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Critical Supply Chain Vulnerabilities Affecting Supply Chain Resilience of Industrialized Construction in Hong Kong

Abstract

Purpose: Industrialized Construction (IC) has been recognized as a game-changing approach in Hong Kong (HK). However, the increasing risks of disruptions in IC Supply Chains (SCs) raise SC vulnerability levels, prompting attention to developing Supply Chain Resilience (SCR). Since SCR is only attainable through overcoming Critical Supply Chain Vulnerabilities (CSCV) with enhanced SC capabilities, this study first aimed to determine the most CSCV of ICSCs by addressing this current research gap and practical need.

Design/methodology/approach: Drawing on SCV factors identified from a precursor literature review, an empirical study of IC in HK was conducted using a questionnaire survey and interviews with industry experts. Focused significance analysis of the data collected through questionnaire survey enabled the selection of 26 CSCV as appropriate to IC. Next, factor analysis was conducted, enabling the grouping of these CSCV under five components. The results were verified and reinforced by interview findings.

Findings: The results revealed 26 CSCV pertinent to resilient ICSCs in HK with five underlying components: economic, technological, procedural, organizational, and production-based vulnerabilities. Loss of skilled labour is the most critical vulnerability, whereas organizational SCV is the most critical component identified.

Originality/value: Findings of this study 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. This should trigger future studies to map CSCV with appropriate capabilities in developing an envisaged powerful assessment model for evaluating the SCR in IC in HK.

Keywords: Industrialized Construction (IC); Supply Chain Vulnerabilities (SCV); Critical Supply Chain Vulnerabilities (CSCV); Supply Chain Resilience (SCR)

Introduction

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). The construction industry is reputed to be an engine of growth for economies in general, including of Hong Kong (HK) whose gross domestic product 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 their pivotal role, 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 Hong Kong around the turn of this century (Egan, 1998; C21, 1999; CIRC, 2001). 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 Hong Kong (CICID, 2011; Wang et al., 2019).

In one major response, Industrialized Construction (IC) is proliferating worldwide (Goodier et al., 2019), enabling better quality, improved safety and reliability in the construction process (Wang et al., 2019). IC covers the streamlining of processes and products from offsite fabrication (Gibb, 1999). 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.

In this context, IC has been widely adopted in Hong Kong (HK) construction practices, 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 labour, an ageing workforce, space constraints, and escalating costs, the government has encouraged IC (Zhai et al., 2019). Space and logistics constraints are especially serious in Hong Kong 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 (Ekanayake et al., 2019). Overall, IC is a game-changing and innovative approach that transforms cumbersome in-situ construction methods into more integrated, value-driven production and assembly processes of mostly prefabricated components.

However, rapidly increasing expectations from IC in HK have highlighted risks from potential Supply Chain Vulnerabilities (SCV), thereby opening a hitherto neglected research area of achieving resilient Supply Chains in IC (ICSCs). The ICSCs span across three phases, of factory prefabrication, logistics, and on-site assembly (Luo et al., 2019), and are hence, subject to the weaknesses of fragmentation, poor interoperability, and discontinuity (Li et al., 2018). These weaknesses, in turn, arise from and foster numerous vulnerabilities that have been shown to adversely influence the performance of ICSCs (Ekanayake et al., 2020). Clearly, the vulnerabilities in ICSCs would necessarily be more in number and deeper in impact than in traditional construction SCs 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 on site, or even closer to site and in the same jurisdiction. Such geographically (more) dispersed and complex ICSCs may generate continual turbulence and trigger unpredictable disruptions, causing significant threats to project implementation (Ekanayake et al., 2019). Hence, effective management of SCV is critical for ensuring timely project delivery in IC (Li et al., 2018). Since traditional risk management practices are unable to cope with all these vulnerabilities fully and effectively (Van Der Vegt et al., 2015; Zainal and Ingirige, 2018; Ekanayake et al., 2019), it is timely to develop and implement Supply Chain Resilience (SCR) measures that enhance SC capabilities to alleviate, if not overcome, SCV in general (Pettit et al., 2019) and those in IC in particular (Ekanayake et al., 2020). Besides, 80% of global organizations assign SCR the top priority in handling SCV (Sabahi and Parast, 2020). SCR provokes anticipation, flexibility, and visibility of SCs to ensure high performance and customer value (Chowdhury et al., 2019). Thus, effective withstanding of SCV could reduce additional cost implications, project delays, and safety hazards by boosting ICSC 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). Therefore, it is vital to accurately identify SCV, especially the Critical SCV (CSCV), affecting SCR 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 (Enshassi et al., 2019; Du et al., 2019). Given the above-mentioned industry imperatives 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. By focusing on the CSCV identified from this study, it is expected that the industry professionals will be far better informed on the resilience imperatives for value-enhanced ICSCs in HK. The level of criticality of the vulnerabilities is further explained, facilitating a better understanding of the critical vulnerability factors which enables decisions on developing appropriate capability measures to counteract them more effectively. Moreover, the findings of this study are expected to encourage a future exercise to develop an integrated model of CSCV and appropriate capability initiatives to counteract these CSCV, in turn, pointing to directions and suitable strategies for boosting SCR in IC in HK. Based on the above premises, an empirical study was conducted to realise the study aim. The details of the research methodology adopted, results derived, consequential discussion and conclusions drawn from this study are described in the forthcoming sections.

