# MANAGING VULNERABILITIES AND CAPABILITIES FOR SUPPLY CHAIN RESILIENCE IN INDUSTRIALISED CONSTRUCTION


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Industrialised Construction (IC), as a modern construction technology is superior to conventional cast-in-situ concrete construction in many ways and has attracted immense attention from many countries over the past two decades. This widespread interest can be largely explained by the inherent superiority of the technology and its products. However, a major challenge faced by managers of IC is to anticipate and withstand its innate supply chain disruptions. Indeed, the IC supply chain is found to be quite complex, resulting in potential disruptions that can significantly affect performance levels. This, therefore, requires a new focus on disruption management that transcends 'conventional wisdom' and standard practices. Supply chain resilience (SCR) as a focus area for a new initiative, has emerged in other industries to address supply chain related challenges in effective disruption management by calling for supply chains that are less brittle and more adaptive. There is a dearth of literature in construction SCR, while the research gap is even wider and also more critical for SCR in IC. Therefore, a systematic literature review followed by an initial empirical study with site visits were performed in Hong Kong, by gathering, analysing and consolidating the relevant research data and findings, to develop a framework that identifies and maps vulnerabilities and capabilities for SCR in IC, thereby enabling deeper examination of how best to address and manage them together and more effectively. Thus, the main thrust of this study is to propose a basic framework to enhance SCR in IC by first identifying potential supply chain disruptions; and next proposing well-informed management strategies to withstand these disruptions.



Keywords: industrialised construction, supply chain resilience, vulnerabilities


## INTRODUCTION

The construction industry has suffered for decades from remarkably poor productivity compared to the other industrial sectors (Barbosa *et al.,* 2017). Hence, a recent report from the McKinsey Global Institute, suggests seven areas that can boost construction sector productivity, including improving its Supply Chain (SC) and onsite execution. According to this report, it should be possible to achieve a 5-10 times productivity boost by partially moving to a manufacturing-style production system. In this context, Industrialised Construction (IC) based on prefabricated building components and systems has emerged as an attractive approach that is perceived to improve efficiency,


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Mudiyanselage, A C E E, Shen, G Q P and Kumaraswamy, M M (2019) Managing Vulnerabilities and Capabilities for Supply Chain Resilience in Industrialised Construction *In:* Gorse, C and Neilson, C J (Eds) *Proceedings of the 35th Annual ARCOM Conference,* 2-4 September 2019, Leeds, UK, Association of Researchers in Construction Management, 811-820.

flow and quality of the construction (Lawson *et al.,* 2011), reduce project duration and the associated costs and, to improve the working conditions at site (Bataglin *et al.,* 2017). IC is seen as a means to address a series of dilemmas and constraints in the construction industry, including in Hong Kong (HK) IC is also envisaged to gain momentum owing to its potential benefits such as environment-friendly, better quality, cleaner and safer working environment (Li, 2016). However, the fragmented nature of prefabricated SC; design, manufacturing, transportation, and on-site assembly generates a variety of vulnerabilities in IC in HK, and these disruptions beset the industrial performance (Li *et al.,* 2016). Although conventional Risk Management (RM) is designed to help to address these vulnerabilities, it is evident that it cannot adequately address all the SC disruptions (Van Der Vegt *et al.,* 2015), hence requiring a new focus on disruption management that transcends 'conventional wisdom' and standard practices. In this context, the emerging concept of 'resilience' has recently attracted the growing interest of academic researchers and industry practitioners.

Resilience goes beyond mitigating risks. It enables organisations to deal with disruptions more effectively (Fiksel, 2015). Supply Chain Resilience (SCR) also goes beyond the traditional SC RM practices (Zavala *et al.,* 2018) and enables handling the disruptions which cannot be handled within the traditional RM framework. However, there is a dearth of literature findings on SCR in construction practices [only one publication was found; Zainal and Ingirige (2018)], and there was no known or published research found for SCR in IC. Therefore, this study aims to propose a basic framework to enhance SCR in IC by first identifying potential SC vulnerabilities; and next recommending well-informed capabilities to withstand them effectively.

