and Design Management, 11*(3), 163–184.

Green, P. E. J. (2015). *Enterprise risk management: A common framework for the entire organization*. Oxford: Butterworth-Heinemann.

Grötsch, V. M., Blome, C., & Schleper, M. C. (2013). Antecedents of proactive supply chain risk management–a contingency theory perspective. *International Journal of Production Research, 51*(10), 2842–2867.

Hair, J. F., Marko, S., Lucas, H., & Volker, G. K. (2014). Partial least squares structural equation modeling (PLS-SEM): An emerging tool in business research. *European Business Review, 26*(2), 106–121.

Hair, J. F., Ringle, C. M., & Sarstedt, M. (2011). PLS-SEM: Indeed a silver bullet. *Journal of Marketing Theory and Practice, 19*(2), 139–152.

Han, Y., Skibniewski, M. J., & Wang, L. (2017). A market equilibrium supply chain model for supporting self-manufacturing or outsourcing decisions in prefabricated construction. *Sustainability, 9*(11), 2069:1-18.

Handfield, R., Walton, S. V, Sroufe, R., & Melnyk, S. A. (2002). Applying environmental criteria to supplier assessment: A study in the application of the Analytical Hierarchy Process. *European Journal of Operational Research, 141*(1), 70–87.

Heckmann, I., Comes, T., & Nickel, S. (2015). A critical review on supply chain risk–Definition, measure and modeling. *Omega, 52*, 119–132.

Henseler, J., Ringle, C. M., & Sarstedt, M. (2012). Using partial least squares path modeling in advertising research: basic concepts and recent issues. *In Handbook of research on international advertising*. Cheltenham: Edward Elgar Publishing.

Hertz, D. B., & Thomas, H. (1983). *Risk analysis and its applications*. NJ: Wiley.

Hong, J., Shen, G. Q., Li, Z., Zhang, B., & Zhang, W. (2018). Barriers to promoting prefabricated construction in China: A cost–benefit analysis. *Journal of Cleaner Production, 172*, 649–660.

Hong Kong Special Administrative Region Government. (2017). *The Chief Executive's 2017 Policy Address-Policy Agenda*. https://www.policyaddress.gov.hk/2017/eng/pdf/Agenda.pdf. [Accessed 10 March 2020].

Hong, Y., & Chan, D. W. M. (2014). Research trend of joint ventures in construction: a two-decade taxonomic review. *Journal of Facilities Management, 12*(2), 118–141.

Hsieh, H.F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research, 15*(9), 1277–1288.

Hsu, P.Y., Aurisicchio, M., & Angeloudis, P. (2017). Establishing outsourcing and supply chain plans for prefabricated construction projects under uncertain productivity. In proceedings of the *International Conference on Computational Logistics*, 18-20 October 2017. Southampton, United Kingdom. pp. 529–543.

Hwang, B.G., Shan, M., & Looi, K.Y. (2018). Key constraints and mitigation strategies for prefabricated prefinished volumetric construction. *Journal of Cleaner Production, 183*, 183–193.

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

Ivanov, D. (2018). Revealing interfaces of supply chain resilience and sustainability: a simulation study. *International Journal of Production Research, 56*(10), 3507–3523. https://doi.org/10.1080/00207543.2017.1343507

Ivanov, D., Dolgui, A., & Sokolov, B. (2017). Scheduling of recovery actions in the supply chain with resilience analysis considerations. *International Journal of Production Research, 56*(19), 6473–6490.

Ivanov, D., Dolgui, A., & Sokolov, B. (2018). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research, 57*(3), 829–846.

Iyer, K. C., Kumar, R., & Singh, S. P. (2020). Understanding the role of contractor capability in risk management: a comparative case study of two similar projects. *Construction Management and Economics, 38*(3), 223–238.

Jaillon, L., Poon, C.S., & Chiang, Y. H. (2009). Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management, 29*(1), 309–320.

Jamshidi, M. (1997). Fuzzy control of complex systems. *Soft Computing, 1*(1), 42–56.

Jiang, L., Li, Z., Li, L., & Gao, Y. (2018). Constraints on the promotion of prefabricated construction in China. *Sustainability, 10*(7), 2516:1-17.

Jiang, R., Mao, C., Hou, L., Wu, C., & Tan, J. (2018). A SWOT analysis for promoting off-site construction under the backdrop of China's new urbanisation. *Journal of Cleaner Production, 173*, 225–234.

Johnson, N., Elliott, D., & Drake, P. (2013). Exploring the role of social capital in facilitating supply chain resilience. *Supply Chain Management, 18*(3), 324–336. https://doi.org/10.1108/SCM-06-2012-0203

Johnsson, H., & Meiling, J. H. (2009). Defects in offsite construction: timber module prefabrication. *Construction Management and Economics, 27*(7), 667–681.

Joint Practice Note. (2002). *Joint practice note no. 2: Second package of incentives to promote green and innovative buildings.* Jointly issued by Buildings Department, Lands Department and Planning Department, February. [Accessed 10 March 2020].

Jonsson, H., & Rudberg, M. (2014). Classification of production systems for industrialized building: a production strategy perspective. *Construction Management and Economics, 32*(1–2), 53–69.