Research Background

Disruptions at any point of time or in any 'link' of an ICSC will cascade through the SC to impact on the entire process, as ICSCs are relatively unchangeable once contractually fixed and scheduled (Zhai & Huang, 2017) on a project. Further, SCs are currently quite complex due to extensive outsourcing. In this circumstance, identifying and overcoming SCV are key to minimizing unanticipated disruptions and achieve resilient SCs (Ekanayake et al., 2019). Furthermore, research on SCV in the context of SCR has been motivated over recent years (Zainal & Ingirige, 2018) and recently emerged in the construction industry.

CSCV in IC, affecting SCR

The configuration of the SCs and the associated SCV differ across countries (Luo et al., 2019) and different industries (Pettit et al., 2019), thereby necessitating separate studies for different industrial contexts. The construction industry is unique and different from other industries such as manufacturing (Ekanayake et al., 2020), but, IC is expected to draw on the best practices of both construction and manufacturing industries. Therefore, IC supply chains are also distinctive from traditional construction SCs. Considering IC, Ekanayake et al. (2020) identified 37 vulnerabilities through an in-depth systematic review of the literature. However, the findings did not reveal the level of criticality of each SCV and encouraged an empirical study to unveil CSCV that are appropriate and applicable to IC in HK. Compared to other jurisdictions, the IC sector in HK faces identical SC disruptions due to lack of skilled workforce and a very high cost of construction (CIC, 2019). Further, the specially limited space allocation of HK construction sites (Zhai et al., 2019) makes on-site logistics more complex and require more attention to site planning and management in this particularly high-density/high-rise city. These constraints are aggravated by the contractors not having in-house prefabrication yards in HK. Therefore, prefabrication yards are located in Mainland China, and it is required to transport prefabricated components across the border to HK. The additional distances, constraints and cross border logistics exposes the entire SC to more vulnerabilities and disruptions, causing cost and time overruns. Critical disruptions would cause serious issues to project success and delivery (Wu et al., 2019). Hence, CSCV would cause acute disruptions in achieving resilient SCs and would significantly disturb the normal SC operations of IC significantly.

Some studies attempted to identify critical factors related to IC in general (Wuni and Shen, 2020) and stakeholder-related SC risks in HK IC (Luo et al., 2019). According to Luo et al. (2019), poor planning of resources and schedule leads to the highest risk in IC. In China, the highest risk is ‘higher overall cost’ (Wang et al., 2019) and in Singapore, poor coordination between stakeholders is responsible for more risks (Hwang et al., 2018). In HK, ICSCs are highly vulnerable to transport disruptions due to the extensive outsourcing of prefabricated components from China (Ekanayake et al., 2019). These could be due to port stoppages, customs clearance issues, traffic jams, and damages to the units during transporting (Zhai and Huang, 2017). Also, the SCs are affected by technical problems with vehicles, late or too early delivery, and carrying oversized segments (Ekanayake et al., 2020). Communication issues, including breakdowns, result in variations (Luo et al., 2019) which are the most cost significant issues in IC, as ICSC arrangements are relatively fixed after scheduling (Zhai and Huang, 2017). Loss of talent and unavailability of skilled workforce and labour strikes also affect SC performance and become more important in IC, especially in HK, as skilled labour is a critical resource (Ekanayake et al., 2020). Further, inventory losses, machine breakdowns, safety hazards, including damages and accidents, are also common in the assembly process (Zhai and Huang, 2017).

Although these disruptions affect the performance of ICSCs, the criticality of each factor has not been investigated in previous research and attempts were not focused on developing resilient SCs. Besides, shortfalls in construction industry performance levels adversely affect national economic productivity, since the construction industry is a key economic driver (Bao et al., 2020) as explicated at the outset in the Introduction. Given this background, this study, firstly, attempted to identify CSCV associated with ICSCs in HK and then to investigate and suggest strong measures to prevent/ mitigate/adapt these CSCV, developing resilient and value-enhanced SCs in IC. In turn, resilient SCs would enhance the performance (Chowdhury et al., 2019) of the construction industry by significantly contributing to global economic development as well (Ahmad et al., 2020).

