A Fuzzy Synthetic Evaluation of Capabilities for Improving Supply Chain Resilience of Industrialised Construction: A Hong Kong Case Study

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Abstract

Inspired by multiple benefits, including competitive advantages from developing resilient supply chains, this study was designed for the development of effective assessment models to evaluate Supply Chain Capabilities (SCC), improving resilience in Industrialized Construction (IC) in one of the high-density cities: Hong Kong (HK). First identifying appropriate SCC, this study aimed to develop multi-stage-mathematical models to evaluate the adoption of SCC of IC in HK. Experts' judgements were solicited and analyzed using fuzzy synthetic evaluation. Forty-one measurement items were grouped under nine critical SCC components, and their 'importance' and 'current practice' indices were determined. The importance index of SCC is high, spotlighting the significance of the contribution of SCC to resilience whereas the current practice index is comparatively low, highlighting the dire need to bridge this gap with capability improvements. To the authors' knowledge, these evaluation models are the first set of structured models designed to assess SCC of IC, providing valuable insights to practitioners for well-informed decision-making in formulating strategies to initiate and nurture resilient supply chains in IC in HK.

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

Introduction

A highly volatile and interconnected global market (Gölgeci and Kuivalainen 2020), ever-changing demands of clients and fierce competition amongst major suppliers necessitate a strategic shift towards a modern Supply Chain (SC) management philosophy: Supply Chain Resilience (SCR) (Tan 2020; Sahu et al. 2017). Also, organizational SCs are surprisingly fragile and easily susceptible to unforeseen crises (BCI 2019), as vividly demonstrated by catastrophic disruptions to global SCs by COVID-19 as this paper is being compiled. Organizations face disruptions daily, even under normal conditions, and these disruptions endanger an organization's ability to perform effectively (Gölgeci and Kuivalainen 2020). Also, the growing complexity of the global SCs and their increased vulnerability to disruptions (Mandal 2020) have threatened the long-term success and survival of organizations and their parent industries.

In response, SCR enables organizations to respond effectively during disruptions with the swift restoration of SCs (Tan 2020). Besides, resilient SCs are less vulnerable to disruptions and can also handle any vulnerabilities that trigger problems (Ekanayake et al. 2019). Probing deeper, SCR can only be achieved by appropriate application of relevant Supply Chain Capabilities (SCC) (Pettit et al. 2013) which enhance the adaptive capacities of the SCs (Ekanayake et al. 2019). Therefore, the imperative has clearly emerged for identifying the critical SCC for improving SCR in various industries. However, the literature is sparse on how SCR is measured and evaluated since only a few articles attempted to assess SCR (Kamalahmadi and Parast 2016). The research gap is significant since it is difficult to provide effective remedies without proper assessment of SCR (Tan 2020) based on its two fundamental dimensions of SC vulnerabilities (SCV) and SCC (Pettit et al. 2013). Considering published articles, Pettit et al. (2013) implemented an assessment tool for global manufacturing and service firms, Pavlov et al. (2017) proposed a theory based hybrid fuzzy-probabilistic approach to SCR assessment, Fakoor et al. (2013) suggested a method for measuring SCR in the automobile industry, and Sahu et al. (2017) proposed a fuzzy-based SCR evaluation system for candidate industry. However, the literature remains silent on an assessment model to evaluate SCR in the construction industry, although the industry needs more resilient SCs.

Furthermore, an industry-specific study is a precursor to recommendations on improving SCR since the construction industry is unique, and the construction project SC configurations are distinctive (Zainal and Ingirige 2018). Moreover, while superposing valuable advantages from offsite manufacturing, IC supply chains are more complicated than in traditional construction SCs as they encompass the SC phases of manufacturing-factory, logistics and onsite assembly (Ekanayake et al. 2019). The type of manufactured unit, hence corresponding SC configurations and vulnerability levels, differ across jurisdictions. For example, Singapore has developed 'Pre-engineered Prefinished Volumetric Construction' (PPVC) based on 'bigger' pre-engineered volumetric units (Hwang et al. 2018). A different module assembly process is used in Japan (Barlow et al. 2003). The types and vulnerability levels in supply chains when manufacturing and delivering such different unit types would thereby differ (Ekanayake et al. 2021).

Focusing on the construction industry in Hong Kong (HK), construction SCs have weathered various disruptions over the years (CIC 2019). Although Industrialized Construction (IC) practices in HK have introduced innovations through safe, clean and efficient construction methods (Wang et al. 2020), IC supply chains are still drastically affected by inherent SC disruptions (Ekanayake et al. 2019). In the HK context, all the prefabricated units are transported from Mainland China; hence SCs are commonly affected by transportation and cross border logistics-related vulnerabilities (Ekanayake et al. 2019) compared to other jurisdictions. Therefore, separate jurisdiction-specific studies are critical in detecting appropriate SC capability imperatives to ameliorate jurisdiction-specific SCV. Further, it is becoming crucial for IC organizations to build more resilient SCs through enhanced SCC to effectively respond to escalating threats since the construction industry is a key driver and a contributor to the national economy. These foregoing imperatives establish the importance of probing and assessing industry and jurisdiction-specific SCC and determining the current practice gaps in IC.

In this context, the researchers were motivated to develop evaluation modes to assess SCC, given the importance of addressing industry needs to boost current levels of SCC in IC in HK. In line with this research motivation, Ekanayake et al. (2021) conducted a systematic review of literature through meta-analysis and identified 58 SCC specific to IC. However, there is no published research on evaluating the SCC of IC firms targeting resilience, although the analysis of their capabilities is essential to develop further strategies. Even more extensive research seems needed for the specific development of IC supply chains in HK. Further, the development of SC capability imperatives should enhance SCR by improving the adaptive capability of SCs to withstand vulnerabilities (Kamalahmadi and Parast 2016). Thus, in IC, SCR initiatives would boost performance and productivity by reducing the additional cost implications, delays and safety hazards arising from uncontrolled SCV.

Given this background, this study was designed to develop multi-stage mathematical models to evaluate the level of importance of SCC in improving the SCR in IC in HK by soliciting experts' judgments and analyzing them using a soft computing approach, namely, the Fuzzy Synthetic Evaluation (FSE). This study further assessed the current practice level in terms of the relevant SCC, thereby highlighting a practice gap in the industry through the developed models. Besides, this study contributes to the SCR knowledge domain by initiating the first evaluation models that assess IC capability levels, highlighting this study's originality. Relevant industry stakeholders can effectively utilize these decision-aid models to improve their own and cross-party resilience, thereby the sustainability and performance of HK industrialized construction SCs. The forthcoming sections explicate in turn: the systematic literature review conducted to identify the important SCC; details of the empirical study conducted to solicit the views of construction industry experts on the ‘importance’ and ‘current practice’ indicators of identified SCC; research methods adopted to formulate the fuzzy evaluation models; followed by a focused discussion; and finally conclusions drawn from this study with a suggested way forward.