Jüttner, U., & Maklan, S. (2011). Supply chain resilience in the global financial crisis: An empirical study. *Supply Chain Management, 16*(4), 246–259.

Kadir, M. R. A., Lee, W. P., Jaafar, M. S., Sapuan, S. M., & Ali, A. A. A. (2005). Factors affecting construction labour productivity for Malaysian residential projects. *Structural Survey, 23*(1), 42–54.

Kadir, M. R. A., Lee, W. P., Jaafar, M. S., Sapuan, S. M., & Ali, A. A. A. (2006). Construction performance comparison between conventional and industrialised building systems in Malaysia. *Structural Survey, 24*(5), 412–424.

Kaiser, H. F. (1974). An index of factorial simplicity. *Psychometrika, 39*(1), 31–36.

Kamalahmadi, M., & Parast, M. M. (2016). A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. *International Journal of Production Economics, 171*, 116–133.

Keane, P., Sertyesilisik, B., & Ross, A. D. (2010). Variations and change orders on construction projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 2*(2), 89–96.

Ketikidis, P. H., Koh, S. C. L., Gunasekaran, A., Cucchiella, F., & Gastaldi, M. (2006). Risk management in supply chain: a real option approach. *Journal of Manufacturing Technology Management, 17*(6), 700–720.

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

Kim, S.-H., & Tomlin, B. (2013). Guilt by association: Strategic failure prevention and recovery capacity investments. *Management Science, 59*(7), 1631–1649.

Kisi, K. P., Mani, N., Lee, N., Shrestha, K. J., Shrestha, K., & Kayastha, R. (2019). Opportunities and challenges for modular construction in developing nations: A case study in the nepalese construction industry. In proceedings of the *7th Canadian Society for Civil Engineers (CSCE) Annual Conference*, 14-17 June 2011. Ottawa, Ontario, Canada, CON231:1-9.

Kochan, C. G., & Nowicki, D. R. (2018). Supply chain resilience: a systematic literature review and typological framework. *International Journal of Physical Distribution & Logistics Management, 48*(8), 842–865.

Kochan, C. G., Nowicki, D. R., Sauser, B., & 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*, 168–185.

Koolwijk, J. S. J., van Oel, C. J., Wamelink, J. W. F., & Vrijhoef, R. (2018). Collaboration and integration in project-based supply chains in the construction industry. *Journal of Management in Engineering, 34*(3), 4018001.

Koskela, L. (2003). Is structural change the primary solution to the problems of construction? *Building Research & Information, 31*(2), 85–96.

Kothari, C. R. (2004). *Research methodology: Methods and techniques*. Delhi: New Age International.

Kristianto, Y., Gunasekaran, A., Helo, P., & Hao, Y. (2014). A model of resilient supply chain network design: A two-stage programming with fuzzy shortest path. *Expert Systems with Applications, 41*(1), 39–49.

Kumar, V., & Viswanadham, N. (2007). A CBR-based decision support system framework for construction supply chain risk management. In proceedings of the *3rd IEEE International Conference on Automation Science and Engineering, IEEE CASE*, 22-25 September 2007. Scottsdale, USA. pp. 980–985.

Kurniawan, R., & Zailani, S. (2010). Supply chain vulnerability and mitigation strategy of the manufacturing firms in Indonesia: Manager's perspectives. *International Business Management, 4*(3), 116–123.

Langston, C. (2016). The reliability of currency and purchasing power parity conversion for international project cost benchmarking. *Benchmarking: An International Journal, 23*(1), 61–77.

Lawson, R. M., Ogden, R. G., & Bergin, R. (2012). Application of Modular Construction in High-Rise Buildings. *Journal of Architectural Engineering, 18*(2), 148–154.

Le, Y., Shan, M., Chan, A. P. C., & Hu, Y. (2014). Investigating the causal relationships between causes of and vulnerabilities to corruption in the Chinese public construction sector. *Journal of Construction Engineering and Management, 140*(9), 5014007.

Lederer, A. L., Maupin, D. J., Sena, M. P., & Zhuang, Y. (2000). The technology acceptance model and the World Wide Web. *Decision Support Systems, 29*(3), 269–282.

Lee, A. H. I., Chen, W.C., & Chang, C.J. (2008). A fuzzy AHP and BSC approach for evaluating performance of IT department in the manufacturing industry in Taiwan. *Expert Systems with Applications, 34*(1), 96–107.

Lengnick-Hall, C. A., Beck, T. E., & Lengnick-Hall, M. L. (2011). Developing a capacity for organizational resilience through strategic human resource management. *Human Resource Management Review, 21*(3), 243–255.

Lessing, J., Stehn, L., & Ekholm, A. (2015). Industrialised house-building - Development and conceptual orientation of the field. *Construction Innovation, 15*(3), 378–399.

Li, C. Z. (2017). *Management of schedule risks of prefabrication housing production in Hong Kong*. The Hong Kong Polytechnic University.