Research Method and Approach

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. Figure 1 visually summarizes the research methods, their flow and interactions in this study.

(Insert Figure 1 here)

Accordingly, a set of 37 SCV affecting SCR in IC was determined from a systematic literature review study of Ekanayake et al. (2020). A preliminary study was then conducted to test the significance, comprehensiveness, and applicability to HK IC, of the selected list of SCV factors. Four professors who possess vast relevant knowledge and industry experience were approached in this exercise. After a thorough consideration of the factors, the participants recommended to remove ‘nuclear/radiation attacks’ since they are improbable in HK IC. A relevant and complete list of 36 SCV were confirmed after the preliminary study (Table 1). Thereafter, a mixed-method approach to data collection was employed using survey and interviews as the strategies. The time horizon was cross-sectional in this study in which a single dataset was collected.

(Insert Table 1 here)

Data Collection

A questionnaire was developed containing 36 confirmed SCV factors following the preliminary study. A five-point Likert scale was adopted, and the questionnaire respondents were requested to grade the identified SCV from 1 (not vulnerable) to 5 (extremely vulnerable). This scale was used due to its relative brevity (Adabre and Chan, 2019). Finally, additional rows were provided for open-ended responses to add any known SCV that were not captured in the preliminary study. Also, a semi-structured interview guideline was prepared to obtain additional information regarding SCV. These data collection tools were refined and used for further data collection after 'pilot testing' of them 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.

According to Table 2, the respondents selected for the main 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. A purposive sampling approach was first chosen to arrive at the selection of suitable respondents for this study (Owusu and Chan, 2018) and the respondents were identified by exploring their business profiles, attending seminars related to IC conducted by them, and through industry-based contacts. Thereafter, snow-ball sampling technique was also used to expand the respondent 'catchment area' for this study. All the respondents were contacted face-to-face or through online (Skype) interviews. 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. The total of 76 valid responses obtained were regarded as suitable for further analysis, considering 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 the international survey-based studies (Adabre and Chan, 2019; Owusu and Chan, 2018; Darko and Chan, 2018), while this sample size is generally adequate to derive significant conclusions regarding a subject area of this nature (Owusu and Chan, 2018). According to Ott and Longnecker (2015), a sample size of 30 is deemed to be representative of any group. Table 2 presents the background information of the respondents.

(Insert Table 2 here)

Data Analysis

This paper mainly presents the results of the quantitative data analysis. The collected qualitative data were used to provide empirical justifications to the quantitative findings in the discussion section. The Statistical Package for Social Sciences (SPSS), IBM version 25, was used to analyze the questionnaire findings. Following the studies of Osei-Kyei and Chan (2017); Adabre and Chan (2019), this study also deployed the descriptive means and normalization analysis to determine the CSCV factors. 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 SCV factor are shown in Table 1. SCV were ranked according to the M value. As several factors received the same M score, those factors were ranked considering their SD.

Internal reliability, and data normality test

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, 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 and Dennick, 2011). Acceptable values of alpha, ranging from 0.70 to 0.95, whereas the effective limit is between 0.70-0.90 (Tavakol and Dennick, 2011). In this study, the alpha coefficient of 0.863 shows 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 and Chan, 2018). Therefore, the Shapiro-Wilk test was conducted as it is commonly used to determine data distribution (Owusu and Chan, 2018) since it is 'the most powerful normality test' (Razali and Wah, 2011). The null hypothesis for this test stipulates 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 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.

Factor analysis

Factor analysis 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, 2011). Therefore, factor analysis was conducted in this study to appropriately categorize and group the identified CSCV. The Kaiser-Meyer-Olkin test (KMO) and Bartlett's test of sphericity were conducted to verify data for the factor analysis (Adabre and 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 and 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 and Chan, 2018). 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, 2011). However, 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). 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 3.

(Insert Table 3 here)

Thereby, factor extraction was done using the principal component analysis approach to determine the relevant variables. The eigenvalue was set as the criterion for selecting the variables, where variables 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 3). Only 24 CSCV were successfully loaded into the five underlying components. 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 and 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 3 shows the variables with factor loadings above 0.50, along with the developed five components. The naming was done using the common themes that were underlying the variables (Owusu and Chan 2018). However, when there was no clearly discernible common theme, naming was done using the underlying theme of the variables, which are with higher factor loadings (Owusu and Chan 2018; Zhang et al., 2017; Le et al., 2014). These five components are elaborated in the forthcoming section.