Summary of Literature Analysis and Synthesis

Resilience typically refers to the ability to deal with shocks, which may include global economic crises, natural disasters, extreme weather events, and environmental threats (Tan et al. 2017). According to Cutter et al. (2010), it is an outcome measure with an end goal of limiting damage (resistance), mitigating the consequences (absorption), and recovery to the pre-event state (restoration). Without focusing on the predictive events, resilience needs to be improved to respond adequately to uncertainties (Comes and Van de Walle 2014). Further, resilience straddles across diverse disciplines, while the resilience of supply chains is critical to overall resilience in industries such as construction and, even more so, in Industrialized Construction (IC). Therefore, Supply Chain Resilience (SCR) is a significant ‘cluster’ researched in the ‘resilience’ knowledge domain.

The concept of SCR has received a notable eminence in recent years (Gölgeci and Kuivalainen 2020) and has become a key topic in the SC management research domain and practice (Tan 2020). SCR is 'the adaptive capability of an SC to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the SC to a robust state of operations' (Kamalahmadi and Parast 2016). The SCR concept advances the traditional risk management approaches by enabling more effective disruption management in SCs (Fiksel 2015; Van Der Vegt et al. 2015). Thus, improving SCR ensures high performance and customer value (Chowdhury et al. 2019) by reducing the additional cost implications, delays and safety hazards resulting from SCV. However, SCR can only be achieved by deploying adequate SCC (Pettit et al. 2013), which explains why Morash (2001) highlighted SCC as the building blocks for improving SC strategy, operational excellence and healthy clients' relationships. Indeed, it is essential to determine the appropriate SCC with their respective levels of relative importance and applicability potential to apply these better in the SC process (Ekanayake et al. 2020).

Industrialized Construction-Supply Chains (IC-SCs) in HK face distinctive challenges of fragmentation, weak traceability, inadequate real-time information (Wang et al. 2020), an ageing workforce, labour shortage, space constraints, escalating costs (Zhai et al. 2019), limited site access and space, expensive land acquisition costs, floating population, heavy traffic near the site, and higher project capital and rental costs (Choi et al. 2019). Therefore, the industry calls for SCR, which includes initiating essential improvements to the SCC to help deal with the consequential disruptions (Ekanayake et al. 2020).

Besides, SCC provide drivers for improving SC strategy (Morash 2001) while also providing counter-balancers of SCV (Zavala et al. 2018). SCC have recently received increasing research interest, and many research studies have been conducted in different knowledge domains (Pettit et al. 2019; Gölgeci and Kuivalainen 2020). Ponis and Koronis (2012) also studied how supply chain capabilities could mitigate potential disruptions and improve SCR. SCC are twofold: reactive and proactive, where reactive capabilities enable rapid response, and proactive capabilities enhance SC withstanding ability towards vulnerabilities (Wieland and Wallenburg 2013). Moving beyond identifying SC capability factors, such as transhipping, dual sourcing, and visibility (Christopher and Peck 2004), Pettit et al. (2013) developed an SCR assessment tool, including 14 capability components based on manufacturing and service firms. The model proposed flexibility, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, organization, market position, security and financial strength as SCC while including more than 70 sub-factors (measurement items) to withstand SC vulnerability categories of turbulence, deliberate threats, external pressures, resource limits, sensitivity, connectivity and supplier/customer disruptions. Jain et al. (2017) proposed a model to boost SCR practice by integrating 13 key enablers using the interpretive structural modelling method. Ali et al. (2017) proposed a portfolio of enablers, barriers and risks in building resilience in Australian SMEs.

Further, Chowdhury and Quaddus (2017) developed a scale using dynamic capability theory to measure SCR. The findings were in line with those in the Bangladesh apparel industry and included 12 SCC with more than 45 measurement items. A model developed by Jafarnejad et al. (2019) tested the impact of 10 SCC appropriate to medical equipment SCs using fuzzy and Delphi methods. Focusing on the construction industry, Zainal and Ingirige (2018) identified 12 SCC, including several measurement items based on Malaysian public construction projects and their SC dynamics. These findings further signify that the SCC are specific to the industries explored and their respective jurisdictions, hence justifying the need for an IC-based separate study in HK.

Moreover, Sahu et al. (2017), Fakoor et al. (2013), and Pavlov et al. (2018) attempted to assess SCR by applying fuzzy logic as inspired by the associated strengths of the method, including ease of application and practicality. Although these research exercises have been carried out for assessing SCR, there is still a major research gap in evaluating SCR in the construction industry. In contrast, a more specific and important gap is recognized in IC itself. Therefore, following on from the studies above and identifying the research importance of such SCR imperatives for IC, Ekanayake et al. (2021) conducted a systematic literature search through meta-analysis and determined nine SCC components with 58 measurement items specifically for IC, as shown in Table 1. According to Chowdhury and Quaddus (2016), the measurement dimensions of SCR are readiness, response and recovery. SCs with higher readiness have the capabilities of flexibility, collaboration, redundancy, visibility, financial strength, market strength, and efficiency, while adaptability and anticipation add more responsiveness to the SCs (Chowdhury and Quaddus 2016). Further, dispersion is essential for a speedy recovery, and dispersion facilitates swift but sound responses during disruptions (Ekanayake et al. 2020). Indeed, SC capacity, adaptability and resourcefulness improve the absorption of shocks and reduce impact or loss during recovery. As stated in Table 1 [and as categorized later in Table 3], the list of 58 SCC measurement items identified by Ekanayake et al. (2021) includes and covers all the three measurement dimensions of SCR, providing a sound basis for this study.

Expanding the research horizons further and by addressing the research lacuna of an evaluation model of SCC in IC, this study aimed to compute two mathematical models to assess SCC and contribute positively to SCR in HK industrialized construction through empirical research. These two models will be useful in the effective evaluation of SCR in IC in HK targeting adaptive SCs. The forthcoming section provides a detailed explanation of the empirical research conducted for yielding the key research outputs of this study.

Research Methods

The research methodology followed in this study is illustrated in Figure 1.