Li, C. Z., Hong, J., Xue, F., Shen, G. Q., Xu, X., & 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., Shen, G. Q., & Alshawi, M. (2014). Measuring the impact of prefabrication on construction waste reduction: An empirical study in China. *Resources, Conservation and Recycling, 91*, 27–39.

Li, C. Z., Xu, X., Shen, G. Q., Fan, C., Li, X., & Hong, J. (2018a). A model for simulating schedule risks in prefabrication housing production: A case study of six-day cycle assembly activities in Hong Kong. *Journal of Cleaner Production, 185*, 366–381.

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

Li, C. Z., Hong, J., Fan, C., Xu, X., & Shen, G. Q. (2018c). Schedule delay analysis of prefabricated housing production: A hybrid dynamic approach. *Journal of Cleaner Production, 195*, 1533–1545.

Li, H., Guo, H. L., Skitmore, M., Huang, T., Chan, K. Y. N., & Chan, G. (2011). Rethinking prefabricated construction management using the VP‐based IKEA model in Hong Kong. *Construction Management and Economics, 29*(3), 233‐245.

Li, S., & Lin, B. (2006). Accessing information sharing and information quality in supply chain management. *Decision Support Systems, 42*(3), 1641–1656.

Li, T. H. Y., Ng, S. T., & Skitmore, M. (2013). Evaluating stakeholder satisfaction during public participation in major infrastructure and construction projects: A fuzzy approach. *Automation in Construction, 29*, 123–135.

Li, X., Shen, G. Q., Wu, P., & Yue, T. (2019). Integrating building information modeling and prefabrication housing production. *Automation in Construction, 100*, 46–60.

Li, Y. Y., Chen, P.H., Chew, D. A. S., Teo, C. C., & Ding, R. G. (2011). Critical project management factors of AEC firms for delivering green building projects in Singapore. *Journal of Construction Engineering and Management, 137*(12), 1153–1163.

Lim, B. T. H., Ling, F. Y. Y., Ibbs, C. W., Raphael, B., & Ofori, G. (2011). Empirical analysis of the determinants of organizational flexibility in the construction business. *Journal of Construction Engineering and Management, 137*(3), 225–237.

Lin, S.C. (2015). An analysis for construction engineering networks. *Journal of Construction Engineering and Management, 141*(5), 4014096.

Liu, C.L., Shang, K.C., Lirn, T.C., Lai, K.H., & Lun, Y. H. 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.

Lo, S. M. (1999). A fire safety assessment system for existing buildings. *Fire Technology, 35*(2), 131–152.

Loosemore, M. (2000). *Crisis management in construction projects*. American Society of Civil Engineers.

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

Luo, L., Mao, C., Shen, L., & Li, Z. (2015). Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system. *Engineering, Construction and Architectural Management, 22*(6), 622–643.

Luo, L., Qiping Shen, G., Xu, G., Liu, Y., & 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), 5018015.

Machado, S. M., Paiva, E. L., & da Silva, E. M. (2018). Counterfeiting: addressing mitigation and resilience in supply chains. *International Journal of Physical Distribution & Logistics Management, 48*(2), 139–163.

Madenas, N., Tiwari, A., Turner, C., & Peachey, S. (2015). An analysis of supply chain issues relating to information flow during the automotive product development. *Journal of Manufacturing Technology Management, 26*(8), 1158–1176.

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

Mandal, S. (2012). An empirical investigation into supply chain resilience. *IUP Journal of Supply Chain Management, 9*(4), 46–61.

Mandal, S., Sarathy, R., Korasiga, V. R., Bhattacharya, S., & Dastidar, S. G. (2016). Achieving supply chain resilience. *International Journal of Disaster Resilience in the Built Environment, 7*(5), 544–562.

March, J. G., & Shapira, Z. (1987). Managerial perspectives on risk and risk taking. *Management Science, 33*(11), 1404–1418.

Masood, R., & Choudhry, R. M. (2010). Identification of risk factors for construction contracting firms-Encompassing mitigation stance. In proceedings of the *2nd International Conference on Construction in Developing Countries*, 3-5 August 2010. Cairo, Egypt, pp. 251–260.

Mayring, P. (2004). Qualitative content analysis. *A Companion to Qualitative Research, 1*(2004), 159–176.

McKinsey Global Institute. (2020). *Risk, resilience, and rebalancing in global value chains*. https://www.mckinsey.com/business-functions/operations/our-insights/risk-resilience-and-rebalancing-in-global-value-chains [Accessed 21 January 2021].

Meinel, U., & Abegg, B. (2017). A multi-level perspective on climate risks and drivers of entrepreneurial robustness – Findings from sectoral comparison in alpine Austria. *Global Environmental Change, 44*, 68–82.

Mensah, P., & Merkuryev, Y. (2014). Developing a resilient supply chain. *Procedia-Social and Behavioral Sciences, 110*, 309–319.

Mensah, P., Merkuryev, Y., & Manak, S. (2015). Developing a resilient supply chain strategy by exploiting ICT. *Procedia Computer Science, 77*, 65–71.

Mikkola, J. H. (2006). Capturing the degree of modularity embedded in product architectures. *Journal of Product Innovation Management, 23*(2), 128–146.