Results and 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. The 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 SC or SCR. Besides, vulnerability is not exactly equivalent to risk. The level of vulnerability also varies with the withstanding capacity of a supply chain (Ekanayake et al., 2020). Focusing specifically on the ICSC (targeting SCR), Ekanayake et al. (2020) identified six vulnerability categories namely: project-organizational, procedural, supplier/customer, technological, environmental and financial-based, based on a systematic review of the literature. Besides, this study identified CSCV in ICSC, specifically in the context of HK through an empirical research exercise. Therefore, in addition to organizational, procedural, and technological SCV categories, this categorization includes economic and production-based SCV as follows, 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.

Component 1: Economic SCV (ESCV)

Component 1 consists of seven underlying factors which are closely related to the disruptions due to the economic changes, and hence, named ESCV. This component occupies the highest variance percentage, i.e. 24.054, with the highest variable 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 ICSCs 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 the variable 'cost overrun' as proven by Wang et al. (2019). HK IC 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). SC 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., 2019). 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 variable (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 ICSCs 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 ICSCs.

Component 2: Technological SCV (TSCV)

Component 2 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 variable ‘technology failure’ with a significant M value of 3.200, indicating high factor significance. ICSCs are considerably susceptible to technological problems (Wang et al., 2018). Further, a shortage of industrial technology management personnel during construction is a vulnerability factor 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 ICSC often results in information loss/misuse in the industry (Ekanayake et al., 2019). Information sharing with the SC members is quite complicated, while implementing the information systems is costly (Tran et al., 2016). However, inadequate information sharing tends to trigger SC 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 SC collaboration, requesting substantial attention to technical and social aspects of information sharing in equal measure (Wu et al., 2019). In these circumstances, Building Information Modelling (BIM) and Radio Frequency Identification (RFID) enabled IT platforms were seen as helping to achieve real-time visibility and traceability of ICSCs (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 ICSCs (Li et al., 2011). Further, these technological breakdowns result in industrial disputes and SC inefficiencies and exert strong direct influences on other IC vulnerabilities, such as design changes/variations/rework (Luo et al., 2019).

Variations/rework in ICSCs are due to fragmentation of the SC 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 labour (Shahparvari et al., 2019). Compared to traditional construction SCs, 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 SC disruptions should receive attention from the beginning of the SC process without passing problems over to the on-site assembly stage, mitigating cost, and time overruns. However, ICSCs are still struggling with vulnerabilities due to variation/rework, endangering budget and schedule. Therefore, the variable variations/rework 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 ICSC process.

Component 3: Procedural SCV (PSCV)

PSCV refers to the disruptions arising from the operation at any node of the SC. 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 factors as the common SCV in IC in HK. As the largest contributing factor to the component, safety issues occupy the highest factor loading, and this is also with the second-highest M value within the category. Safety is a serious concern when installing prefabricated components (Zhai and Huang, 2017). Most of the precast elements are oversized and heavy, leading to hazardous and challenging installation requirements (Li et al., 2011). Although IC can provide a safer working environment than in traditional in-situ construction, collapsing elements can cause severe hazards, that HK has also faced (Ekanayake et al., 2019).

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, the accidents are likely during the installation, especially from collisions with other components and occasionally even with workers (Li et al., 2011). Besides, near misses cause frequent disruptions that ICSCs observe while installing components in HK. However, such problems are not minimized through novel safety technologies and are currently avoided by employing skilled workers and careful monitoring of the SC 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). Compared to other IC projects, in public housing projects initiated by the HK Housing Authority, a specific safety management system is maintained, where a safety assessment is conducted once in every three months. 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. Recently, the HK economy has been concerned with multiple street demonstrations, while transportation routes were also disturbed. Machine breakdowns occur due to poor or negligent maintenance (Wang et al., 2018), and the system can fail, for instance, with failures in the manufacturing plant (Li et al., 2018). Also, this variable 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.

ICSCs are highly susceptible to transport network disruptions in HK, as most of the uncertainties arise in the logistics processes. The leading causes underlying these, are damages to the units in transport, delays from traffic jams, inefficiencies of customs clearance (Zhai and Huang, 2017), technical problems with vehicles, too late or too early delivery, and insufficient transportation capacity (Wang et al., 2018). Since prefabricated units are transported from Mainland China, transportation disruptions significantly affect ICSCs in HK. 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 the disruption compared to the traditional construction.