## LITERATURE REVIEW

Also called as the off-site construction and prefabricated construction, IC refers to structures built at a location other than the location of assembly (Gibb, 1999). IC includes various approaches: precast panels, columns and other components, prefabricated units and more recently pre-engineered modular units (Gosling *et al.,* 2016). Encouraging IC through the extensive use of pre-cast technology and minimising on-site construction, would boost the productivity of the construction industry (Barbosa *et al.,* 2017). This was recently exemplified by the Mini Sky City construction in China: A 57 storied skyscraper construction. It required 19 working days instead of more than one-year construction required by the conventional construction methods (Chang *et al.,* 2018). Besides, IC provides an effective alternative to the traditional site-based construction with improved quality, reduced waste, lowered labor requirements at site (Rwamamara, 2007), reduced lifecycle cost, improved sustainability (Gibb and Pendlebury, 2006), better controlled built environment and enhanced safety (Chang *et al.,* 2018). IC has attracted worldwide concern because of its significant role in the creation of sustainable growth (Hong *et al.,* 2018). Therefore, there is no major general argument holding back the application of IC in many countries; Japan, Singapore, UK, and USA (Jaillon and Poon, 2009). Application of IC in the HK construction industry is also not new due to its wide application in the public housing sector (Li *et al.,* 2016). However, the application of IC in HK remains at a low level compared to the other developed countries (Li *et al.,* 2016). Lack of accurate information on managing the pre-cast units, poor information sharing among the project stakeholders and fragmentation and discontinuity of the entire prefabrication SC, are the possible causes behind the issue. In IC SC, there are three phases namely; prefabrication, logistics and onsite assembly (Zhai and Huang, 2017). All these phases are fragmented and subjected to discontinuity, also given the different stakeholders assigned to perform different tasks (Zhai *et al.,* 2017). Hence, design information should be shared in a timely manner with manufacturers without leaving ambiguities, while prefabricated elements should be received on site without any disturbances to on-site assembly, to ensure the timely completion of projects. However, disruptions such as machine breakdown, traffic jam, low efficiency of customs clearance and damages to the modular units, are common in each phase of the IC SC (Zhai and Huang, 2017). If these situations are not managed effectively and efficiently, time and cost savings from adopting IC will easily wither away. Any disturbance at any point of the IC SC will impact the entire process, since it is relatively unchangeable and fixed once scheduled (Zhai and Huang, 2017). This highlights the need for extensive SC management in IC.

Although there are numerous RM strategies applied in the construction industry to manage these disruptions (Zavala *et al.,* 2018), they involve hazard identification, risk assessment, controlled implementation and review (Pettit *et al.,* 2010) by employing empirical data, mathematical modelling and probability distributions, in making future predictions where it is highly difficult to identify all potential risks to conduct adequate risk assessments (Van Der Vegt *et al.,* 2015). Mostly, the disruptions have emerged as a set of joint events and generate cascading impacts which are hard to anticipate and predict. Indeed, these approaches are unable to respond to low-probability, high-impact disruptive events adequately, and they cannot deal with the enforceable events (Pettit *et al.,* 2010). Hence, the growing attention of academic researchers and the industry practitioners have shifted towards SCR which goes beyond the traditional SC RM practices (Zavala *et al.,* 2018) and, enables handling the disruptions which cannot be coped within the RM framework.

SCR is defined as ‘the ability to react proactively to disturbances and to return to its original state or a more desirable one’ (Ponomarov and Holcomb, 2009). It is the balance between vulnerabilities [key disruptions which disturb the normal construction process and are unanticipated and unplanned (Zavala *et al.,* 2018)] and the associated capabilities that enable an enterprise to anticipate and withstand vulnerabilities (Pettit *et al.,* 2013). Based on the empirical findings, Pettit *et al.,* (2013) developed a SCR assessment tool for manufacturing and service firms. Recently, considering the dynamics of SC vulnerabilities and capabilities, Zainal and Ingirige (2018) proposed a SCR framework for Malaysian public construction projects. However, less attention has been paid to researching on SCR in the construction industry (Zainal and Ingirige, 2018). As an emerging research area, the research gap is highly significant in IC, and it is essential to explore SCR in IC due to the following reasons; (a) IC SCs are complex and associated with inherent disruptions (Zhai and Huang, 2017), (b) they are also vulnerable to many unforeseeable disruptions (Luo *et al.,* 2018); (c) IC SCs are relatively fixed and unchangeable once scheduled (Zhai *et al.,* 2017) hence the disruptions may alleviate the cascading impacts; and (d) although the industry practices traditional RM approaches, they are unable to assess the SC complexities, and prepare SCs for future unknowns including black swan events. The foregoing reasons underpin the rationale and imperative for this study which aims to propose a basic framework to enhance SCR in IC for a value-added SC.