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

Mok, K. Y., Shen, G. Q., & Yang, J. (2015). Stakeholder management studies in mega construction projects: A review and future directions. *International Journal of Project Management, 33*(2), 446–457.

Mok, K. Y., Shen, G. Q., & Yang, R. J. (2017). A network theory-based analysis of stakeholder issues and their interrelationships in large construction projects: a case study. *International Journal of Construction Management, 17*(3), 210–227.

Mooi, E., Sarstedt, M., & Mooi-Reci, I. (2018). *Principal component and factor analysis. In Market Research* (pp. 265–311). NY: Springer.

Morash, E. A. (2001). Supply chain strategies, capabilities, and performance. *Transportation Journal, 41*(1), 37–54.

Murphy, J. (2006). *Managing Supply Chain Risk: Building in Resilience and Preparing for Disruption*. White Paper, WisdomNet Inc.

Nagapan, S., Rahman, I. A., Asmi, A., & Adnan, N. F. (2013). Study of site's construction waste in Batu Pahat, Johor. *Procedia Engineering, 53*, 99–103.

Namdar, J., Li, X., Sawhney, R., & Pradhan, N. (2018). Supply chain resilience for single and multiple sourcing in the presence of disruption risks. *International Journal of Production Research, 56*(6), 2339–2360.

Noguchi, M. (2003). The effect of the quality-oriented production approach on the delivery of prefabricated homes in Japan. *Journal of Housing and the Built Environment, 18*(4), 353–364.

Noor, K. B. M. (2008). Case study: A strategic research methodology. *American Journal of Applied Sciences, 5*(11), 1602–1604.

Nunnally, J. C. (1978). *An overview of psychological measurement. In Clinical diagnosis of mental disorders* (pp. 97–146). NY: Springer.

Olivares-Aguila, J., & ElMaraghy, W. (2020). System dynamics modelling for supply chain disruptions. *International Journal of Production Research*, *59*(6), 1757-1775.

Oppenheim, A. N. (2000). *Questionnaire design, interviewing and attitude measurement*. London: Bloomsbury Publishing.

Osei-Kyei, R., & Chan, A. P. C. (2015). Review of studies on the Critical Success Factors for Public–Private Partnership (PPP) projects from 1990 to 2013. *International Journal of Project Management, 33*(6), 1335–1346.

Osei-Kyei, R., Chan, A. P. C., & Dansoh, A. (2020). Project selection index for unsolicited public–private partnership proposals. *International Journal of Construction Management, 20*(6), 555–566.

Ott, R. L., & Longnecker, M. T. (2015). *An introduction to statistical methods and data analysis.* Canada: Nelson Education.

Owusu, E. K., & Chan, A. P. C. (2019). Barriers affecting effective application of anticorruption measures in infrastructure projects: Disparities between developed and developing countries. *Journal of Management in Engineering, 35*(1), 4018056.

Owusu, E. K., Chan, A. P. C., DeGraft, O.M., Ameyaw, E. E., & Robert, O.K. (2019). Contemporary review of anti-corruption measures in construction project management. *Project Management Journal, 50*(1), 40–56.

Owusu, E. K., Chan, A. P. C., & Hosseini, M. R. (2020). Impacts of anti-corruption barriers on the efficacy of anti-corruption measures in infrastructure projects: Implications for sustainable development. *Journal of Cleaner Production, 246*, 119078.

Owusu, E. K., Chan, A. P. C., Hosseini, M. R., & 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*(1), 66–82.

Owusu, E. K., Chan, A. P. C., & Shan, M. (2019). Causal factors of corruption in construction project management: An overview. *Science and Engineering Ethics, 25*(1), 1–31.

Palaneeswaran, E., Kumaraswamy, M., Rahman, M., & Ng, T. (2003). Curing congenital construction industry disorders through relationally integrated supply chains. *Building and Environment, 38*(4), 571–582.

Pallant, J. (2020). *SPSS survival manual: A step by step guide to data analysis using IBM SPSS*. Oxfordshire: Routledge.

Pan, W., Gibb, A. G. F., & Dainty, A. R. J. (2007). Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Construction Management and Economics, 25*(2), 183–194.

Panova, Y., & Hilletofth, P. (2018). Managing supply chain risks and delays in construction project. *Industrial Management & Data Systems, 118*(7), 1413–1431.

Patton, M. Q. (2005). *Qualitative research. In Encyclopedia of statistics in behavioral science*. NJ: Wiley Online Library.

Peck, H. (2005). Drivers of supply chain vulnerability: An integrated framework. *International Journal of Physical Distribution & Logistics Management, 35*(4), 210–232.

Peltokorpi, A., Olivieri, H., Granja, A. D., & Seppänen, O. (2018). Categorizing modularization strategies to achieve various objectives of building investments. *Construction Management and Economics, 36*(1), 32–48.

Pettit, T. J. (2008). *Supply chain resilience: development of a conceptual framework, an assessment tool and an implementation process*. Ohio State Univ Columbus.

Pettit, T. J., Croxton, K. L., & Fiksel, J. (2013). Ensuring supply chain resilience: Development and implementation of an assessment tool. *Journal of Business Logistics, 34*(1), 46–76.

