A Fuzzy Synthetic Evaluation of Vulnerabilities Affecting Supply Chain Resilience of Industrialized Construction in Hong Kong

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Abstract

Purpose: Demands for Industrialized Construction (IC) have intensified with growing construction industry imperatives to (A) boost performance; (B) reduce reliance on 'in-situ and on-site' operations; and (C) strengthen Supply Chain Resilience (SCR) not just for survival, but also to fulfil obligations to clients in the COVID-19-induced 'new normal'. In addressing these imperatives, this paper targets more effective leveraging of latent efficiencies of off-site-manufacture, based on findings from a Hong Kong (HK) based study on assessing and improving SCR in IC in a high-density city.

Design/methodology/approach: Starting with the identification of Critical Supply Chain Vulnerabilities (CSCV), this study developed a multi-level-multi-criteria mathematical model to evaluate the vulnerability levels of IC supply chains in HK based on an in-depth questionnaire survey followed by experts' inputs and analyzing them using fuzzy synthetic evaluation (FSE).

Findings: The overall vulnerability index indicates that IC in HK is substantially vulnerable to disruptions, while production-based vulnerabilities have the highest impact. Top management attention is needed to address these Critical Supply Chain Vulnerabilities (CSCV) in IC in HK.

Originality/value: To the authors' knowledge, 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 SCs.

Keywords: Supply Chain Resilience (SCR); Industrialized Construction (IC); Supply Chain Vulnerabilities (SCV); Fuzzy Synthetic Evaluation (FSE)

1. Introduction

Every year, around three-quarters of organizations, encounter significant Supply Chain (SC) disruptions (BCI, 2018; Scholten et al., 2019), adversely affecting the performance of the SCs and consequentially the organizations they support. These disruptions are two-fold; natural or human-induced, and the threats are greater and more dynamic as organizations are progressively interconnected via global networks (BCI, 2018). In addition, heightened exposure or increased vulnerability towards these disruptions results in loss of productivity, customer dissatisfaction, increased cost of working, loss of revenue, and impaired service outcome (BCI, 2019). The level of vulnerability due to the disruptions depends on the severity and duration of the disruptive event and the capacity of the SCs (Scholten et al., 2019) to withstand it. Resilient SCs tackle these vulnerabilities well and proactively by employing adequate SC capabilities to counter threats (Sheffi and Rice, 2005). In this regard, Supply Chain Resilience (SCR) is recognized as the 'winning initiative' of Supply Chain Management (SCM) (Sahu et al., 2017), and it is at the heart of contemporary SC thinking and management (Melnyk et al., 2014). SCR is an enhancement of traditional SC risk management (Pettit et al., 2019). It is the SC's capacity to continue operations in the face of turbulence without decreasing its performance (Christopher and Peck, 2004) or the ability to re-emerge in a better state (Tukamuhabwa et al. 2015; Scholten et al., 2019). All of the foregoing observations and conclusions are now amplified by the shockwaves generated by COVID-19 in 2020, alerting the construction industry to the imperatives to address them faster and better.

Construction SCs in Hong Kong (HK) also face various disruptions such as lack of skilled workforce and very high construction costs (CIC, 2019). Meanwhile, the primary advantages of Industrialized Construction (IC) that could potentially reduce such disruptions, have been built upon by the latest developments in modular integrated construction (Xu et al., 2020). However, even in IC, the fragmented nature of SCs, discontinuity and poor interoperability still induce significant impacts on the entire SC network (Ekanayake et al., 2019; Li et al., 2018).

These limitations, in turn, foster numerous vulnerabilities that could adversely affect the performance of IC supply chains (Ekanayake et al., 2020a). Hence, there is an urgent and crucial need to address these debilitating issues to enhance industrial productivity and competitiveness for the sustained economic growth of HK (CIC, 2019). This requires, identifying SCV, and then, determining their levels of criticalities and impacts based on their levels of vulnerabilities. Although recent studies of Ekanayake et al. (2019), Ekanayake et al. (2020a), and Ekanayake et al. (2020b) reviewed and empirically examined the SCV affecting SCR in IC in HK, neither these studies nor any others that the authors could find, facilitated the evaluation of different levels of vulnerabilities and their overall impact on the entire SC network. Poor understanding by industry stakeholders of the 'weaker links' with higher vulnerability levels in IC SCs can lead to project failures. Besides, the proper assessment of relative criticality levels of SCV is a precursor to determining appropriate SC capabilities to withstand specific corresponding vulnerabilities and develop resilient SCs in IC.

In addressing the above, this study was designed to develop a multi-level-multi-criteria mathematical model to evaluate the various vulnerability levels of IC SCs in HK by unearthing and analyzing the deep knowledge and judgments of experts using a soft computing approach, namely, fuzzy synthetic evaluation (FSE). The developed model is, to the authors' knowledge, the first evaluation model that assesses IC vulnerability levels, thereby providing a valuable decision-aid for industry practitioners to improve the resilience, sustainability, and performance of SCs in IC in HK. Based on the above premises, an empirical study was conducted to realize the study aim. The details of the research methodology adopted, results derived, consequential discussion and conclusions drawn from this study with suggested further research directions are described in the forthcoming sections.

2. Literature Synthesis

The construction industry in HK, together with its associated sectors, contributes substantially to the gross domestic product and the direct and indirect growth of employment and plays a vital role in assuring a sustainable future for HK (CIC, 2019). As the industry, especially in the IC sub-sector, is facing increasing challenges of SC disruptions, amidst step-changes while moving through successive 'waves'' and from severe to acute post-COVID-19. It is now important to extract findings from the various lessons learned to inject fresh SCR concepts and solutions into the SCM process. Since effective SCM is now a prerequisite for organizational success, withstanding SCV needs high levels of SCR that have been identified as the 'winning initiative of effective SCM' (Sahu et al., 2017).