## RESEARCH METHODOLOGY

This paper presents an important part of an ongoing PhD study which aims at developing an evaluation model to enhance SCR in IC in HK. Hence, this study targets to build a basic framework for improving SCR in IC, based on the data retrieved from the published literature and then strengthen the findings through a preliminary empirical study. Therefore, an in-depth systematic review of literature through meta-analysis was first conducted as suggested by the studies of Osei-Kyei and Chan (2015) and Owusu *et al.,* (2018) to identify, retrieve, and examine the extensive literature on SC vulnerabilities and capabilities in IC SCs. This approach consisted of two phases namely; (a) searching for and identifying the targeted papers and (b) examining and analysing the selected papers. During phase 1, two broad preparatory desktop searches were conducted separately through a powerful search engine Scopus using title/ abstract/keyword search option to identify the research papers on vulnerabilities and capabilities in SCR. 139 and 167 publications on vulnerabilities and capabilities were retrieved separately from this initial search and 54 and 41 papers were filtered to the secondary screening based on an in-depth visual examination on the title/abstract/ keywords. After thorough scrutiny, 36 and 28 publications (respectively) were finally selected for further investigation and analysis. Selected publications were then subjected to the content analysis and 37 vulnerabilities, and 58 capabilities were retrieved as appropriate for this specific IC focused study.

These factors were then categorised under 6 vulnerability constructs and 12 capability constructs based on a thematic analysis process. During the thematic analysis of the variables, the authors identified identical relationships separately within these vulnerability factors and also within these determined capability factors, respectively. Hence, by adhering to the studies of Pettit *et al.,* (2013) and Zainal and Ingirige (2018); and the thematic analysis research method, identified 37 variables were categorised under six constructs.

| Vulnerability Category | Explanation | Referred studies for categorisation |
|---|---|---|
| Project organisational Vulnerabilities | Arising from the inadequate strategic business decisions undertaken, poor management decisions and staff within the organisation and human resources availability | Pettit, Croxton, and Fiksel (2013) – 7 categories based on global manufacturing and service firms; Zainal and Ingirige (2018) – 11 categories based on Malaysian public projects; Owusu et al. (2018) - thematic analysis research method for developing constructs |
| External Environmental Vulnerabilities | Arising from the external environment which is beyond the SC's control | |
| Procedural Vulnerabilities | Arising from the operation at any node of the SC and can be considered as the process-based disruptions | |
| Technological Vulnerabilities | Arising from technology changes or failures in a SC | |
| Financial Vulnerabilities | Arising from liquidity or credit issues relating to money and poor management of monitory assets and insolvency | |
| Supplier/Customer Vulnerabilities | Arising from the susceptibility factors allied with suppliers and customers of the SC | |

| Capability Category | Explanation | Referred studies for categorisation |
|---|---|---|
| Flexibility | Ability to quickly mobilise resources when required | Pettit et al., (2010) – 14 categories related to the limited brands in the manufacturing industry; Zainal and Ingirige (2018) – 12 constructs related to Malaysian public projects; Owusu et al. (2018) - thematic analysis research method for developing constructs |
| Capacity | Availability of resources in the SC to enable continuous output in IC | |
| Efficiency | SC capability to produce outputs with minimum resources | |
| Visibility | Having knowledge on the status of current operating resources in the SC and the SC environment | |
| Adaptability | Ability to modify operations in response to disruptions or opportunities | |
| Anticipation | Ability to detect potential future disruptive events in the SCs | |
| Recovery | Ability to promptly return to normal operational state after a disruption | |
| Dispersion | SC capability which enables decentralisation of resources and clients | |
| Collaboration | Ability to work effectively with the other parties for mutual benefit | |
| Market Position | Status of an organisation or its products/services in specific markets | |
| Security | Ability to defend against deliberate intrusions | |
| Financial Strength | Capacity to absorb fluctuations in the cash flow | |

*Figure 1: Categorisation of factors*

Similarly, 58 SCC were categorised into 12 constructs based on the study protocols and developments by Pettit *et al.,* (2010) and Zainal and Ingirige (2018) during the thematic analysis process. Figure 1 clearly explicates the categorisation process and the development of the constructs in this study. Finally, these findings contributed to developing a conceptual framework for achieving SCR in IC and furthered to a preliminary empirical study.