Pettit, T. J., Croxton, K. L., & 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., Fiksel, J., & Croxton, K. L. (2010). Ensuring supply chain resilience: development of a conceptual framework. Journal of Business Logistics, 31(1), 1–21.

Polit, D. F., & Hungler, B. P. (1999). *Nursing Research: Principles andMethods*. Philadelphia: Lippicot.

Polonsky, M. J., & Waller, D. S. (2018). *Designing and managing a research project: A business student's guide*. NY: Sage publications.

Ponis, S. T., & Koronis, E. (2012). Supply chain resilience: Definition of concept and its formative elements. *Journal of Applied Business Research, 28*(5), 921–930.

Ponomarov, S. Y., & Holcomb, M. C. (2009). Understanding the concept of supply chain resilience. *The International Journal of Logistics Management, 20*(1), 124–143.

Purvis, L., Spall, S., Naim, M., & Spiegler, V. (2016). Developing a resilient supply chain strategy during 'boom' and 'bust.' *Production Planning and Control, 27(7–8)*, 579–590.

Qudrat-Ullah, H., & 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.

Rajesh, R. (2019). A fuzzy approach to analyzing the level of resilience in manufacturing supply chains. *Sustainable Production and Consumption, 18*, 224–236.

Razali, N. M., & Wah, Y. B. (2011). Power comparisons of shapiro-wilk, kolmogorov-smirnov, lilliefors and anderson-darling tests. *Journal of Statistical Modeling and Analytics, 2*(1), 21–33.

Reeves, M., & Varadarajan, R. (2020). *When Resilience is More Important than Efficiency*. BCG/Henderson Institute, Boston.

Remenyi, D., Williams, B., Money, A., & Swartz, E. (1998). *Doing research in business and management: an introduction to process and method*. NY: Sage publications.

Richardson, G. P., & Pugh, A. L. (1981). Introduction to system dynamics modeling with *DYNAMO. 48*(11), 1146–1146.

Riley, J. M., Klein, R., Miller, J., & Sridharan, V. (2016). How internal integration, information sharing, and training affect supply chain risk management capabilities. *International Journal of Physical Distribution & Logistics Management, 46*(10), 953–980.

Rowley, J. (2002). Using case studies in research. *Management Research News, 25*(1), 16–27.

Rwamamara, R. (2007). Risk assessment and anlysis of workload in an industrialised construction process. *Construction Information Quarterly, 9*(2), 80–85.

Saad, M., Jones, M., & James, P. (2002). A review of the progress towards the adoption of supply chain management (SCM) relationships in construction. *European Journal of Purchasing & Supply Management, 8*(3), 173–183.

Sabahi, S., & Parast, M. M. (2020). Firm innovation and supply chain resilience: a dynamic capability perspective. *International Journal of Logistics Research and Applications, 23*(3), 254–269.

Said, H. (2015). Prefabrication best practices and improvement opportunities for electrical construction. *Journal of Construction Engineering and Management, 141*(12), 4015045.

Santos, J. R. A. (1999). Cronbach's alpha: A tool for assessing the reliability of scales. *Journal of Extension, 37*(2), 1–5.

Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research methods for business students*. NY: Pearson education.

Scholten, K., & Schilder, S. (2015). The role of collaboration in supply chain resilience. *Supply Chain Management, 20*(4), 471–484.

Scholten, K., Scott, P. S., & Fynes, B. (2014). Mitigation processes - antecedents for building supply chain resilience. *Supply Chain Management, 19*(2), 211–228.

Scott, J. (2000). *Social network analysis: A handbook. In 2nd edtion*. SAGE publications.

Scott, John, & Carrington, P. J. (2011). *The SAGE handbook of social network analysis*. NY: SAGE publications.

Senge, P. M. (1990). *The art and practice of the learning organization*. NY: Doubleday.

Seuring, S. (2013). A review of modeling approaches for sustainable supply chain management. *Decision Support Systems, 54*(4), 1513–1520.

Shahbaz, M. S., Soomro, M. A., Bhatti, N. U. K., Soomro, Z., & Jamali, M. Z. (2019). The impact of supply chain capabilities on logistic efficiency for the construction projects. *Civil Engineering Journal, 5*(6), 1249–1256.

Shahparvari, M., Robinson, H., Fong, D., & Ebohon, O. J. (2019). Exploiting automated technologies for reduction of rework in construction housing supply chain. In proceedings of the *Creative Construction Conference (2019)*, 29 June – 2 July 2019. Budapest, Hungary. pp. 48–54.

Sharafi, P., Rashidi, M., Samali, B., Ronagh, H., & Mortazavi, M. (2018). Identification of factors and decision analysis of the level of modularization in building construction. *Journal of Architectural Engineering, 24*(2), 4018010.

Sheffi, Y., & Rice, J. B. J. (2005). A supply chain view of the resilient enterprise. *MIT Sloan Management Review, 47*(1), 41–48.

Singh, N. P., & Singh, S. (2019). Building supply chain risk resilience. *Benchmarking: An International Journal, 26*(7), 2318–2342.