From relevant literature: Sheffi (2001) and Christopher and Peck (2004) researched ways to recover from severe disruptions by reducing vulnerabilities. Yu and Yang (2008) identified SC risk sources in developing a theoretical framework for achieving resilient SCs. Guoping and Xinqiu (2008) presented a theory-based evaluation index using the black-box method. Ponis and Koronis (2012) studied the interaction between SCV and capabilities under the concept of SCR. Studies by Wieland and Wallenburg (2013) and Mensaha and Merkuryev (2014) also dig into the SCV and SCR analysis, indicating research milestones of this research domain. Pettit et al. (2013) significantly contributed to this knowledge domain by developing an assessment model to measure SCR based on the manufacturing industry. Zavala et al. (2018) offered quantitative metrics to analyze SCR and related costs. Recently, Zainal and Ingirige (2018) suggested an SCR approach for Malaysian public construction projects.

Further, the fuzzy-method has been used in SCR research studies, given its ability to solve problems dealing with vague or imprecise data (Rajesh, 2019). Fuzzy-methods are more advantageous in dealing with inconsistent information evaluation (Sahu et al., 2017). As resilience measurements are explicated subjectively in most SCR studies, those studies are characterized by inconsistency and incompleteness. In responding to this shortfall, fuzzy synthetic evaluation helps avoid subjectivity by converting subjective linguistic terms to objective mathematical models (Xu et al., 2010). On the other hand, as Sahu et al. (2017) explained, the data related to resilient performance evaluation are difficult to analyze using standard statistical analysis tools due to missing records and unavailability of quantitative data. In such cases, fuzzy-theory can be effectively used to develop unique resilience evaluation indices. However, fuzzy-methods ignore the co-relationships among the resilience measurement items of vulnerabilities and consider vulnerability relationships to be linear and hierarchical (Moeinzadeh and Hajfathaliha, 2009). Although this limits the application of fuzzy-theory in SCR research, it can be overcome by employing multi-attribute synthetic evaluation methods together with fuzzy-theory in SCR research (Moeinzadeh and Hajfathaliha, 2009), which would also constitute a novel research direction.

The application of the fuzzy-method was mostly to measure resilience as a whole without considering its two indicators of vulnerabilities and capabilities as separate measures. Hence, the findings were quite generic. Quantitative evaluation of overall SCR is indeed a difficult task (Sahu et al., 2017) and thus, necessitates individual vulnerability and capability analysis research. In this regard, studies such as those of Fakoor et al. (2013) developed a method for measuring resilience in the automobile industry using fuzzy numbers. Sahu et al. (2017) established an appraisement index for measuring and monitoring the candidate industry's resilient performance using fuzzy set theory. Rajesh (2019) attempted to analyze SCR in the manufacturing industry through the fuzzy analytic hierarchy process. However, each of these studies has not deeply examined a mechanism to measure the individual and overall impact of SCV considering probability and severity indicators as measures of vulnerability levels. This research gap is especially significant, given the needs of the IC sector in HK. Therefore, a specific study seemed essential in HK since SCVs would vary with the contexts of the local industry and the parent jurisdiction as well.

SCV lead to significant, albeit often unanticipated disruptions that affect the normal SC process (Zavala et al., 2018; Ekanayake et al., 2019). BCI (2019) identified IT-based disruptions, adverse weather, cyber-attacks and data breach, loss of skills, and transport network disruptions as the major SCV industries faced during the past twelve months. Further, the BCI report predicts the five major disruptions possible within the next twelve months as cyber-attacks and data breach, IT-based disruptions, political change, adverse weather and new laws or regulations. More specific to IC in HK, Ekanayake et al. (2020b) identified transport disruptions, systems or machines breakdown, supply-demand mismatches or shortages, site logistics, safety issues, quality loss, loss of skilled labor, financial vulnerabilities, and inadequate IT systems as the critical SC disruptions, based on a HK IC case study. These results align well with the global indicators, and there are some identical issues, such as site logistics, given that traditional construction projects are unique, unlike in streamlined factory settings. Pettit et al. (2013) grouped SCV into seven categories: turbulence, deliberate threats, external pressures, resource limits, sensitivity, connectivity, and supplier/customer vulnerabilities considering seven global manufacturing and service firms. Following on, Zainal and Ingirige (2018) categorized SCV into 11 categories as appropriate to Malaysian public projects. Being specific to IC, Ekanayake et al. (2020a) conducted a systematic review of literature through meta-analysis and identified 36 SCV factors. Thereafter, Ekanayake et al. (2020b) identified Critical SCV (CSCV) associated with IC in HK through empirical research (Table 1). However, different levels of vulnerability of IC supply chains due to these critical disruptions was not explored until now, despite vulnerability assessment being essential to determine appropriate capabilities to achieve SCR. To address this important need, the authors decided to develop an evaluation model to assess SCV and their impact on IC supply chains in HK.

(Insert Table 1 here)

3. Research Methods

A quantitative research design based on a positivist epistemology (Chan et al., 2018) deployed an expert-based approach for developing an evaluation model to assess SCV and their impact on IC in HK. Based on the extensive literature search by Ekanayake et al. (2020a) and empirical research by Ekanayake et al. (2020b), this study first identified 26 CSCV affecting SCR in IC in HK. This provided a sound basis for a questionnaire survey, as explicated below since a questionnaire survey offers a valid, reliable and quick source of information with a minimal resource requirement (Ameyaw et al., 2017). Figure 1 illustrates the methodological framework followed in this study.

(Insert Figure 1 here)

3.1 Questionnaire development

A questionnaire was constructed based on the 26 CSCV mentioned above. The grading scale technique was used to solicit better assessments of industry experts. Further, a five-point Likert scale linked to linguistic terms for Fuzzy Synthetic Evaluation [FSE] (Owusu et al., 2020) was deployed to assess the criticalities of the identified SCV. Before the survey, the questionnaire was pilot tested with four senior academics who are also well experienced in IC projects. This confirmed the relevance, language structure, understandability and comprehensiveness of the questionnaire.