Selection of SCC measurement items

This study was initiated with a systematic and exhaustive literature review through meta-analysis, which captured 58 SCC measurement items in the IC context as by Ekanayake et al. (2021). While inappropriate and impractical to describe this in detail again here, it was the foregoing platform used to launch an empirical study as follows. Fifty-eight SCC measurement items identified through the comprehensive literature review provided a basis for an expert opinion survey using the questionnaire as illustrated below. However, before including these 58 items in the questionnaire, they were pilot-tested for significance, comprehensiveness and their applicability to this study. Four professors with academic and industry experience on IC of more than 20 years each were involved. After careful consideration of all factors, the participants recommended removing the 'brand equity of the organizations'. They thought this SCC is not highly influential in the construction industry since IC is practised in the industry by the reputed construction organizations that had already developed significant brand equity within the industry. Although the professors did not 'highly agree' with the SC capability of 'conducting parallel processes instead of series processes', they suggested retaining the factor but later reconsider whether to eliminate or include it after the primary data collection. Hence, 57 SCC measurement items were confirmed after the pilot-study (as in Table 1) and included in the questionnaire.

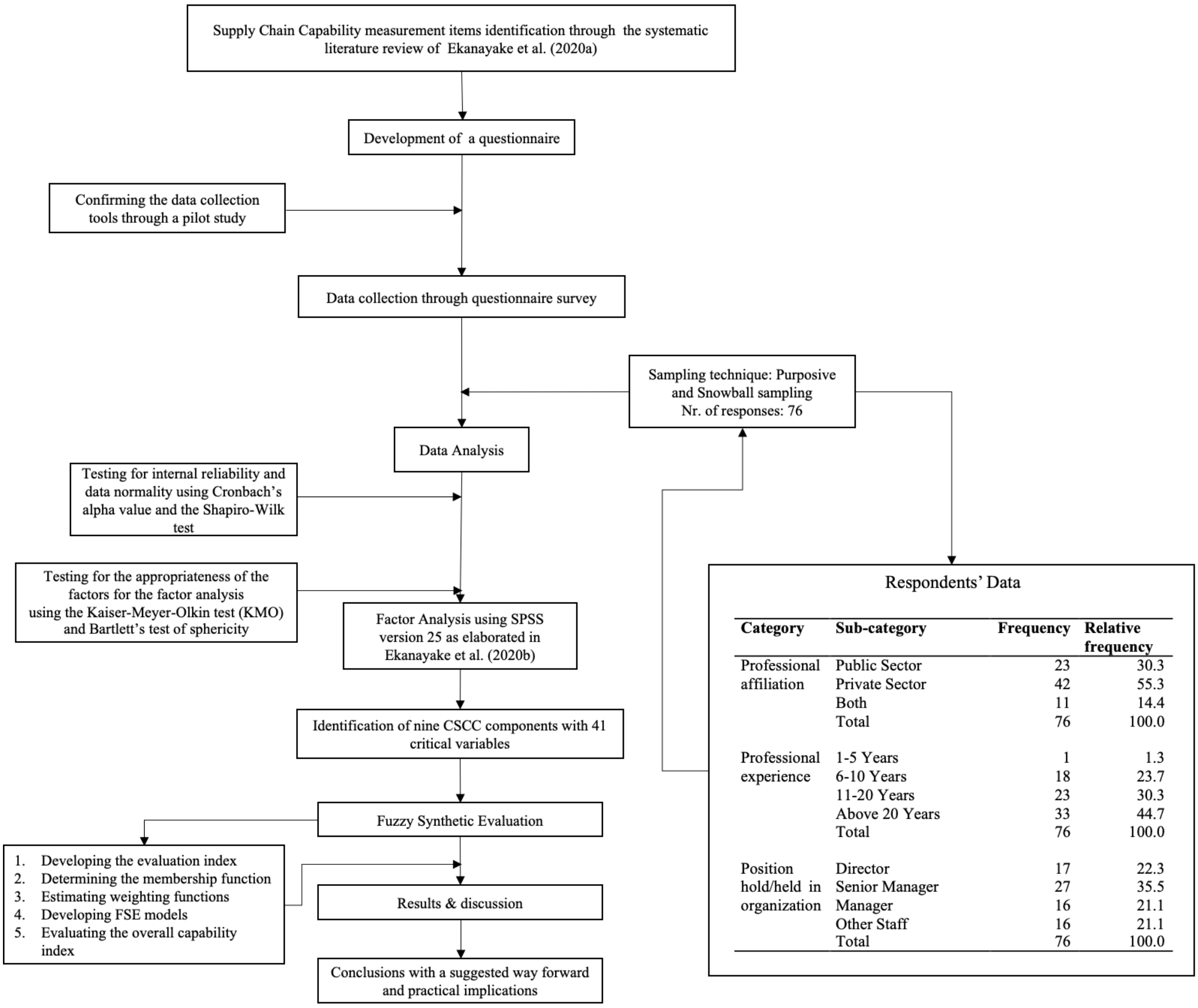
Table 1: SCC measurement items extracted from the comprehensive literature search
Source: (Ekanayake et al. 2021)

Code	SCC measurement items
C01	Modular product design
C02	Multiple uses
C03	Supplier contract flexibility
C04	Multiple sources/suppliers
C05	Alternate distribution channels/multimodal transportation
C06	Risk pooling/sharing
C07	Production postponement
C08	Vertical integration
C09	Integrating inventory management with SCM tools
C10	Reserves capacity/inventory buffers (materials, equipment & labor)
C11	Redundancy
C12	Backup equipment facilities
C13	Backup utilities
C14	Waste elimination
C15	Higher labour productivity
C16	Avoid variations/rework
C17	Failure prevention
C18	Products, assets, people visibility
C19	Business intelligence gathering
C20	Efficient IT system & information exchange
C21	Finite capacity scheduling tools with procurement visibility/e-procurement
C22	Fast rerouting of requirements
C23	Lead time reduction
C24	Conducting process simulation

C25	Alternative innovative technology development
C26	Learning from experience
C27	Deploying IT-based reporting tools
C28	Maintaining buffer time
C29	Conducting parallel operations
C30	Monitoring early warning signals
C31	Forecasting/predictive analysis
C32	Risk management
C33	Cross-training/intensive training
C34	Deploying tracking and tracing tools
C35	Quality control
C36	Business intelligence and disruption management research
C37	Distributed decision making
C38	Distributed capacity and assets
C39	Decentralization of key resources
C40	Professional response team
C41	Effective communications strategy
C42	Consequence mitigation
C43	Collaborative information exchange & decision making
C44	Collaborative forecasting
C45	Obtain more competitive price from suppliers and subcontractors
C46	Procure materials globally
C47	Public-private collaboration
C48	Strong reputation for quality
C49	Market share of the organisations
C50	Close and healthy client-contractor relationships
C51	Faster delivery
C52	Cyber-security
C53	Personnel security
C54	Financial reserves and funds
C55	Good insurance coverage
C56	Portfolio diversification
C57	Good price margin

Questionnaire development

This study used a questionnaire survey to capture and grade 57 SCC measurement items since questionnaire surveys offer reliable, valid and quick information with a lower resource requirement (Ameyaw et al. 2015). Hence, a questionnaire was developed by including both open-ended and closed-ended questions. Experts' opinions for close-ended questions were captured using a five-point grading scale. The respondents' views were captured using open-ended questions. Further, the criticalities of the identified SCC measurement items were assessed using a five-point Likert scale as the linguistic terms for the FSE technique (Owusu et al. 2020). Before proceeding with the sampling and data collection, the questionnaire was pilot tested for the relevance and comprehensiveness of the questions, language structure and understandability. As stated above, four academic professors participated in this pilot testing and confirmed the questionnaire's suitability for collecting the targeted data. The sample questionnaire is attached as Annexure A.