Component 4: Organisational SCV (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. Communication breakdowns generally disrupt and distort the decision-making process, and hence, unexpected time overruns are expected. These communication breakdowns result in SC inefficiencies and industrial disputes in IC and exert substantial cascading impacts on other IC vulnerabilities, such as variations/rework (Luo et al., 2019). 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 HK IC, 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 a skilled workforce (Ekanayake et al., 2019). The labour 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 labour is lower there. The shortage of skilled workforce thus becomes another critical SC vulnerability. ICSCs need outsourcing since modules are manufactured in a factory environment in Mainland China and pose significant challenges such as demand uncertainty, assembly problems (Wang et al., 2018), and poor visibility of SCs (Zainal and Ingirige, 2018). 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 SC process severely (Ekanayake et al., 2019). To address this, 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 factor within this category. Construction SCs 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).

Component 5: Production-based SCV (PBSCV)

PBSCV accounts for 5.814 variance percentage, with a significant M value (3.217), including three factors with higher factor loadings (quality loss, supply-demand mismatch/shortages, and labour strikes/disputes). This category consists of the factors which are allied with the production of IC. In HK, the quality loss is associated with tolerance shortfalls (Enshassi et al., 2019). Unless a reasonable tolerance is provided, if a unit is cast with even a 1mm error, it becomes vulnerable to on-site assembly problems. It can cause considerable cost and time overrun (Ekanayake et al., 2019). It was found that vulnerabilities at the manufacturing factory cause a supply-demand mismatch in IC, which also poses a severe problem in HK. Supply resource scarcity is another cause behind this (Zhai and Huang, 2017). Also, sometimes, manufacturing factories supply incorrect orders, causing assembly delays (Ekanayake et al., 2020). Besides, the accumulated supply-demand vulnerabilities result in unmet client needs. Similar to the 'loss of skilled labour', 'labour strikes' also affect the productivity and efficiency of IC (Ekanayake et al., 2020). However, labour strikes are visible in manufacturing factories compared to the other SC phases. Therefore, taken together, this component also offers a set of CSCV affecting SCR, hence motivating industry stakeholders to develop possible solutions to withstand them.

Figure 2 presents a profile of CSCV with the vulnerability levels obtained from relevant significance analysis. The first ranking factor is 'loss of skilled workforce' (V03) with an M value of 3.653. Without skilled labour, on-site assembly of components is impossible. Besides, in the current practice, this labour 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 labour. Further, Luo et al. (2019) identified three major stakeholders-associated SC risks in IC, including poor planning, poor control of workflows, and inadequate information sharing. However, considering the entire ICSC process, the highest vulnerability is due to the loss of a skilled workforce, the next ranked is variations, while communication issues are ranked third.

(Insert Figure 2 here)

According to the viewpoint of industry experts, including project managers, IC is a game-changing approach in HK construction practices, particularly with the recent development of modular integrated construction. However, these ICSCs are significantly vulnerable towards outsourcing decision due to substantial labour costs, transport of over-weight, over-sized prefab units, on-site safety, extensive use of skilled-labour on-site, complex on-site logistics, and especially 'tolerance' adherence issues which affects the overall quality and delivery. Therefore, injecting SCR imperatives would be a timely solution which should accompany technological advancements. Use of BIM and RFID enabled platforms can help to ameliorate these issues and alleviate any residual consequences. Along these lines, further possibilities are opening up with the development of blockchain technologies that can help streamline authentications, payments, other transactions including critical elements of the ICSC process, where even semi-automation can reduce CSCV further.

Conclusions

IC has been developed to address the quality and productivity conundrum in the construction industry in HK. However, the fragmented ICSCs in HK are prone to vulnerabilities that compromise and at times, even negate the generic benefits of IC by compromising performance in practice. SCR is targeted as an innovative solution to address such vulnerabilities. SCR mobilises inherent, albeit sometimes dormant abilities of SCs to successfully withstand vulnerabilities. Although SCR is necessitated by the industry to resist acute SC disruptions, the literature remains largely silent on this phenomenon, especially on IC. Therefore, this study attempted to identify CSCV (thereby focusing on the most substantial disruptions) associated with IC in HK as the first step to translate SCR imperatives and objectives into practice.

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 SCs, while 'loss of skilled labour' is identified as the most influential factor. Variations/rework and communication issues are the second and third CSCV. The factor analysis in this study led to five CSCV components being identified, namely, economic, technological, procedural, organizational, and production-based vulnerabilities. Although the economic component showed a higher variance percentage, the highest influential component is the OSCV with the highest mean score value, highlighting its significance for IC in HK.