3.2 Survey

An expert survey was then conducted to solicit the views of managerial level or high-level industry experts working/worked in IC projects in HK. This data collection method proved productive since this: (a) enabled rich and reliable information; (b) requires less time than other methods; and (c) facilitated the expansion of the respondent 'catchment area' through participants' suggestions and recommendations (Ameyaw et al., 2017). Purposive sampling: a non-probability sampling method was used since there was no sampling frame for this study (Zhao et al., 2014) and obtained a representative sample for the analysis (Chan et al., 2018).

With the snowball sampling method, this study enabled obtaining a valid and expanded sample size and rich information gathering through referral and social networks, as in previous construction management research (Zhang et al., 2011, Chan et al., 2018, Owusu and Chan, 2018). Finally, the 76 valid responses received were regarded as suitable for further analysis. The profile of the industry experts are presented in Figure 1. This response rate is higher than those obtained in some similar survey-based studies (Adabre and Chan, 2019, Darko and Chan, 2018, Chan et al., 2018) and could derive meaningful results, hence considered as adequate to derive significant conclusions (Ott and Longnecker, 2015, Sproull, 2002).

4. Data Analysis and Findings

First, two pre-tests were conducted to measure data reliability and normality, namely Cronbach's alpha test and Shapiro-Wilk test using SPSS version 25. Cronbach's alpha coefficients of 0.863 and 0.893 confirmed that the factors' probability and severity indicators are internally reliable and consistent (Santos, 1999). Also, Shapiro-Wilk test statistics proved that this study's data is non-normally distributed (Gel et al., 2007).

4.1 Factor analysis

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, based on the studies of Ameyaw and Chan (2016) and Owusu et al. (2020), the impact of the SCV were calculated, referring to Equation (1) in this study. Mean score values derived based on experts' assessment of SCV were used to ascertain each vulnerability variable's impact. These detailed assessment results and the impact evaluation matrices are given in Table 1.

Equation (1):

$$\text{Impact (I)} = (\text{probability X severity})^{\wedge}0.5 \quad (1)$$

Twenty-six factors captured in the questionnaire survey were then subjected to factor analysis. The factor analysis results enabled categorizing the selected CSCV into five components (Mooi et al., 2018, Pallant and Manual, 2010), considering the similarities of the underlying factor themes. These five components are economic, technological, procedural, organizational, and production-based SCV (Ekanayake et al. 2020b). Following the two key stages in factor analysis, factor extraction and rotation were done. Hence, 24 SCV, which are above eigenvalue one, were remained. Then, varimax rotation yielded five underlying factor components that explain 65.14% of the total variance. Kaiser-Meyer-Olkin test (KMO) and Bartlett's test of sphericity were conducted to check the appropriateness of data to the factor analysis (Adabre and Chan, 2019, Le et al., 2014). The value obtained for KMO in this study is 0.700, which is above the required minimum of 0.5 (Kaiser, 1974). Bartlett's test of sphericity statistic is 1228.963 with a significance level of 0.000. Therefore, the data set is appropriate for factor analysis, and the correlation matrix is not an identity matrix (Kaiser, 1974, Owusu and Chan, 2018). Table 2 presents the results of the factor analysis.

(Insert Table 2 here)

4.2 Application of the soft computing approach- FSE

Fuzzy Synthetic Evaluation (FSE), which is a fuzzy logic-based approach, has been used in several research disciplines for evaluation in multicriteria decision making (Xu et al., 2010), given 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 CSCV in IC in HK. The following five steps were subsequently pursued to find the overall impact index and develop the model to assess the impact of CSCV in IC in HK. Also, these five steps are clearly illustrated in Figure 2.

(Insert Figure 2 here)

4.2.1 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.

$$I_{pi} = (I_{escv} + I_{tscv} + I_{pscv} + I_{oscv} + I_{pbscv}) \quad (2)$$

The individual CSCV factors within the components, as presented in Table 3, were then defined as the second level index system, as shown as follows:

$$I_{escv} = (I_{escv1}, I_{escv2}, I_{escv3}, I_{escv4}, I_{escv5}, I_{escv6}, I_{escv7}) \quad (2.1)$$
$$I_{tscv} = (I_{tscv1}, I_{tscv2}, I_{tscv3}, I_{tscv4}, I_{tscv5}) \quad (2.2)$$
$$I_{pscv} = (I_{pscv1}, I_{pscv2}, I_{pscv3}, I_{pscv4}, I_{pscv5}) \quad (2.3)$$
$$I_{oscv} = (I_{oscv1}, I_{oscv2}, I_{oscv3}, I_{oscv4}) \quad (2.4)$$
$$I_{pbscv} = (I_{pbscv1}, I_{pbscv2}, I_{pbscv3}) \quad (2.5)$$

These established FSE's input variables apply to both probability and severity indicators alike. The identified CSCV within their respective components were deemed representative of input variables in FSE calculations, as in Table 3.

4.2.2 Determining the membership function

The membership grade of CSCV factors 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 factors 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, the Membership Function (MF) of a given component I_{in}, was computed using the following Equation (3) (Chan et al., 2011, Ameyaw et al., 2015, Owusu et al., 2020).

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

MF = Membership Function of a given component I_{in}, which represents the n[th] vulnerability factor of a given component i ($i = I_{escv}, I_{tscv}, I_{pscv}, I_{oscv}, I_{pbscv}$).

$P_{fI_{in}}$ ($f = 1, 2, 3, 4, 5$) denotes the percentage of respondents who assigned a grade for the individual vulnerability factors based on probability and severity. Further, $P_{fI_{in}}/h_i$ indicates the association of $P_{fI_{in}}$ and the relevant grading scale instead of the mathematical function (fraction) used here. Similarly, '+' in Equation (3) denotes a symbol instead of the mathematical function (addition) implied in mathematics. Hence, Equation (3) can be converted to Equation (4) as follows.