Snyder, L. V., & Shen, Z.J. M. (2006). *Managing Disruptions to Supply Chains. Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2006 Symposium*, Washington, DC: The National Academies Press. 139–167.

Snyder, L. V, Scaparra, M. P., Daskin, M. S., & Church, R. L. (2006). Planning for disruptions in supply chain networks. In proceedings of the *Models, methods, and applications for innovative decision making INFORMS*, 4-7 November 2006. Pittsburgh, United States. pp. 234–257.

Soni, U., Jain, V., & Kumar, S. (2014). Measuring supply chain resilience using a deterministic modeling approach. *Computers and Industrial Engineering, 74*(1), 11–25.

Starr, R., Newfrock, J., & Delurey, M. (2003). Enterprise resilience: managing risk in the networked economy. *Strategy and Business, 30*, 70–79.

Stearman, J. (2000). Systems thinking and modeling for a complex world. *MIT Sloan Management, 6*. 1-29.

Sterman, J. D. (1992). *System dynamics modeling for project management*. Cambridge, MA.

Stolker, R. J. M., Karydas, D. M., & Rouvroye, J. L. (2008). A comprehensive approach to assess operational resilience. In proceedings of the *Third Resilience Engineering Symposium*, 28-30 October 2008. Antibes-Juan-les-Pins, France, pp. 247–253.

Strydom, H., & Venter, L. (2005). *Sampling and sampling methods* (192–203). CSL.

Surjan, A., Kudo, S., & Uitto, J. I. (2016). *Risk and vulnerability. In Sustainable development and disaster risk reduction* (pp. 37–55). NY: Springer.

Tam, V. W. Y., Fung, I. W. H., Sing, M. C. P., & Ogunlana, S. O. (2015). Best practice of prefabrication implementation in the Hong Kong public and private sectors. *Journal of Cleaner Production, 109*, 216–231.

Tan, J., Zhang, P., Lo, K., Li, J., & Liu, S. (2017). Conceptualizing and measuring economic resilience of resource-based cities: Case study of Northeast China. *Chinese Geographical Science, 27*(3), 471–481.

Tan, W. C. K. (2002). *Practical research methods*. NJ: Prentice Hall.

Tan, W. J. (2020). *Modelling and simulation of supply chain resilience using complex system approaches*. Nanyang Technological University, Singapore.

Tang, C. S. (2006). Robust strategies for mitigating supply chain disruptions. *International Journal of Logistics: Research and Applications, 9*(1), 33–45.

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education, 2011*(2), 53–55.

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal, 18*(7), 509–533.

Tesch, R. (2013). *Qualitative research: Analysis types and software*. Oxfordshire: Routledge.

Thanoon, W. A., Peng, L. W., Kadir, M. R. A., Jaafar, M. S., & Salit, M. S. (2003). The Experiences of Malaysia and other countries in industrialised building system. In proceedings of the *International Conference on Industrialised Building Systems*, 10-11 September 2003. Kuala Lumpur, Malaysia, pp. 255–261.

Thomas, J., & Harden, A. (2008). Methods for the thematic synthesis of qualitative research in systematic reviews. *BMC Medical Research Methodology, 8*(1), 45.

Thomé, A. M. T., Scavarda, L. F., & Scavarda, A. J. (2016). Conducting systematic literature review in operations management. *Production Planning & Control, 27*(5), 408–420.

Tichy, N. M., Tushman, M. L., & Fombrun, C. (1979). Social network analysis for organizations. *Academy of Management Review, 4*(4), 507–519.

Tomlin, B. (2006). On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science, 52*(5), 639–657.

Trading Economics. (2020). *Hong Kong GDP.* https://tradingeconomics.com/ hong-kong/gdp

Tran, T. T. H., Childerhouse, P., & Deakins, E. (2016). Supply chain information sharing: challenges and risk mitigation strategies. *Journal of Manufacturing Technology Management, 27*(8), 1102–1126.

Treiblmaier, H. (2018). Optimal levels of (de)centralization for resilient supply chains. *International Journal of Logistics Management, 29*(1), 435–455.

Truong Quang, H., & Hara, Y. (2018). Risks and performance in supply chain: the push effect. *International Journal of Production Research, 56*(4), 1369–1388.

Tsai, C. C., & Lydia Wen, M. (2005). Research and trends in science education from 1998 to 2002: A content analysis of publication in selected journals. *International Journal of Science Education, 27*(1), 3–14.

Tsai, Y. Y., Chang, K. C., Lin, C. L., Lee, H., Tsai, F. J., Cheng, Y. W., & Tseng, S. H. (2005). Expression in pterygium by immunohistochemical analysis: a series report of 127 cases and review of the literature. *Cornea, 24*(5), 583–586.

Tserng, H. P., Dzeng, R., Lin, Y., & Lin, S. (2005). Mobile construction supply chain management using PDA and bar codes. *Computer‐Aided Civil and Infrastructure Engineering, 20(*4), 242‐264.

Tukamuhabwa, B. R., Stevenson, M., Busby, J., & Zorzini, M. (2015). Supply chain resilience: Definition, review and theoretical foundations for further study. *International Journal of Production Research, 53*(18), 5592–5623.