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

Survey

The questionnaire survey was designed to solicit the views of industry experts who are working or worked on IC projects in HK. To obtain a representative sample for this study (Chan et al. 2018), purposive sampling: being a 'non-probability sampling' (Zhao et al. 2014), was used initially. Thereafter, the snowball sampling method was deployed to obtain a valid and expanded sample size, enabling rich data gathering through social networks as employed in previous construction management studies by Zhang et al. (2011) and Chan et al. (2018). Seventy-six responses from the experts were obtained with special efforts to overcome the difficulties of gathering responses due to time constraints and busy schedules of the respondents and deemed as appropriate for the analysis since a sample size of 30 is representative of any group (Ott and Longnecker 2015) and adequate to develop significant conclusions in a subject area of this nature (Owusu et al. 2020). The 76 responses indicate a higher response rate than obtained in some previous survey-based construction management studies (Adabre and Chan 2019; Owusu et al. 2020; Darko and Chan 2018). Figure 1 presents the survey respondents' profile, highlighting that these respondents possess managerial level experience on IC projects and justifying that their responses are valid. Indeed, the number of such experts in HK with 'managerial level experience on IC projects', (i.e. the total population from which this sample is drawn) is itself not large, further justifying the reliability of findings derived from the sample of 76.

Data Analysis and Findings

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

Data normalization, mean index and factor analysis

In this study, the importance or the criticality of the SCC measurement items (hereafter considered as variables) and their current levels in present practice were separately assessed using the questionnaire survey. Mean score values based on the experts' assessment were used to establish the 'importance' and the 'current practice' of each SCC variable. The details of the survey results are given in Table 2. The data normalization process was undertaken before moving to the factor analysis to screen out critical SC Capability (CSCC) variables following the studies of Adabre and Chan (2019) and Osei-Kyei and Chan (2017). Therefore, variables above 0.5 (normalized value) were regarded as critical and considered in the factor analysis. During the factor analysis, the selected SC capability variables were grouped into nine components based on the similarities of the underlying factor themes (Mooi et al. 2018). These nine components are the capabilities of IC-SCs; namely, resourcefulness, flexibility, capacity, adaptability, efficiency, financial strength, visibility, anticipation, and dispersion. The factor analysis results and CSCC variables selection are explained in detail in Ekanayake et al. (2020).

Table 2: Evaluating CSCC measures

CSCC Measurement Item	**Level of importance**			**Level of current practice**		
	Mean	**SD**	**N-V**	**Mean**	**SD**	**N-V**
C35	4.413	0.660	1.00	3.800	0.735	0.83
C55	4.373	0.785	0.96	3.907	0.701	0.92
C54	4.347	0.707	0.93	3.693	0.788	0.74
C16	4.253	0.660	0.83	3.440	0.663	0.53
C40	4.240	0.612	0.81	3.747	0.680	0.79
C26	4.240	0.803	0.81	3.893	0.938	0.91
C17	4.187	0.630	0.75	3.440	0.793	0.53
C41	4.187	0.651	0.75	3.547	0.664	0.62
C50	4.187	0.800	0.75	4.000	0.717	1.00
C05	4.180	0.734	0.75	3.213	0.703	0.34
C01	4.173	0.724	0.74	3.680	0.701	0.73
C42	4.147	0.651	0.71	3.413	0.718	0.51
C15	4.147	0.748	0.71	3.680	0.808	0.73
C02	4.133	0.741	0.70	3.640	0.671	0.70
C14	4.107	0.764	0.67	3.253	0.773	0.38
C45	4.107	0.781	0.67	3.573	0.720	0.64
C28	4.093	0.903	0.65	3.533	0.759	0.61
C18	4.080	0.712	0.64	3.347	0.626	0.46
C48	4.067	0.622	0.60	4.000	0.678	1.00
C37	4.067	0.704	0.62	3.893	0.798	0.91
C43	4.067	0.704	0.62	3.720	0.689	0.77
C51	4.053	0.634	0.61	3.867	0.811	0.89
C53	4.053	0.884	0.61	3.400	0.822	0.50

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

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

Factor extraction was done after the factor analysis. Factors whose eigenvalues are above one were retained. Then, varimax rotation yielded 41 measurement items with nine underlying components of CSCC, which explain 79.77% of the total variance. The respective test statistics of the Kaiser-Meyer-Olkin test (KMO=0.810) and Bartlett's test of sphericity statistic (3370.583 with a significance level of 0.000) indicated that the data set is appropriate for factor analysis and the correlation matrix is not an identity matrix (Kaiser 1974; Ekanayake et al. 2020). The results generated from the factor analysis are presented in Table 3.

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

Multi-criteria decision making was enriched with FSE so-called fuzzy logic approach in many research disciplines (Xu et al. 2010). This is because of the ease of applying the method and its practicality of application (Lo 1999). Given that this method avoids imprecision, vagueness, and the inconsistency associated with evaluating subjective information, the fuzzy theory is used in SCR related research (Fakoor et al. 2013; Sahu et al. 2017; Pavlov et al. 2018; Jafarnejad et al. 2019). Hence, this study employed FSE as a soft computing approach to evaluate the importance and the current practice of CSCC in IC in HK. The following five steps guided this study to develop SC capability indexes and the models to evaluate CSCC for improving SCR in IC in HK. Also, these five steps are clearly illustrated in Figure 2.