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

The members of the set of equations applied in Equation (2.1) - Equation (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 (5).

$$\sum_{f=1}^{5} P_{fI_{in}} = 1 \quad (5)$$

The MF of a given component is created by assessing the overall responses received from the expert survey as explicated in Equation (4). Thus, considering the variable 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 (3), MF of ESCV1(p) is as follows.

$$MF_{ESCV1_{(p)}} = \frac{0.04}{very\ low} + \frac{0.29}{low} + \frac{0.45}{moderate} + \frac{0.19}{high} + \frac{0.03}{very\ high} \quad (5.1)$$

As per Equation (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 (5.2). Therefore, $MF_{ESCV1_{(s)}}$ = (0.03, 0.27, 0.40, 0.23, 0.08).

$$MF_{ESCV1_{(s)}} = \frac{0.03}{very\ low} + \frac{0.27}{low} + \frac{0.40}{moderate} + \frac{0.23}{high} + \frac{0.08}{very\ high} \qquad (5.2)$$

The same calculation method was employed for all the other variables, and the generated results are presented in Table 3. Thereby, the respective component groups' MF were derived using the computed weightings of the individual factors within the components. The estimation of weighting functions is explained in the next section.

4.2.3 Estimating weighting functions

The weighting function indicates the relative importance of each factor or a component, based on the gradings assigned by the respondents (Ameyaw et al., 2015; Ameyaw and Chan, 2016). The normalized mean technique or analytic hierarchy process technique can be used to estimate the weighting functions (Lo, 1999; Cheng, 1997; Lee et al., 2008). The normalized mean method was used in this study since it is a straightforward method (Lo, 1999; Ameyaw et al., 2015; Owusu et al., 2020). The appropriate weight functions of the variables were calculated by the following Equation (6).

$$w_i = \frac{M_i}{\sum_{i=1}^{5} M_i}, 0 < w_i < 1, where \sum_{i=1}^{5} w_i = 1 \qquad (6)$$

w_i indicates the weighting function of the i^{th} vulnerability variable or the component regarding probability or severity. M_i is the mean index of any vulnerability variable or a component as estimated from the survey data. As explicated in Equation (6) and following Equation (4), the summation of the means within a weight function set must be one and can be represented in Equation (7).

$$w_i = (w_1, w_2, \ldots, w_n) \qquad (7)$$

Equation (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 (7.2). Thereby, a similar approach was adopted in computing all the weighting functions of variables and components that belonged to both probability and severity indicators. These computed weighting functions are clearly presented in Table 3.

$$w_{ESCV1_{(p)}} = \frac{2.87}{2.87 + 2.96 + 2.65 + 2.96 + 3.14 + 2.81 + 2.96} = \frac{2.87}{20.36} = 0.141 \quad (7.1)$$

$$w_{ESCV_{(p)}} = \frac{20.34}{20.34 + 16.25 + 16.13 + 13.55 + 9.65} = \frac{20.34}{75.94} = 0.268 \quad (7.2)$$

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

$$\sum_{i=1}^{5} w_{ESCV_{(p)}} = (0.141 + 0.145 + 0.130 + 0.145 + 0.155 + 0.138 + 0.145) = 1.0 \quad (7.3)$$

4.2.4 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 experts' gradings. Second, the MF and WF of factor components were constructed, and the impact was estimated. Third, the overall indicator of the impact of vulnerabilities on IC supply chains, was 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 vulnerability variables within their respective component groups. The following MFs determined under Equation (3), functions of vulnerability variables within their respective components (for both probability and severity indicators) can be presented as in Equation (8).

$$R_i = \begin{vmatrix} MF_{I_{i1}} \\ MF_{I_{i2}} \\ MF_{I_{i3}} \\ \cdots \\ MF_{I_{in}} \end{vmatrix} = \begin{vmatrix} P_{1I_{i1}} & P_{2I_{i1}} & P_{3I_{i1}} & P_{4I_{i1}} & P_{5I_{i1}} \\ P_{1I_{i2}} & P_{2I_{i2}} & P_{3I_{i2}} & P_{4I_{i2}} & P_{5I_{i2}} \\ P_{1I_{i3}} & P_{2I_{i3}} & P_{3I_{i3}} & P_{4I_{i3}} & P_{5I_{i3}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{1I_{in}} & P_{2I_{in}} & P_{3I_{in}} & P_{4I_{in}} & P_{5I_{in}} \end{vmatrix} \quad (8)$$

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

$$R_{OSCV_{(p)}} = \begin{vmatrix} MF_{OSCV1} \\ MF_{OSCV2} \\ MF_{OSCV3} \\ MF_{OSCV4} \end{vmatrix} = \begin{vmatrix} 0.00 & 0.17 & 0.32 & 0.32 & 0.19 \\ 0.01 & 0.04 & 0.35 & 0.48 & 0.12 \\ 0.01 & 0.33 & 0.28 & 0.29 & 0.08 \\ 0.01 & 0.19 & 0.37 & 0.36 & 0.07 \end{vmatrix} \quad (8.1)$$

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

$$K_i = R_i \bullet W_i = (k_{i1}, k_{i2}, k_{i3}, \ldots, k_{in}) \quad (9)$$

Hence,

$$K_i = (w_1, w_2, w_3, \ldots, w_n) \bullet \begin{vmatrix} P_{1I_{i1}} & P_{2I_{i1}} & P_{3I_{i1}} & P_{4I_{i1}} & P_{5I_{i1}} \\ P_{1I_{i2}} & P_{2I_{i2}} & P_{3I_{i2}} & P_{4I_{i2}} & P_{5I_{i2}} \\ P_{1I_{i3}} & P_{2I_{i3}} & P_{3I_{i3}} & P_{4I_{i3}} & P_{5I_{i3}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{1I_{in}} & P_{2I_{in}} & P_{3I_{in}} & P_{4I_{in}} & P_{5I_{in}} \end{vmatrix} = (k_{i1}, k_{i2}, k_{i3}, \ldots, k_{in}) \quad (9.1)$$

In Equation (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 integrating $R_{OSCV_{(p)}}$ and $W_{OSCV_{(p)}}$ can be mathematically presented as in Equation (9.2). Explicating further $K_{OSCV_{(p)}}$ denotes the fuzzy matrix for the probability indicators of the identified organizational SC vulnerability component. Similarly, K_i values for all the components (considering both probability and severity) were computed. These computed matrices are shown in Table 3 in the column 'MF at level 2'.