Tummala, V. M. R., & Schoenherr, T. (2011). An implementation decision framework for supply chain management: a case study. *International Journal of Logistics Systems and Management, 8*(2), 198–213.

Ulrich, K. T. (2003). *Product design and development*. NY: Tata McGraw-Hill Education.

Vaidyanathan, K., & O'Brien, W. (2004). Opportunities for IT to support the construction supply chain. Towards a Vision for Information Technology in Civil Engineering, In proceedings of the *4th Joint Symposium on IT in CE*, 15-16 November 2004. Nashville, Tennessee, pp. 1–19.

Vaismoradi, M., Turunen, H., & Bondas, T. (2013). Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. *Nursing & Health Sciences, 15*(3), 398–405.

Van Der Vegt, G. S., Essens, P., Wahlström, M., & George, G. (2015). *Managing risk and resilience.* Academy of Management Briarcliff Manor, NY.

Vecchi, A., & Vallisi, V. (2016). *Supply chain resilience. In Handbook of Research on Global Supply Chain Management*. IGI Global. https://doi.org/10.4018/978-1-4666-9639-6.ch009

Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *European Journal of Purchasing & Supply Management, 6*(3–4), 169–178.

Wang, J., Su, K., & Wu, Y. (2018). The Reliable Facility Location Problem Under Random Disruptions. *Wireless Personal Communications*, *102*(4), 2483-2497.

Wang, L. C., Lin, Y.-C., & Lin, P. H. (2007). Dynamic mobile RFID-based supply chain control and management system in construction. *Advanced Engineering Informatics, 21*(4), 377–390.

Wang, T., He, Q., Lu, Y., & Yang, D. (2018). How does organizational citizenship behavior (OCB) affect the performance of megaprojects? Insights from a system dynamic simulation. *Sustainability, 10*(6), 1708.

Wang, W., & Li, Y. (2016). Supply chain investments in capacity construction and disruption prevention. In proceedings of the *13th International Conference on Service Systems and Service Management, ICSSSM 2016*. 24-26 June 2016. Kunming, China. pp. 1-4.

Wang, Yaowu, Xue, X., & Shen, Q. (2005). MANS3C: An Agent-Based Multi-Attribute Negotiation Framework for Construction Supply Chain Coordination. In proceedings of the *Construction Research Congress 2005: Broadening Perspectives*, 5-7 April 2005. San Diego, California. pp. 1–10.

Wang, Yimin, Gilland, W., & Tomlin, B. (2010). Mitigating supply risk: Dual sourcing or process improvement? *Manufacturing & Service Operations Management, 12*(3), 489–510.

Wang, Z., Hu, H., & Gong, J. (2018). Simulation based multiple disturbances evaluation in the precast supply chain for improved disturbance prevention. *Journal of Cleaner Production, 177*, 232–244.

Wang, Z. L., Shen, H. C., Zuo, J., Shen, H. C., & Zuo, J. (2019). Risks in Prefabricated Buildings in China: Importance-Performance Analysis Approach. *Sustainability, 11*(12), 3450.

Wang, Z., Wang, T., Hu, H., Gong, J., Ren, X., & Xiao, Q. (2020). Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Automation in Construction, 111*, 103063.

Wedawatta, G., Ingirige, B., & Amaratunga, D. (2010). Building up resilienc e of construction sector SMEs and their supply chains to extreme weather events. *International Journal of Strategic Property Management, 14*(4), 362–375.

Wieland, A., & Wallenburg, C. M. (2012). Dealing with supply chain risks. *International Journal of Physical Distribution & Logistics Management, 42*(10), 887–905.

Wieland, A., & Wallenburg, C. M. (2013). The influence of relational competencies on supply chain resilience: A relational view. *International Journal of Physical Distribution and Logistics Management, 43*(4), 300–320.

Wikberg, F., Olofsson, T., Ekholm, A., Wikberg, F., Olofsson, T., & Ekholm, A. (2014). Design configuration with architectural objects : linking customer requirements with system capabilities in industrialized house-building platforms Design configuration with architectural objects : linking customer requirements with system capabilities in. *Construction Management and Economics, 32*(1–2), 196–207.

Wisner, B., Blaikie, P. M., Blaikie, P., Cannon, T., & Davis, I. (2004). *At risk: natural hazards, people's vulnerability and disasters*. UK: Psychology Press.

Wong, R., Hao, J., & Ho, C. M. F. (2003). Prefabricated building construction systems adopted in Hong Kong. In proceedings of the *International Association for Housing Science on Word Congress of Housing: Process and Product*, June 2003. Montreal, Canada.

Wu, L., Chuang, C.-H., & Hsu, C.-H. (2014). Information sharing and collaborative behaviors in enabling supply chain performance: A social exchange perspective. *International Journal of Production Economics, 148*, 122–132.

Wu, P., Xu, Y., Jin, R., Lu, Q., Madgwick, D., & Hancock, C. M. (2019). Perceptions towards risks involved in off-site construction in the integrated design & construction project delivery. *Journal of Cleaner Production, 213*, 899–914.