These 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 respondents was relatively small in this study. The authors 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. Despite the limitations of this study, the research findings contribute substantially to both practice and theory. These findings provide pointers to determine the level of criticality of the vulnerabilities, drawing the attention of industry professionals to suitably address CSCV by developing value-enhanced, resilient SCs in IC in HK. Besides, the five components that were identified unveil the underlying groupings of CSCV that can be addressed together to increase the SCR. Moreover, the successful withstanding of these CSCV would overcome some barriers to increasing productivity and triggering a breakthrough in the performance conundrum faced by the HK construction industry. The originality and significance of the present findings is heightened by the more serious constraints encountered in the particularly high-density/high-rise urban setting in HK; and where cross-border logistics are also necessitated in IC projects. In terms of further study, the determination of appropriate critical SC capabilities is suggested, to proactively combat the identified CSCV proactively. Looking ahead from another angle, an evaluation model to assess SCR in IC in HK could also be developed by first evaluating the degrees of vulnerability of different underlying components, as well as the individual CSCV themselves, so that more attention could be paid to the relatively more extensive (in numbers) and intensive (in potential impact CSCV in IC in HK.

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Table 1: Ranking of potential CSCV in IC in HK

Code	Variables	Mean	SD	SWT	N value	Rank
V03	Loss of skilled workforce	3.653	0.796	0.000	1.00[a]	1
V10	Variations and/or rework	3.586	0.886	0.000	0.97[a]	2
V02	Communication breakdown/issues	3.520	0.991	0.000	0.94[a]	3
V08	Transport disruptions including port stoppages	3.506	1.018	0.000	0.93[a]	4
V13	Safety hazards	3.426	0.791	0.000	0.89[a]	5
V09	Quality loss	3.426	0.932	0.000	0.89[a]	6
V16	Supply-demand mismatch/shortages	3.320	0.856	0.000	0.84[a]	7
V17	Inappropriate supplier selection	3.280	0.893	0.000	0.82[a]	8
V19	Information loss	3.226	0.831	0.000	0.79[a]	9
V20	Technology failure	3.200	0.821	0.000	0.78[a]	10
V28	Implication of new laws/regulation	3.173	0.794	0.000	0.77[a]	11
V27	Adverse weather	3.160	0.838	0.000	0.76[a]	12
V22	Inadequate IT systems	3.146	0.865	0.000	0.75[a]	13
V29	Industry/market pressures	3.146	0.800	0.000	0.75[a]	14
V12	Systems/machines breakdown	3.133	0.827	0.000	0.75[a]	15
V06	Disruptions due to outsourcing	3.093	1.001	0.000	0.73[a]	16
V23	IT system failure	3.093	1.002	0.000	0.73[a]	17
V36	Cost overrun	2.960	0.845	0.000	0.66[a]	18
V33	Price fluctuations	2.960	0.892	0.000	0.66[a]	19
V26	Economic policy	2.960	0.950	0.000	0.66[a]	20
V01	Labour strikes/disputes	2.906	1.054	0.000	0.64[a]	21

V31	Physical damage to the buildings/accidents	2.893	0.878	0.000	0.64[a]	22
V34	Exchange rate fluctuations	2.866	0.859	0.000	0.62[a]	23
V21	Information misuse	2.813	0.925	0.000	0.59[a]	24
V07	Poor project definition	2.800	1.013	0.000	0.59[a]	25
V35	Liability claims	2.653	0.779	0.000	0.52[a]	26
V14	Site inventory losses/theft	2.626	0.941	0.000	0.50	27
V05	Loss of trust/fraud	2.480	0.875	0.000	0.43	28
V11	Utility disruptions i.e. electricity, water	2.453	0.842	0.000	0.42	29
V32	Cash flow issues	2.440	0.842	0.000	0.41	30
V37	Economic crises	2.440	0.775	0.000	0.41	31
V24	Natural disasters	2.360	0.924	0.000	0.37	32
V04	Closing/selling off the organisations	1.960	1.005	0.000	0.18	33
V18	Forced take over by the client	1.880	0.899	0.000	0.14	34
V15	Energy scarcity	1.826	0.828	0.000	0.11	35
V25	Terrorism/war	1.680	0.917	0.000	0.05	36
V30	Epidemics/viruses/bacteria	1.586	0.755	0.000	0.00	37

Note: SD = Standard Deviation
N Value = Normalization Value = (Mean-Minimum Mean)/(Maximum Mean-Minimum Mean)
[a] indicates the normalised value > 0.50 and considered as a critical SCV
SWT = Shapiro-Wilk test