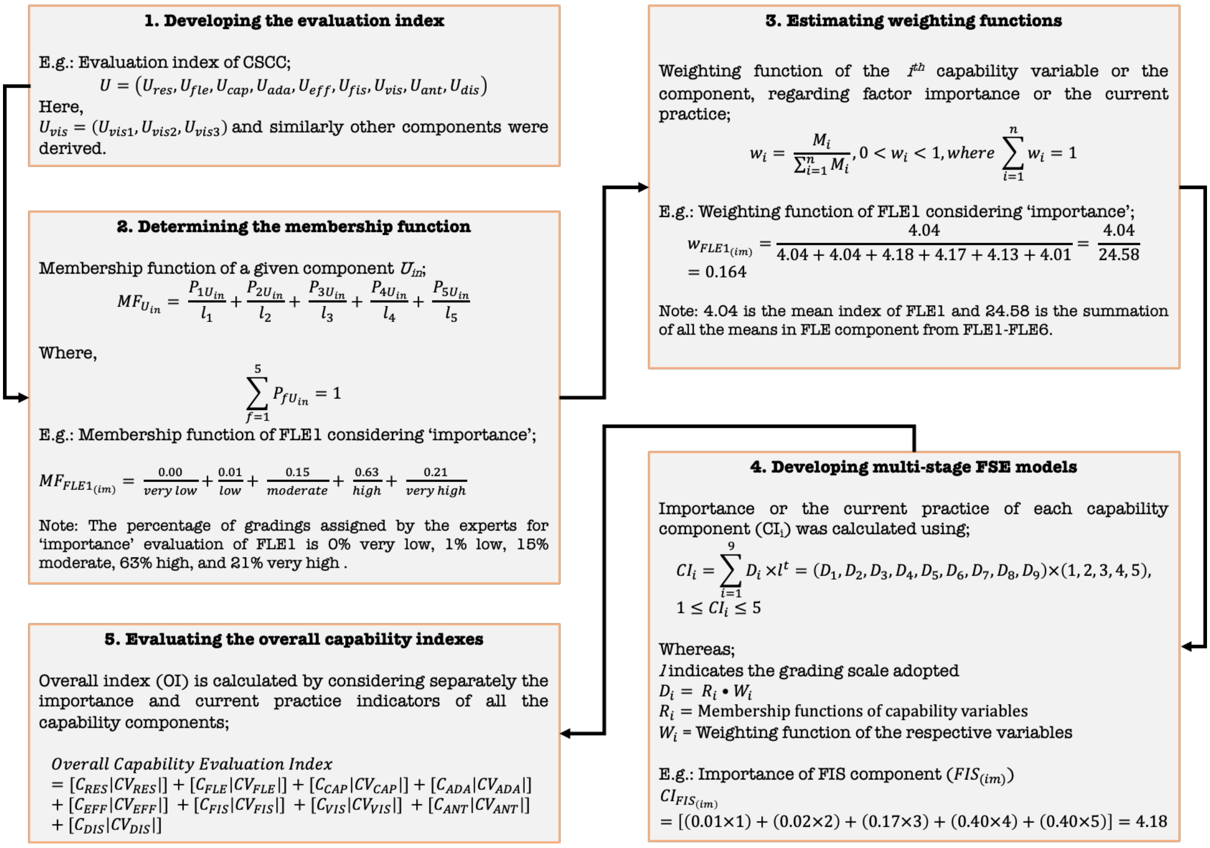


Figure 2: Workflow of the FSE modelling in this exercise

Step 1: Developing the evaluation index system

First, an evaluation index was created [Equation (1)] by defining CSCC components as the first level index system. In generating the following FSE equations, this study followed the studies of Ameyaw et al. (2015), Li et al. (2013), and Owusu et al. (2020).

$$U = (U_{res}, U_{fle}, U_{cap}, U_{ada}, U_{eff}, U_{fis}, U_{vis}, U_{ant}, U_{dis}) \quad (1)$$

The second level index system was then defined by considering the individual CSCC variables within the SC capability components, as shown in Table 4.

$$U_{res} = (U_{res1}, U_{res2}, U_{res3}, U_{res4}, U_{res5}, U_{res6}, U_{res7}) \tag{1.1}$$
$$U_{fle} = (U_{fle1}, U_{fle2}, U_{fle3}, U_{fle4}, U_{fle5}, U_{fle6}) \tag{1.2}$$
$$U_{cap} = (U_{cap1}, U_{cap2}, U_{cap3}, U_{cap4}, U_{cap5}) \tag{1.3}$$
$$U_{ada} = (U_{ada1}, U_{ada2}, U_{ada3}, U_{ada4}, U_{ada5}) \tag{1.4}$$
$$U_{eff} = (U_{eff1}, U_{eff2}, U_{eff3}, U_{eff4}, U_{eff5}) \tag{1.5}$$
$$U_{fis} = (U_{fis1}, U_{fis2}, U_{fis3}, U_{fis4}) \tag{1.6}$$
$$U_{vis} = (U_{vis1}, U_{vis2}, U_{vis3}) \tag{1.7}$$
$$U_{ant} = (U_{ant1}, U_{ant2}, U_{ant3}, U_{ant4}, U_{ant5}) \tag{1.8}$$
$$U_{dis} = (U_{dis1}) \tag{1.9}$$

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

Step 2: Determining the membership function

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

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

MF of a given component U_{in} indicates the n[th] capability variable of the given component *i* (*i* = I_1, I_2, I_3, I_4, I_5, I_6, I_7, I_8, I_9).

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

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

The members used in Equation (1.1) - Equation (1.9) range between '0' to '1'. Besides, their summation should be equal to one since they represent weighted average calculations. Equation (4) explicates this requirement further.

$$\sum_{f=1}^{5} P_{fU_{in}} = 1 \quad (4)$$

Further to Equation (4), MFs of the components were created by assessing the experts' overall responses. For instance, considering the variable FLE1, the experts' assigned grading percentages for criticality evaluation are 0% very low, 1% low, 15% moderate, 63% high, and 21% very high. Hence, the MF of $FLE1_{(im)}$ is as follows.

$$MF_{FLE1_{(im)}} = \frac{0.00}{very\ low} + \frac{0.01}{low} + \frac{0.15}{moderate} + \frac{0.63}{high} + \frac{0.21}{very\ high} \quad (4.1)$$

As per Equation (4), $MF_{FLE1_{(im)}}$ can be presented as: (0.00, 0.01, 0.15, 0.63, 0.21). Similarly, the current practice indicator for FLE1 can be formulated as shown in Equation (4.2). Therefore, $MF_{FLE1_{(cp)}}$ = (0.00, 0.20, 0.56, 0.21, 0.27).

$$MF_{FLE1_{(cp)}} = \frac{0.00}{very\ low} + \frac{0.20}{low} + \frac{0.56}{moderate} + \frac{0.21}{high} + \frac{0.27}{very\ high} \quad (4.2)$$

Accordingly, a similar approach was used to calculate the MFs of all the variables, and the generated results are given in MF for Level 3 in Table 4. After that, the MFs of all the component groups were calculated using the individual components' computed weightings. The following section further explicates the calculations.