Wuni, I. Y., Shen, G. Q. P., & Mahmud, A. T. (2019). Critical risk factors in the application of modular integrated construction: a systematic review. *International Journal of Construction Management*, https://doi.org/10.1080/15623599.2019.1613212.

Xiao, W., Liu, Z., & Zhong, W. (2011). Multi-level fuzzy synthesis evaluation on construction supply chain risk. In proceedings of the *2011 Chinese Control and Decision Conference, CCDC 2011*, 23-25 May 2011, Mianyang, China, pp. 266–269.

Xiong, B., Skitmore, M., & Xia, B. (2015). A critical review of structural equation modeling applications in construction research. *Automation in Construction, 49*, 59–70. https://doi.org/https://doi.org/10.1016/j.autcon.2014.09.006

Xu, Y., Yeung, J. F. Y., Chan, A. P. C., Chan, D. W. M., Wang, S. Q., & Ke, Y. (2010). Developing a risk assessment model for PPP projects in China—A fuzzy synthetic evaluation approach. *Automation in Construction, 19*(7), 929–943.

Xu, Z., Zayed, T., & Niu, Y. (2020). Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore. *Journal of Cleaner Production, 245*, 118861.

Xue, X., Wang, Y., Shen, Q., & Yu, X. (2007). Coordination mechanisms for construction supply chain management in the Internet environment. *International Journal of Project Management, 25*(2), 150–157.

Yang, R. J., & Zou, P. X. W. (2014). Stakeholder-associated risks and their interactions in complex green building projects: A social network model. *Building and Environment, 73*, 208–222.

Yang, R. J., Zou, P. X. W., & Wang, J. (2016). Modelling stakeholder-associated risk networks in green building projects. *International Journal of Project Management, 34*(1), 66–81.

Yi, H., & Wang, Y. (2013). Trend of the research on public funded projects. *The Open Construction and Building Technology Journal, 7*(1), 51–62.

Yi, W., & Chan, A. P. C. (2014). Critical review of labor productivity research in construction journals. *Journal of Management in Engineering, 30*(2), 214–225.

Yin, R. K. (2017). *Case study research and applications: Design and methods.* Sage publications.

Yu, H., Al-Hussein, M., Al-Jibouri, S., & Telyas, A. (2013). Lean transformation in a modular building company: A case for implementation. *Journal of Management in Engineering, 29*(1), 103–111.

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control, 8*(3), 338–353.

Zainal, N. A., & Ingirige, B. (2018a). The dynamics of vulnerabilities and capabilities in improving resilience within Malaysian construction supply chain. *Construction Innovation, 18*(4), 412–432.

Zainal, N. A., & Ingirige, B. (2018b). Identification of the "pathogenic" Effects of Disruptions to Supply Chain Resilience in Construction. *Procedia Engineering, 212*, 467–474.

Zavala, A., Nowicki, D., & Ramirez-Marquez, J. E. (2019). Quantitative metrics to analyze supply chain resilience and associated costs. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 233*(2), 186–199.

Zhai, Y., Chen, K., Zhou, J. X., Cao, J., Lyu, Z., Jin, X., Shen, G. Q. P., Lu, W., & Huang, G. Q. (2019a). An Internet of Things-enabled BIM platform for modular integrated construction: A case study in Hong Kong. *Advanced Engineering Informatics, 42*, 100997.

Zhai, Y., & Huang, G. Q. (2017). Operational Hedging and Coordination in Prefabrication Construction Industry. *Procedia Manufacturing, 11*, 1178–1183.

Zhai, Y., Xu, G., & Huang, G. Q. (2019b). Buffer space hedging enabled production time variation coordination in prefabricated construction. *Computers & Industrial Engineering, 137*, 106082.

Zhai, Y., Zhong, R. Y., & Huang, G. Q. (2015). Towards operational hedging for logistics uncertainty management in prefabrication construction. *IFAC-PapersOnLine, 48*(3), 1128–1133.

Zhai, Y., Zhong, R. Y., & Huang, G. Q. (2018). Buffer space hedging and coordination in prefabricated construction supply chain management. *International Journal of Production Economics, 200*, 192–206.

Zhai, Y., Zhong, R. Y., Li, Z., & Huang, G. (2017). Production lead-time hedging and coordination in prefabricated construction supply chain management. *International Journal of Production Research, 55*(14), 3984–4002.

Zhang, B., Le, Y., Xia, B., & Skitmore, M. (2017). Causes of business-to-government corruption in the tendering process in China. *Journal of Management in Engineering, 33*(2), 5016022.

Zhang, H., & Yu, L. (2020). Dynamic transportation planning for prefabricated component supply chain. *Engineering, Construction and Architectural Management, 27*(9), 2553–2576.

Zhao, X., & Singhaputtangkul, N. (2016). Effects of Firm Characteristics on Enterprise Risk Management: Case Study of Chinese Construction Firms Operating in Singapore. *Journal of Management in Engineering, 32*(4), 5016008.

Zhong, R. Y., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., Ng, S. T., Lu, W., Shen, G. Q. P., & Huang, G. Q. (2017). Prefabricated construction enabled by the Internet-of-Things. *Automation in Construction, 76*, 59–70.