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

$$= (0.01, 0.18, 0.33, 0.37, 0.12) \quad (9.2)$$

Hence, the criticality of each vulnerability component (CV_i) can be calculated using the following Equation (10), whereas h indicates the grading scale adopted in the questionnaire survey.

$$CV_i = \sum_{i=1}^{5} K_i \times h^t = (K_1, K_2, K_3, K_4, K_5) \times (1, 2, 3, 4, 5), 1 \leq CV_i \leq 5 \quad (10)$$

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

$$CV_{OSCV_{(p)}} = [(0.01 \times 1) + (0.18 \times 2) + (0.33 \times 3) + (0.37 \times 4) + (0.12 \times 5)] = 3.40 \quad (10.1)$$

Analogous to the calculation above, $OSCV_{(s)}$ which is the criticality based on component severity in OSCV component was calculated as in Equation (10.2).

$$CV_{OSCV_{(s)}} = [(0.00 \times 1) + (0.05 \times 2) + (0.39 \times 3) + (0.44 \times 4) + (0.12 \times 5)] = 3.64 \quad (10.2)$$

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 (11) below. Table 4 presents the impact of all the components, computed using Equation (11).

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

4.2.5 Evaluating the overall vulnerability index

In this step, the fuzzy matrix $\overline{R}$ was introduced to evaluate the overall criticality levels of SCV for both probability and severity indicators as in Equation (12).

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

K_1- K_5 represent the five components initiated after the factor analysis, namely, ESCV, TSCV, PSCV, OSCV, and PBSCV. Analogous to Equation (12), overall probability and severity functions of SCV evaluation can be formulated as in Equation (12.1).

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

$$\overline{R_{(s)}} = \begin{vmatrix} 0.01 & 0.13 & 0.44 & 0.33 & 0.08 \\ 0.04 & 0.08 & 0.41 & 0.40 & 0.07 \\ 0.01 & 0.09 & 0.29 & 0.42 & 0.20 \\ 0.00 & 0.05 & 0.39 & 0.44 & 0.12 \\ 0.02 & 0.08 & 0.20 & 0.46 & 0.24 \end{vmatrix} \quad (12.1)$$

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

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

It is emphasized that $\overline{K_i}$ represents the fuzzy matrix for each probability and severity indicators of the SCV components. The fuzzy matrix in Equation (13) can be formulated using the grading scale (h=1,2,3,4,5) established in this study as given in Equation (14) where V_i implies SCV' criticality index *i* (*i = probability or severity indicators*).

$$V_i = \sum_{i=1}^{5} \overline{K}_i \times h^t = \left(\acute{K}_1, \acute{K}_2, \acute{K}_3, \acute{K}_4, \acute{K}_5\right) \times (1, 2, 3, 4, 5), 1 \le V_i \le 5 \quad (14)$$

(Insert Table 4 here)

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 (15) by capturing both the indicators.

$$OI = \sqrt{\left(\sum_{i=1}^{5} \overline{K}_{(p)} \times h^t\right) \times \left(\sum_{i=1}^{5} \overline{K}_{(s)} \times h^t\right)}, \; 1 \le OI \le 5 \quad (15)$$

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 (15.3).

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

$$= (0.03, 0.20, 0.40, 0.30, 0.07) \quad (15.1)$$

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

$$= (0.02, 0.09, 0.36, 0.40, 0.13) \quad (15.2)$$

$$OI = \sqrt{[(1 \times 0.03) + (2 \times 0.20) + (3 \times 0.40) + (1 \times 0.30) + (1 \times 0.07)] \times \sqrt{[(1 \times 0.02) + (2 \times 0.09) + (3 \times 0.36) + (1 \times 0.40) + (1 \times 0.13)]}}$$

$$= 3.36 \quad (15.3)$$

5. Discussion

SCV are the unanticipated events that disturb or affect the typical supply chain operations (Zavala et al., 2018). Vulnerabilities indicate the level of fragility of a system (Ekanayake et al., 2020a) and are characterized by the predisposition to risk, strength-building, and elasticity to withstand shock (Pettit, 2008). Further, even if subjected to the same disruptive events, different SCs may turn out to be more or less vulnerable, depending on their adaptive and coping capacities that withstand the disruptive event (Ekanayake et al., 2020a). As more resilient SCs are more capable of responding to disruptions and recovering from them by maintaining operational continuity, more resilient SCs are less vulnerable to SC disruptions than those that have less inherent resilience (Ekanayake et al., 2020b). Therefore, SCR envisages providing an adequate set of capabilities to SCs to prevent, mitigate, or deal with SCV while enabling restoration and speedy recovery during disruptions.

The indices obtained from the Fuzzy analysis reveal that three of the SCV components (PBSCV, OSCV, and PSCV) are more critical compared to the other two components (TSCV and ESCV). Hence, it is concluded that HK IC projects are not so vulnerable to the negative economic changes and technological disturbances, demarcating their adaptive capabilities for withstanding economic and technological disruptions. 'Variations/rework' was ranked as the second CSCV considering the mean value of the responses, although included in the TSCV component. That may explain why the variable 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.

Component 5 (PBSCV) reflects the SCV related to IC's production with the overall vulnerability impact of 3.52, which is the highest. 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 IC projects. As another variable that affects 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 SCs. 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 can disrupt the manufacturing stage, causing supply shortages, excess cost and time implications and quality shortfalls. Therefore, the industry stakeholders' closer attention should be encouraged, since needed to withstand these CSCV, at the outset to achieve resilient SCs in HK.