The qualitative approach in research facilitates distinct advantages of focusing on a specific set of people, an in-depth study on broad topics, and representing the views and perspectives of the people (Yin, 2017). Therefore, this study adhered to a social constructionism approach by conducting in-depth expert opinion survey in collecting preliminary data to strengthen the conceptual framework and to develop a basic framework of the study. Six semi-structured interviews along with site visits were conducted of relevant industry experts in HK who were well experienced in IC for 10-30 years (Table 1 presents the interviewee profile). Collected information was analysed using N-vivo software. The interview findings provided empirical justifications of the developed constructs in the basic framework based on the actual situation in the industry. However, the ongoing research study will further follow a mixed method approach in collecting data including subject matter expert surveys and case studies to evaluate the constructs and validate the findings for HK construction industry. This paper is based on the initial results of this PhD research study and may be seen to lack dense empirical validation of the results. However, it is an essential first stage output which forms the basis for the next stage. The forthcoming sections of this paper discuss the basic framework, report the findings, and derive the conclusions with a proposed way forward.

*Table 1: Profile of the interviewed experts [Note: statements by them will be cited hereafter, followed by [E1] or [E1, E2] to convey that these were by E1, or both E1 and E2]*

| Interviewee | Experience | Position | Organisation type |
|---|---|---|---|
| E1 | 27 years | Director | Government authority |
| E2 | 12 years | Assistant Project Manager | Private Contractor |
| E3 | 15 years | Project Manager | Private Contractor |
| E4 | 10 years | Site Engineer | Private Contractor |
| E5 | 30 years | Project Manager | Contractor and developer |
| E6 | 22 years | Director | Government authority |

## Basic Framework and Discussion

Results derived from the systematic analysis of the literature on SCR and the results of the preliminary experts' opinion survey were drawn upon to develop the basic framework as shown in Figure 2. As determined from the previous literature, there are six vulnerability constructs namely: Project Organizational; Procedural; Supplier/ customer; Technological; External Environmental; and Financial Vulnerabilities that retard the performance of IC SCs. "There must be many vulnerabilities in a project, and our team has to forecast project programme to check whether these uncertainties can be solved before the project commenced. They claim money, time and affect the completion of project sequence in the short term and the long term" [E2, E3].

External environmental vulnerabilities (disruptions from the external environment which are beyond the SC's control) can be either man-made or 'Act-of-God' situations. "Probability of happening natural disasters, terrorism/war, epidemics are very less in HK. But, political economy changes, adverse weather, initiating new regulations are much common here" [E1]. "Recently, industrialisation was highly vulnerable to the regulation and policy changes. Also, it was very prevalent to see machine breakdowns especially the tower crane breakdowns which caused delays" [E2, E3, E5]." From the last typhoon, we faced damages. We applied to recover them from insurance, so we were safe" [E2]. Although terrorism/war, political instability are ranked top in the literature (Masood and Choudhry, 2010), in IC SCs, mainly logistics are affected by the political and regulatory changes (Chauhan *et al.,* 2015) and assembly is affected by the adverse weather (Wang *et al.,* 2018). "However, the impact is lesser compared to the conventional construction" [E6].

Project organisational vulnerabilities are possible with poor management and operational issues. In IC, labor strikes, disputes are often, and significant (Wang *et al.,* 2018). Communication issues between the stakeholder's cause disputes and exert strong direct influences on other IC vulnerabilities such as design changes/variations (Luo *et al.,* 2018). Planning and scheduling errors, outsourcing also cause assembly problems and poor SC visibility (Wang *et al.,* 2018). "Labour is the problematic resource in HK. Disputes, loss of skilled labour and frauds interrupt the project execution" [E1, E6]. "Inadequate information exchange causes serious design changes and delays" [E5]. "We recently faced such a delay in constructing a column since the allocated gap was not enough to assemble" [E2, E4]. "Mostly they are tolerance issues in IC. If one unit is cast with 1mm error, the process becomes vulnerable to assembly problems which cause cost, time overrun" [E3, E5].