Table 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
Contractor	39	51.3
Manufacturer	4	5.3
Client	15	19.7
Designer	11	14.5
Transporter	1	1.3
Other	6	7.9
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

Table 3: Results of the factor analysis

Code	Critical SCV affecting SCR in IC in HK	Components

		1	2	3	4	5	$\bar{x} = \sum xi / n$
Component 1	Economic SCV (ESCV)						2.908
V34	Exchange rate fluctuations	.867	-	-	-	-	2.866
V33	Price fluctuations	.818	-	-	-	-	2.960
V35	Liability claims	.812	-	-	-	-	2.653
V36	Cost overrun	.746	-	-	-	-	2.960
V29	Industry/market pressures	.648	-	-	-	-	3.146
V21	Information misuse	.533	-	-	-	-	2.813
V26	Economic policy changes	.455	-	-	-	-	2.960
Component 2	Technological SCV (TSCV)						3.250
V20	Technology failure	-	.883	-	-	-	3.200
V23	IT system failure	-	.846	-	-	-	3.093
V22	Inadequate IT systems	-	.746	-	-	-	3.146
V19	Information loss	-	.656	-	-	-	3.226
V10	Variations/rework	-	.511	-	-	-	3.586
Component 3	Procedural SCV (PSCV)						3.226
V13	Safety issues	-	-	.792	-	-	3.426
V28	Implication of new laws/regulation	-	-	.781	-	-	3.173
V12	Systems/machines breakdown	-	-	.743	-	-	3.133
V08	Transport disruptions including port stoppages	-	-	.655	-	-	3.506
V31	Physical damage to the buildings/accidents	-	-	.546	-	-	2.893
Component 4	Organisational SCV (OSCV)						3.387
V02	Communication breakdown/issues	-	-	-	.857	-	3.520
V03	Loss of skilled workforce	-	-	-	.663	-	3.653
V06	Disruptions due to outsourcing	-	-	-	.543	-	3.093
V17	Inappropriate supplier selection	-	-	-	.537	-	3.280
Component 5	Production-based SCV (PBSCV)						3.217
V09	Quality loss	-	-	-	-	.820	3.426
V16	Supply-demand mismatch/shortages	-	-	-	-	.756	3.320
V01	Labour strikes/disputes	-	-	-	-	.637	2.906
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.

$\bar{x} = \sum xi / n$; where $\bar{x}$ = mean, $\sum xi$ = summation of sampled frequency; n = number of responses for a variable or the number of items in a specific component.