The impact of OSCV (vulnerabilities arising from inadequate and/or inappropriate organizational strategies and management decisions, from the staff within the organization and human resources) in achieving SCR in IC in HK is 3.52 and became the second highest here. Communication breakdown (Mean score-3.52) in this category was the third significant vulnerability among all. Indeed, the entire recovery process may collapse from a communication failure during a disruption. Also, these lead to industrial disputes and SC inefficiencies (Luo et al., 2018). As IC projects in HK are vulnerable due to outsourcing (Ekanayake et al., 2019), a decision for self-manufacturing and vertical integration of SC processes could provide an answer (Han et al., 2017). Contracting companies have experienced delays due to poor supplier selection, and this remains a significant concern since the industry is still vulnerable to sub-standard supplier selection (Ekanayake et al., 2019). All these vulnerabilities arise from the organizational level, necessitating improved organizational capacities to help withstand adverse effects.

The PSCV (procedural SCV, referring to disruptions arising from the operations at SC nodes) component is also within the 'critical' range as per the FSE results with their respective overall index and associated model coefficient values of 3.47 and 0.22. The variables within the components can arise at any SC node and common in the HK construction industry. Site safety has become a serious concern during on-site assembly (Zhai and Huang, 2017) since the process consists of lifting heavy and oversized units, unclear instructions, and lack of training regarding installation, collisions with other components, and near misses (Ekanayake et al., 2020b). This 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. On the other hand, transport disruptions are inherent in HK IC, as the prefabricated components are transported from factories in Mainland China. Being another jurisdiction with a border crossing and associated checks, potential disruptions are not just limited to vehicle breakdowns, insufficient transportation capacity, and too late or too early delivery (Wang et al., 2018). In addition, IC in HK is also vulnerable to the impacts of any relevant new laws and regulations (Ekanayake et al., 2020b) and border controls and associated delays, e.g., during COVID-19 or due to additional customs and/or police checks. Although there are still no recorded major problems from these SCV, developing appropriate capabilities may improve their withstanding ability with associated cost and time benefits since these vulnerabilities are common and could potentially cause disruptions.

TSCV (including the technology-based disruptive causes) and ESCV (consisting of factors closely related to the disruptions due to the economic changes) components have received lower impact indices, highlighting their lower contribution towards vulnerabilities. However, their respective impact indices of 3.32 and 3.12 reflect that the industry is moderately vulnerable to the associated disruptions. As an exception to the results, 'Variations and/or rework', the second most critical SC vulnerability, was also grouped in TSCV. Although fragmentation of the IC SCs results in these vulnerabilities (Shahparvari et al., 2019), the impact is less in IC compared to the traditional construction SCs with the availability of early planning and design (Kisi et al., 2019). Under these circumstances, even HK IC would benefit from the integration of robotics, digital twin, and artificial intelligence together with the IC SC process, as indicated by Shahparvari et al. (2019). All the ESCV factors 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. At the current stage, the effect is not very high but considerable in HK (Ekanayake et al., 2020b).

Moreover, all these highly influential SCV could be better managed through the SC capabilities of resourcefulness, flexibility, capacity, adaptability, efficiency, financial strength, visibility, anticipation and dispersion (Ekanayake et al., 2020c). For instance, the vulnerabilities of outsourcing and supply-demand mismatches could be overcome through flexible and capable

SCs. Anticipation and visibility of SCs help recovery during communication issues. Anticipation would help detect tolerance issues, while dispersion would enable recovery and restoration during such disruptions. Also, quality losses could be better handled through these capabilities. SC flexibility, capacity and visibility would provide successful withstanding capacity to handle logistics issues, while resourcefulness could facilitate protection against safety issues. Further, enhanced SC capacity as a capability enables redundancy of SCs during disruptions and provides adequate resources to respond, recover and restore.

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 16. In Equation 16, the coefficients assigned to CSCV components correspond to the respective normalized values.

$$OI = [C_{ESCV}|CV_{ESCV}|] + [C_{TSCV}|CV_{TSCV}|] + [C_{PSCV}|CV_{PSCV}|] + [C_{OSCV}|CV_{OSCV}|] + [C_{PBSCV}|CV_{PBSCV}|] \quad (16)$$

6. Practical Implications

Advanced SC 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 SC disruptions. Hence, achieving resilient, sustainable SCs 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 SC performance before initiating appropriate measures to withstand them. This further includes investigating poorly performing areas of the SC network to target better management, future improvements, and even major reforms. In these circumstances, industry stakeholders, especially the managerial level professionals, can adopt the proposed FSE based soft computing approach in which vulnerability assessment is developed based on industry experts' linguistic judgment. This was appropriately generalized for the IC context in HK using fuzzy triangular numbers via a predefined fuzzy scale to determine the industry's vulnerability levels. Indeed, the study findings could be further strengthened and verified by conducting in-depth discussions/interviews with policy/regulation makers and practitioners in the industry.

Moreover, this multi-criteria-multi-level framework would facilitate effective planning and decision making by the project managers, starting with effective 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 a momentous milestone in achieving SCR in IC in HK, i.e., by establishing an FSE model to evaluate the overall impact of the SCV. This model could help industry professionals whenever they plan to assess their SC uncertainties further to uplift the overall performance of the IC in HK.

7. Conclusions and Further Research

This study enabled the useful mathematical modeling of SCV affecting SCR in IC in HK by applying statistical analysis and fuzzy set theory to in-depth data collected for this purpose. This study further aimed to ascertain the criticality level of each SCV and the overall impact of each on IC. Based on a previously extracted 26 factors, this study solicited experienced IC experts' professional judgments to evaluate the probability and severity of SCV affecting SCR in IC in HK. 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: 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 OI (Overall Impact) is 3.36, indicating the IC SCs are considerably vulnerable to these disruptions. Production-based vulnerabilities (impact-3.52) have the highest impact among the components.