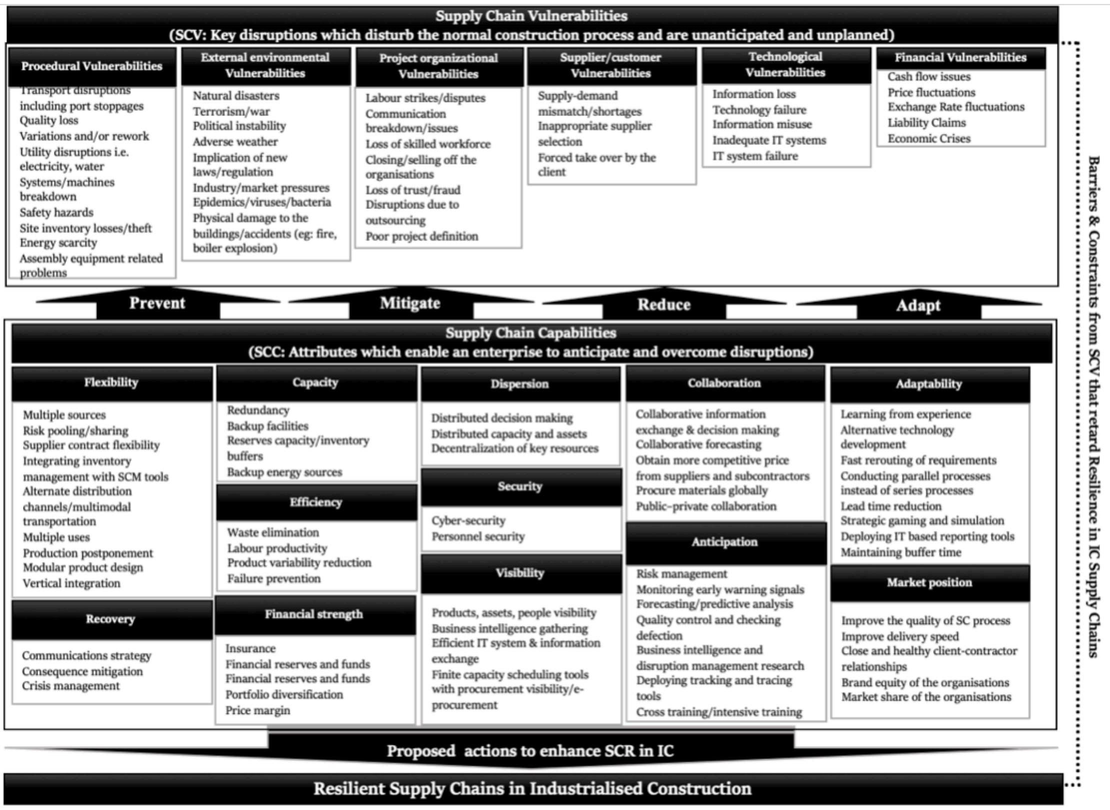


*Figure 2: Basic framework for achieving SCR in IC*

Procedural vulnerabilities occur from the operation at any node of the supply-distribution-assembly chain. IC SCs are profoundly affected by transport disruptions (Zhai and Huang, 2017). "These are due to traffic jams, customs clearance issues, and damages to the units in transporting" [E1-E6]. "Many of our materials come from Mainland China. And we hold the material at the custom for customs clearance. One or two-days delay is expected there. Sometimes they wait until I call them, to inform me of the delay" [E2]. " Some fittings come from Europe. It will take a longer transportation time. Once there was a delay and, logistic company took 3 months for delivery. So, we need to place orders earlier" [E4]. Further, IC SCs are affected by technical problems with vehicles, too late or too early delivery, and insufficient transportation capacity (Wang *et al.,* 2018). Safety hazards are also a concern in IC assembly (Zhai and Huang, 2017). "Although IC provides a safe working environment, collapsing elements may cause severe hazards which we faced a few years ago" [E3]. "The impact of risks on IC is 'violent' due to shorter schedules, difficulty in rectifying errors, its inflexibility to design changes during installation, and the prohibitive cost of reworks compared to traditional construction" [E5].

Technological vulnerabilities arise from disruptions of technology changes or failures. Fragmentation of the IC SC results in information losses (Zhai and Huang, 2017). An IC SC is affected by such technological problems (Wang *et al.,* 2018) and hence developed Building Information Modelling (BIM) and Radio Frequency Identification (RFID) enabled IT platforms to achieve real-time visibility and traceability of data in HK (Zhong *et al.,* 2017). "Although we use advanced IT systems, they are not enough to track the logistics failure. Now we are using RFID to trace the process but, they do not capture the whole sequence. Therefore, we are going to implement a BIM-based platform and are working in collaboration with a university research team" [E2-E4].

It is essential to maintain strong financial consistency to withstand financial vulnerabilities in construction SCs (Zainal and Ingirige, 2018). In IC, it is a must to maintain a healthy cash flow to payback prefab manufacturer on time (Kadir *et al.,* 2005); otherwise, the entire SC may collapse. "As a contractor, our products are affected by price fluctuations in HK. Also, we are open to cost overruns due to the construction sequence changes" [E3]. "Anyway, we try to minimise the impact by allowing contingency in the budget" [E2]. "IC reduces time and cost of construction. It makes savings to the clients. Therefore, these projects are financially feasible in HK, and we haven't faced many issues financially" [E1, E5, E6].