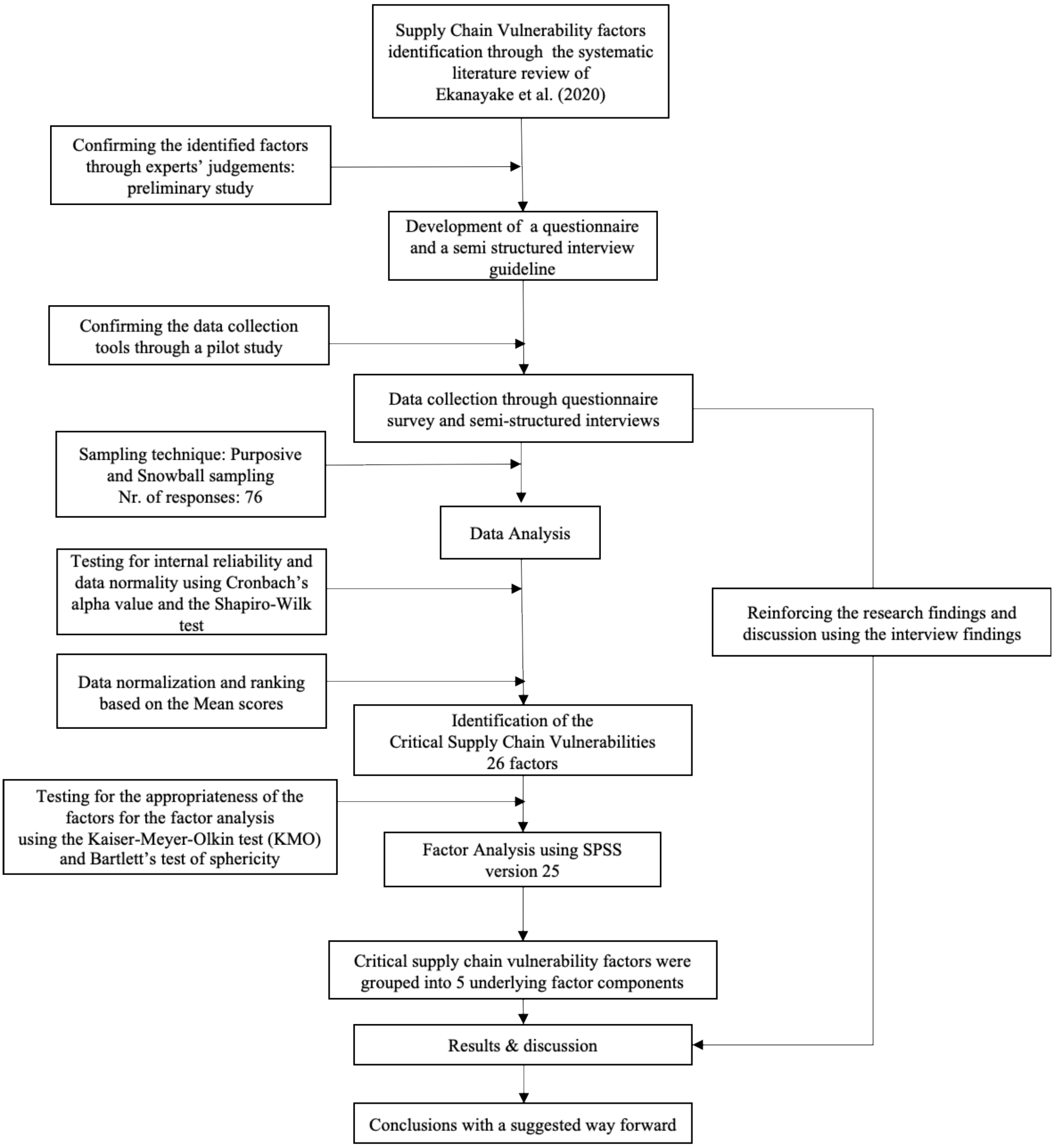

Figure 1: Research methods and flow in this study

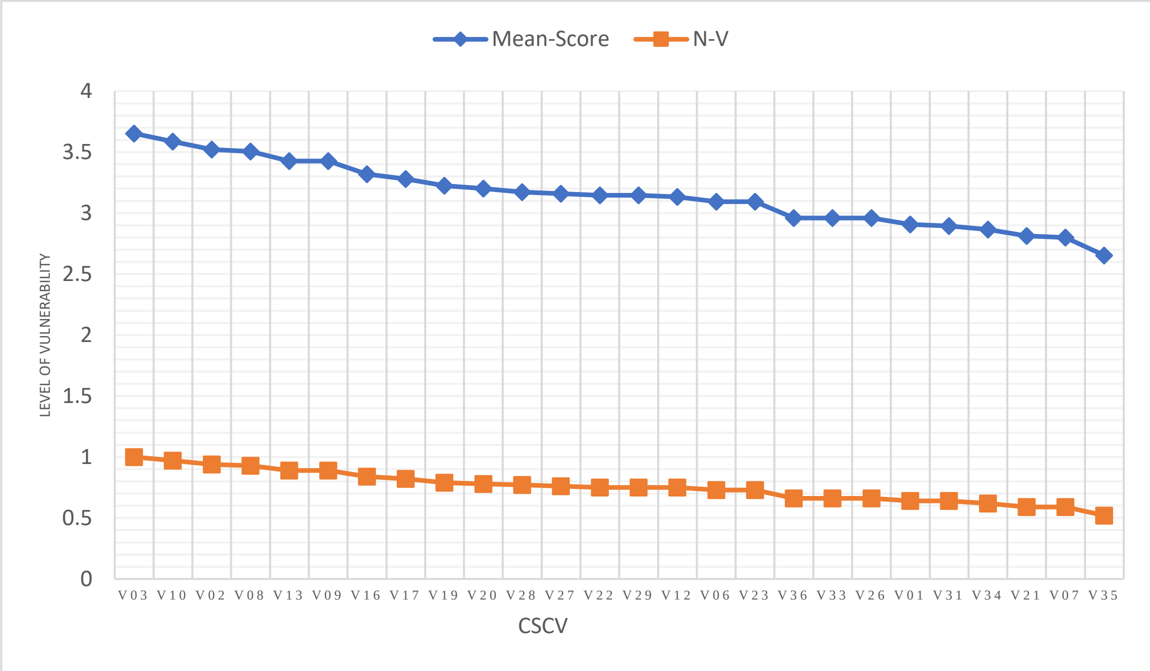

Figure 2: Critical Supply Chain Vulnerabilities (CSCV) affecting supply chain resilience in IC in HK