A limitation of this study may be perceived in the sample size. Although the sample size used here was fully justified in the research method section, and representative of the relatively small 'population' of experts on IC in HK, big data from a bigger sample of a larger future population could enable the development of a more precise model. This study collected data from known experts. Given that such experts may be more familiar with managerial level professionals in IC projects, there is a possibility of some results being unintentionally biased. To minimize any bias and maintain consistency of the data collected, all the respondents were asked at the beginning of the survey, to provide their answers considering all the SC phases. However, such potential subjectivity could be further reduced by expanding the respondents' groups to ensure inclusion of well-experienced mid-level practitioners and also validating the findings using real-life case studies as the next step of this research.

Furthermore, this study focused on the linear relationships between the vulnerabilities based on the fuzzy-method that only enabled static analysis, hence the cascading or co-relational impacts among/across the vulnerabilities could not be considered. Therefore, having established a firm foundation in the presently reported study, dynamic statistical analysis methods should be deployed in further research to analyze those co-relational impacts. Besides, this study also lays the foundation for that enhancement by establishing the FSE theory and protocols for SCV analysis and 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 (Owusu et al., 2020). Hence, future studies may seek more rigorous computational methods to derive impact indices.

Future studies may also give greater weightage to the type of special vulnerabilities that surfaced with the rapid spread of the COVID-19 virus while completing this paper and drastically affected global SCs in most industries. Non-generalization of the results may be another limitation associated with this study. Given that the nature of IC is specific in HK due to its socio-economic background, the model may not directly apply to other countries or industrial contexts. On the other hand, the methodology presented in this paper may be used elsewhere; hence, follow-on research can usefully target similar sets of findings in different regional or national industry contexts. Besides, a multi-layer appraisement model can be formulated to evaluate SC capabilities for improving SCR. Thereby, a decision support model can be created to indicate useful pathways to SCR by balancing identified vulnerability and capability levels. This is expected to be valuable to industry stakeholders.

Moreover, this study contributes a vital component to this growing body of knowledge by evaluating SCV associated with IC projects in HK. Also, the model could be periodically updated by injecting timely information using the same methodology. This would enable updating of the improvement areas, by injecting timely changes to cater to new contexts, scenarios and priorities through an updated, hence applicable model in a rapidly changing world. Although this study employed a rigorous approach in formulating the fuzzy model, the model itself can be easily understood and adopted by industry professionals to identify and understand various proximate root causes of poor performance. This empowers academic or industry researchers and practitioners to develop more comprehensive SCR evaluation models based on their specific regional or industry contexts. Moreover, this study achieves its original purpose of providing a deep understanding of, and a viable methodology for, decision-makers in evaluating SCV in IC in HK, with the underlying aim of contributing to resilient, sustainable and performance-enhanced supply chains.

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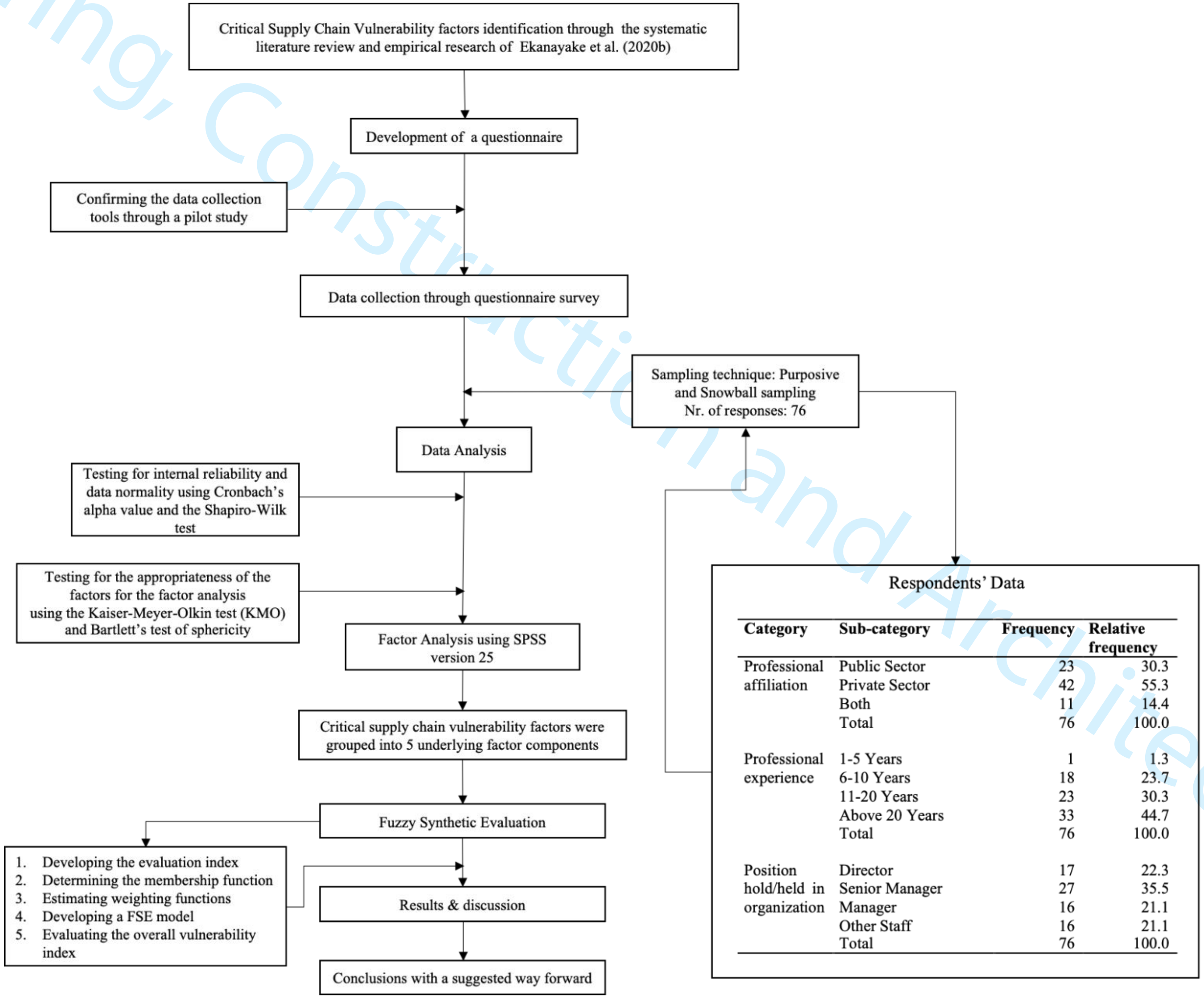