Supplier/customer vulnerabilities arise from the client and the supplier who are the critical nodes of a SC. These begin with the supply resource shortages in IC (Zhai and Huang, 2017), accumulate with the supply-demand mismatch and end up in unmet client needs. Especially in IC, insufficient material quantity, poor quality of materials, scarcity of raw parts, and inadequate production resources such as moulds cause the supply-demand mismatch (Wang *et al.,* 2018). "Delaying prefab items cause very negative impacts on our projects, and we need to be careful in selecting the suppliers. Based on the previous project records, we go for the same suppliers. But, if they were repeating the mistakes, we may find another. Generally, we face delays at least once a month" [E2-E4].

Therefore, there is a dire need for ‘counteractive’ capabilities to successfully withstand these vulnerabilities (Kurniawan and Zailani, 2010). Capabilities including flexibility, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, market position, security, and financial strength can prevent, mitigate, reduce or adapt vulnerabilities. "We can have alternative suppliers, flexible agreements to improve SC flexibility" [E3]. "We can integrate the ERP system with SC management to easily detect resource shortages" [E2]. Further, E5 highlighted the need of multifunctional organisations which have vertically integrated SC configuration between logistics, on-site assembly, and manufacturer to improve the SC flexibility. "As we frequently face tower crane breakdowns, low tolerances cause problems in assembly and supply shortages; it is important to have back-up facilities, safety stocks" [E3, E4]. Also, conducting simulation trials in a virtual environment is beneficial in mitigating the risks and rework cost in assembly (Li *et al.,* 2018). "Most of the precast members are heavy and bulky; we need to pay special attention in installation. Workers need to understand the installation programmes fully. If not, accidents may occur" [E2, E3, E5]. This urges adequate fall protection systems during on-site assembly of components and developing training programmes to the workers for enhanced safety (Fard *et al.,* 2017).

"As IC includes vertical transporting of heavy and bulky items, alternative/multimodal transportation is urged to avoid vulnerabilities" [E3, E5]. Integration of BIM and RFID in IC SCs may increase the visibility, collaborative data interoperability and the traceability of the process (Zhong *et al.,* 2017). Integrating BIM with Geo-Information Systems enhance logistical traceability in IC SCs (Irizarry *et al.,* 2013). "Anyway, efficient IT system is vital in IC SCs to link design, prefab, and on-site assembly processes" [E1]. Cost of rearrangement and tardiness penalty can be reduced by maintaining adequate inventory buffers as hedging against SC uncertainty (Zhai *et al.,* 2018). "We use linear programming to optimise inventory buffers in IC to overcome wastage" [E2, E3]. Production, operational and transportation lead time hedging were considered as effective ways to improve SC adaptability in IC (Zhai *et al.,* 2018). "As there are many delays due to transportation, I used to ensure a larger buffer time for me in the schedule, and I make the orders early" [E4]. "Having insurance and contingency allocations, work as a safeguard to bear the uncertainties and losses. It is essential in IC because the construction sequence is fixed and standardised" [E1-E6]. "In HK, most of the public housing developments are prefabricated constructions. There, contractors work together with the public authorities" [E1-E6]. As witnessed, HK IC effectively maintains public-private collaboration as a risk-sharing mechanism to withstand unforeseeable disruptions (Li *et al.,* 2018, Luo *et al.,* 2015).

## CONCLUSIONS AND A WAY FORWARD

Findings presented in the current paper identify the vulnerabilities that retard the performance of IC SCs while a suite of counteractive capabilities that can help to withstand these vulnerabilities is also identified. Their juxtaposition is found to be useful and timely to investigate the dynamics of SCR in IC. In this respect, the basic framework to achieve SCR in IC was carefully developed by extracting, consolidating and generalising relevant literature findings and reinforcing them through a preliminary empirical study. The framework would be vital to IC SC stakeholders, not just in terms of identifying vulnerabilities, but also for formulating and/or nurturing adequate capability measures to deal with these vulnerabilities and thereby increase the resilience of IC SCs. This research and development framework will be further explored in the next phase of the current research study through strong empirical justifications and case study validations to formulate an evaluation model to enhance SCR in IC in HK. The outcome would provide pointers and add value to IC SC stakeholders in formulating initiatives to boost SCR, hence enhancing SC performance and productivity in IC.

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