Step 3: Estimating weighting functions

The Weighting Function (WF) shows the relative importance of each factor or a component based on the respondents' gradings of the factors and the components (Ameyaw et al. 2015; Owusu et al., 2020). Although both the normalized mean technique and analytic hierarchy process technique can be used to calculate the weighting functions (Lo 1999; Lee et al. 2008), this study used the normalized mean method based on Equation (5) since it is a straightforward method (Lo 1999; Ameyaw et al. 2015).

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

w_i= weighting function of the i^{th} capability variable or the component, regarding factor importance or the current practice. M_i = mean index of any capability variable or a component as estimated from the questionnaire survey data. The summation of the mean within a weight function set must be equal to one and also can be represented in Equation (6).

$$w_i = (w_1, w_2, \dots, w_n) \quad (6)$$

Considering FLE1$_{(im)}$ as an example, Equation (6.1) was computed by calculating the $w_{FLE1_{(im)}}$. Similarly, the weighting factor of the FLE component was calculated and denoted in Equation (6.2). A similar approach was then deployed for calculating all the weighting functions of variables and the respective components that belonged to both the importance and level of current practice indices, as presented in Table 4.

$$w_{FLE1_{(im)}} = \frac{4.04}{4.04+4.04+4.18+4.17+4.13+4.01} = \frac{4.04}{24.58} = 0.164 \quad (6.1)$$

$$w_{FLE_{(im)}} = \frac{24.58}{28.37+24.58+20.57+20.31+20.93+16.70+12.11+20.44+4.07} = \frac{24.58}{168.09} = 0.146 \quad (6.2)$$

Equation (6.3) confirms that the summation of the weighting functions within a component and the total of the components equal to 1.

$$\sum_{i=1}^{6} w_{FLE_{(im)}} = (0.164 + 0.164 + 0.170 + 0.170 + 0.168 + 0.163) = 1.0 \quad (6.3)$$

Step 4: Developing multi-stage FSE models

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

A fuzzy matrix D_i was first determined to evaluate the impact of individual components using the calculated MF and WF of variables within their respective component groups. Following the MFs determined under Equation (2), functions of variables within their respective capability components (for both importance and level of current practice indices) can be presented as follows in Equation (7).

$$R_i = \begin{vmatrix} MF_{U_{i1}} \\ MF_{U_{i2}} \\ MF_{U_{i3}} \\ \cdots \\ MF_{U_{in}} \end{vmatrix} = \begin{vmatrix} P_{1U_{i1}} & P_{2U_{i1}} & P_{3U_{i1}} & P_{4U_{i1}} & P_{5U_{i1}} \\ P_{1U_{i2}} & P_{2U_{i2}} & P_{3U_{i2}} & P_{4U_{i2}} & P_{5U_{i2}} \\ P_{1U_{i3}} & P_{2U_{i3}} & P_{3U_{i3}} & P_{4U_{i3}} & P_{5U_{i3}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{1U_{in}} & P_{2U_{in}} & P_{3U_{in}} & P_{4U_{in}} & P_{5U_{in}} \end{vmatrix} \tag{7}$$

For instance, if the component $FIS_{(im)}$ is considered, the component's importance level can be represented as follows in Equation (7.1).

$$R_{FIS_{(im)}} = \begin{vmatrix} MF_{FIS1} \\ MF_{FIS2} \\ MF_{FIS3} \\ MF_{FIS4} \end{vmatrix} = \begin{vmatrix} 0.03 & 0.01 & 0.21 & 0.47 & 0.28 \\ 0.00 & 0.03 & 0.24 & 0.44 & 0.29 \\ 0.00 & 0.01 & 0.09 & 0.43 & 0.47 \\ 0.00 & 0.01 & 0.15 & 0.29 & 0.55 \end{vmatrix} \tag{7.1}$$

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

$$D_i = R_i \bullet W_i = (d_{i1}, d_{i2}, d_{i3}, \ldots, d_{in}) \tag{8}$$

Hence,

$$D_i = (w_1, w_2, w_3, \ldots, w_n) \bullet \begin{vmatrix} P_{1U_{i1}} & P_{2U_{i1}} & P_{3U_{i1}} & P_{4U_{i1}} & P_{5U_{i1}} \\ P_{1U_{i2}} & P_{2U_{i2}} & P_{3U_{i2}} & P_{4U_{i2}} & P_{5U_{i2}} \\ P_{1U_{i3}} & P_{2U_{i3}} & P_{3U_{i3}} & P_{4U_{i3}} & P_{5U_{i3}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{1U_{in}} & P_{2U_{in}} & P_{3U_{in}} & P_{4U_{in}} & P_{5U_{in}} \end{vmatrix}$$
$$= (d_{i1}, d_{i2}, d_{i3}, \ldots, d_{in}) \tag{8.1}$$

In Equation (8.1), D_i denotes the membership degree of grading scale l_i, for a given component. Accordingly, the fuzzy evaluation matrix for the component FIS(im) was developed by integrating $R_{FIS_{(im)}}$ and $W_{FIS_{(im)}}$ measures as given in Equation (8.2). Moreover, $D_{FIS_{(im)}}$ indicates the fuzzy matrix for the importance indices of the identified financial strength capability. Similarly, D_i values for all the capability components (considering both the importance and level of current practice indices) were computed. These computed matrices are presented in Table 4 in the column 'MF at level 2'.

$$D_{FIS_{(im)}} = (0.238, 0.240, 0.260, 0.262) \begin{vmatrix} 0.03 & 0.01 & 0.21 & 0.47 & 0.28 \\ 0.00 & 0.03 & 0.24 & 0.44 & 0.29 \\ 0.00 & 0.01 & 0.09 & 0.43 & 0.47 \\ 0.00 & 0.01 & 0.15 & 0.29 & 0.55 \end{vmatrix} = (0.01, 0.02, 0.17, 0.40, 0.40) \quad (8.2)$$

The importance of each capability component (CI_i) can be then calculated using Equation (9), whereas *l* indicates the grading scale adopted in the questionnaire survey.