Category	Sub-category	Frequency	Relative frequency
Professional affiliation	Public Sector	23	30.3
	Private Sector	42	55.3
	Both	11	14.4
	Total	76	100.0
Professional experience	1-5 Years	1	1.3
	6-10 Years	18	23.7
	11-20 Years	23	30.3
	Above 20 Years	33	44.7
	Total	76	100.0
Position hold/held in organization	Director	17	22.3
	Senior Manager	27	35.5
	Manager	16	21.1
	Other Staff	16	21.1
	Total	76	100.0

Figure 1: Methodological framework for the study

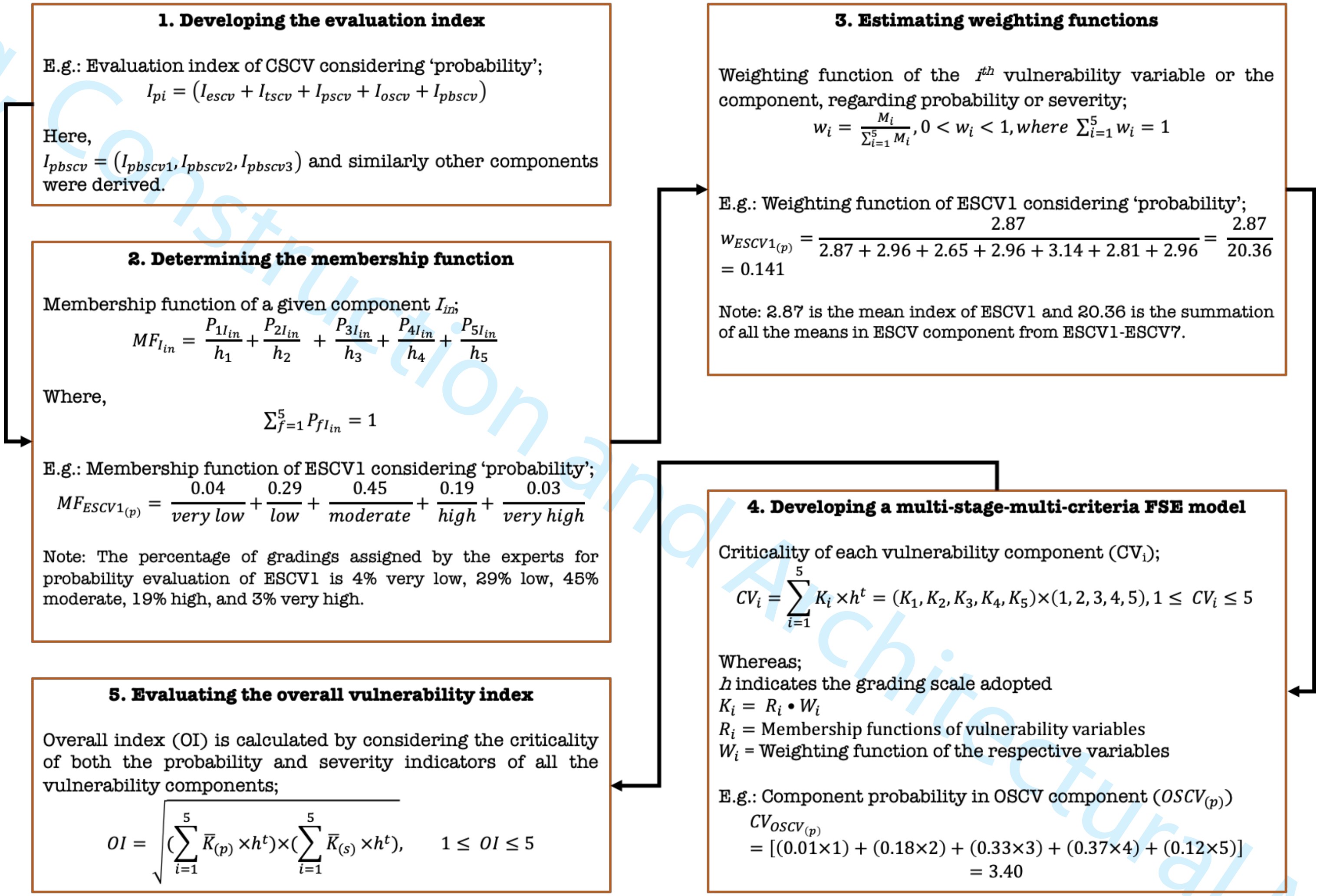

Figure 2: Workflow of the FSE modelling in this exercise

Table 1: Evaluating Critical SCV (CSCV)

Adapted from Ekanayake et al. (2020b)

No	**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**
1	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
2	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
3	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
4	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
5	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
6	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
7	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
8	Inadequate 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
9	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
10	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
11	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
12	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
13	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
14	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
15	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
16	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
17	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
18	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
19	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
20	Labour strikes	2.91	1.055	0.000	0.64	3.61	1.051	0.000	0.75	10.75	3.28	0.71	14
21	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

22	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
23	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
24	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

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

Table 2: Results of the factor analysis

Source: Ekanayake et al. (2020b)

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	Labour 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 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**	**1.000**			**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	

Table 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**			