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

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

$$CI_{FIS_{(im)}} = [(0.01 \times 1) + (0.02 \times 2) + (0.17 \times 3) + (0.40 \times 4) + (0.40 \times 5)] = 4.18 \quad (9.1)$$

Analogous to the calculation above, $FIS_{(cp)}$ which is the level of current practice of FIS component was calculated as in Equation (9.2).

$$CI_{FIS_{(cp)}} = [(0.01 \times 1) + (0.08 \times 2) + (0.34 \times 3) + (0.47 \times 4) + (0.09 \times 5)] = 3.55 \quad (9.2)$$

Table 3: Results of the factor analysis
Source: Ekanayake et al. (2020)

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

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

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

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

Table 4: Membership functions for the CSCC components and their measurement items

CSCC	**Level of importance**				**Level of current practice**			
Components	**Mean**	**Weighting**	**MF for Level 3**	**MF for Level 2**	**Mean**	**Weighting**	**MF for Level 3**	**MF for Level 2**
Resourcefulness (RES)	***28.37***	***0.169***		0.00, 0.03, 0.22, 0.41, 0.34	***24.72***	***0.171***		0.00, 0.07, 0.39, 0.45, 0.09
RES1	4.05	0.143	0.00, 0.07, 0.16, 0.43, 0.35		3.40	0.138	0.00, 0.17, 0.29, 0.49, 0.04	
RES2	4.07	0.143	0.00, 0.01, 0.17, 0.55, 0.27		3.72	0.150	0.00, 0.01, 0.37, 0.49, 0.12	
RES3	4.00	0.141	0.00, 0.05, 0.21, 0.41, 0.32		3.56	0.144	0.00, 0.08, 0.39, 0.43, 0.11	
RES4	4.01	0.141	0.00, 0.08, 0.13, 0.48, 0.31		3.72	0.150	0.00, 0.05, 0.25, 0.61, 0.08	
RES5	4.11	0.145	0.00, 0.00, 0.25, 0.39, 0.36		3.57	0.145	0.00, 0.01, 0.52, 0.35, 0.12	
RES6	4.04	0.142	0.00, 0.00, 0.28, 0.40, 0.32		3.21	0.130	0.01, 0.15, 0.48, 0.33, 0.03	
RES7	4.09	0.144	0.00, 0.01, 0.32, 0.23, 0.44		3.53	0.143	0.01, 0.03, 0.47, 0.40, 0.09	
Flexibility (FLE)	***24.58***	***0.146***		0.00, 0.00, 0.22, 0.51, 0.27	***19.91***	***0.138***		0.00, 0.10, 0.52, 0.33, 0.06
FLE1	4.04	0.164	0.00, 0.00, 0.23, 0.51, 0.27		3.07	0.154	0.00, 0.20, 0.56, 0.21, 0.03	
FLE2	4.04	0.164	0.00, 0.00, 0.33, 0.45, 0.21		2.97	0.149	0.01, 0.19, 0.63, 0.16, 0.01	
FLE3	4.18	0.170	0.00, 0.00, 0.19, 0.45, 0.36		3.21	0.161	0.00, 0.13, 0.55, 0.29, 0.03	
FLE4	4.17	0.170	0.00, 0.00, 0.21, 0.44, 0.35		3.68	0.185	0.00, 0.03, 0.37, 0.49, 0.11	
FLE5	4.13	0.168	0.00, 0.01, 0.19, 0.57, 0.23		3.64	0.183	0.00, 0.01, 0.43, 0.47, 0.09	
FLE6	4.01	0.163	0.00, 0.01, 0.19, 0.57, 0.23		3.33	0.167	0.00, 0.05, 0.61, 0.28, 0.05	
Capacity (CAP)	***20.57***	***0.122***		0.00, 0.00, 0.17, 0.54, 0.29	***17.12***	***0.118***		0.01, 0.07, 0.45, 0.41, 0.06
CAP1	4.00	0.194	0.00, 0.00, 0.27, 0.47, 0.27		3.21	0.188	0.01, 0.15, 0.47, 0.36, 0.01	
CAP2	4.00	0.194	0.00, 0.01, 0.20, 0.56, 0.23		3.20	0.187	0.03, 0.11, 0.52, 0.33, 0.01	
CAP3	4.15	0.202	0.00, 0.00, 0.15, 0.56, 0.29		3.41	0.199	0.00, 0.08, 0.48, 0.39, 0.05	
CAP4	4.19	0.204	0.00, 0.00, 0.13, 0.55, 0.32		3.55	0.207	0.00, 0.03, 0.47, 0.44, 0.07	
CAP5	4.24	0.206	0.00, 0.00, 0.09, 0.57, 0.33		3.75	0.219	0.00, 0.01, 0.35, 0.52, 0.12	
Adaptability (ADA)	***20.31***	***0.121***		0.00, 0.00, 0.22, 0.49, 0.28	***18.75***	***0.130***		0.00, 0.04, 0.33, 0.44, 0.19
ADA1	4.07	0.200	0.00, 0.00, 0.16, 0.61, 0.23		4.00	0.213	0.00, 0.00, 0.23, 0.55, 0.23	
ADA2	3.98	0.196	0.00, 0.00, 0.29, 0.45, 0.25		3.52	0.188	0.00, 0.09, 0.41, 0.37, 0.12	

ADA3	4.05	0.200	0.00, 0.00, 0.17, 0.60, 0.23		3.87	0.206	0.00, 0.01, 0.36, 0.37, 0.25	
ADA4	4.19	0.206	0.00, 0.00, 0.24, 0.33, 0.43		4.00	0.213	0.00, 0.00, 0.25, 0.49, 0.25	
ADA5	4.03	0.198	0.00, 0.00, 0.25, 0.47, 0.28		3.36	0.179	0.01, 0.11, 0.44, 0.39, 0.05	
Efficiency (EFF)	***20.93***	***0.125***		0.00, 0.00, 0.18, 0.45, 0.37	***17.71***	***0.123***		0.00, 0.09, 0.37, 0.41, 0.12
EFF1	4.19	0.200	0.00, 0.00, 0.12, 0.57, 0.31		3.44	0.194	0.00, 0.12, 0.39, 0.43, 0.07	
EFF2	4.25	0.203	0.00, 0.00, 0.12, 0.51, 0.37		3.44	0.194	0.00, 0.05, 0.49, 0.41, 0.04	
EFF3	4.15	0.198	0.00, 0.00, 0.21, 0.43, 0.36		3.68	0.208	0.01, 0.05, 0.29, 0.52, 0.12	
EFF4	4.11	0.196	0.00, 0.01, 0.20, 0.45, 0.33		3.25	0.184	0.00, 0.16, 0.47, 0.33, 0.04	
EFF5	4.24	0.203	0.00, 0.00, 0.23, 0.31, 0.47		3.89	0.220	0.00, 0.08, 0.25, 0.36, 0.31	
Financial Strength (FIS)	***16.70***	***0.099***		0.01, 0.02, 0.17, 0.40, 0.40	***14.12***	***0.098***		0.01, 0.08, 0.34, 0.47, 0.09
FIS1	3.98	0.238	0.03, 0.01, 0.21, 0.47, 0.28		3.20	0.227	0.04, 0.16, 0.40, 0.36, 0.04	
FIS2	4.00	0.240	0.00, 0.03, 0.24, 0.44, 0.29		3.32	0.235	0.00, 0.09, 0.53, 0.33, 0.04	
FIS3	4.35	0.260	0.00, 0.01, 0.09, 0.43, 0.47		3.69	0.262	0.01, 0.04, 0.31, 0.52, 0.12	
FIS4	4.37	0.262	0.00, 0.01, 0.15, 0.29, 0.55		3.91	0.277	0.00, 0.04, 0.17, 0.63, 0.16	
Visibility (VIS)	***12.11***	***0.072***		0.00, 0.02, 0.20, 0.53, 0.25	***10.71***	***0.074***		0.00, 0.03, 0.44, 0.44, 0.09
VIS1	3.99	0.329	0.01, 0.03, 0.24, 0.52, 0.20		3.53	0.330	0.00, 0.03, 0.44, 0.51, 0.03	
VIS2	4.04	0.334	0.00, 0.01, 0.21, 0.49, 0.28		3.83	0.357	0.00, 0.01, 0.36, 0.41, 0.21	
VIS3	4.08	0.337	0.00, 0.03, 0.13, 0.57, 0.27		3.35	0.313	0.00, 0.07, 0.53, 0.39, 0.01	
Anticipation (ANT)	***20.44***	***0.122***		0.00, 0.00, 0.22, 0.47, 0.31	***17.57***	***0.122***		0.01, 0.07, 0.43, 0.40, 0.10
ANT1	4.04	0.198	0.00, 0.00, 0.24, 0.48, 0.28		3.60	0.205	0.00, 0.12, 0.32, 0.40, 0.16	
ANT2	4.04	0.198	0.00, 0.00, 0.24, 0.48, 0.28		3.35	0.190	0.00, 0.05, 0.60, 0.29, 0.05	
ANT3	3.97	0.194	0.00, 0.01, 0.24, 0.51, 0.24		3.47	0.197	0.00, 0.04, 0.53, 0.35, 0.08	
ANT4	4.41	0.216	0.00, 0.00, 0.09, 0.40, 0.51		3.80	0.216	0.00, 0.01, 0.35, 0.47, 0.17	
ANT5	3.98	0.195	0.00, 0.00, 0.28, 0.49, 0.23		3.36	0.191	0.03, 0.11, 0.37, 0.47, 0.03	
Dispersion (DIS)	***4.07***	***0.024***		0.00, 0.01, 0.17, 0.55, 0.27	***3.89***	***0.027***		0.00, 0.03, 0.29, 0.44, 0.24
DIS1	4.07	1.000	0.00, 0.01, 0.17, 0.55, 0.27		3.89	1.000	0.00, 0.03, 0.29, 0.44, 0.24	
			MF at Level 1 (For ‘importance’)	0.00, 0.02, 0.20, 0.47, 0.31			**MF at Level 1 (For ‘current practice’)**	0.00, 0.07, 0.41, 0.42, 0.10

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

Step 5: Evaluating the overall capability indexes

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

$$\bar{R} = \begin{vmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \\ D_6 \\ D_7 \\ D_8 \\ D_9 \end{vmatrix} = \begin{vmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} \\ d_{41} & d_{42} & d_{43} & d_{44} & d_{45} \\ d_{51} & d_{52} & d_{53} & d_{54} & d_{55} \\ d_{61} & d_{62} & d_{63} & d_{64} & d_{65} \\ d_{71} & d_{72} & d_{73} & d_{74} & d_{75} \\ d_{81} & d_{82} & d_{83} & d_{84} & d_{85} \\ d_{91} & d_{92} & d_{93} & d_{94} & d_{95} \end{vmatrix} \tag{10}$$

In Equation (10), D_1- D_9 represent the nine components initiated after the factor analysis, namely, RES, FLE, CAP, ADA, EFF, FIS, VIS, ANT and DIS. Analogous to Equation (10), the overall importance level and level of current practise functions of SCC evaluation can be formulated as in Equation (10.1).

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

$$\overline{R_{(cp)}} = \begin{vmatrix} 0.00 & 0.07 & 0.39 & 0.45 & 0.09 \\ 0.00 & 0.10 & 0.52 & 0.33 & 0.06 \\ 0.01 & 0.07 & 0.45 & 0.41 & 0.06 \\ 0.00 & 0.04 & 0.33 & 0.44 & 0.19 \\ 0.00 & 0.09 & 0.37 & 0.41 & 0.12 \\ 0.01 & 0.08 & 0.34 & 0.47 & 0.09 \\ 0.00 & 0.03 & 0.44 & 0.44 & 0.09 \\ 0.01 & 0.07 & 0.43 & 0.40 & 0.10 \\ 0.00 & 0.03 & 0.29 & 0.44 & 0.24 \end{vmatrix} \tag{10.1}$$

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

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

$$= \left(\acute{D}_1, \acute{D}_2, \acute{D}_3, \acute{D}_4, \acute{D}_5\right) \quad (11)$$

It should be noted that $\overline{D_\iota}$ represents the fuzzy matrix for either 'importance' or 'current practice' indices of the SCC components. This fuzzy matrix can be formulated, as shown in Equation (12), using the grading scale (l=1,2,3,4,5) established in this study. C_i implies SCC evaluation index *i* (*i = importance or current practice indices*). This 'defuzzification approach' transforms fuzzy members into a 'crisp' output using a predefined grading scale which is vital in decision making (Osei-Kyei et al. 2019; Owusu et al. 2020).

$$C_i = \sum_{i=1}^{9} \overline{D}_i \times l^t = \left(\acute{D}_1, \acute{D}_2, \acute{D}_3, \acute{D}_4, \acute{D}_5\right) \times (1, 2, 3, 4, 5), 1 \leq \; C_i \leq 5 \quad (12)$$

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

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

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

$$= (0.00, 0.02, 0.20, 0.47, 0.31) \quad (12.1)$$

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

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

$$= (0.00, 0.07, 0.41, 0.42, 0.10) \tag{12.2}$$

Discussion

The ‘importance’ index is 4.11 (high), reflecting the dire need for boosting SCC in achieving resilient SCs in IC in HK. Comparatively, 3.54 is the ‘current practice’ index, spotlighting a long way to go before attaining resilient SCs in IC in HK. According to the experts, all the CSCC components are very important in achieving SCR. Although efficiency (index-4.19) may at the outset be arguably the most significant SC capability that the industry should pursue, dispersion (index-3.89) is one of the most implemented CSCC in ‘practice’.

Efficiency denotes the SC ability to produce more outputs with less resource usage (Ekanayake et al. 2021). In relation to IC, efficiency contributions are mainly from failure prevention, higher labour productivity, avoiding variations/rework, and waste elimination, while productivity increases after moving up the ‘learning curve’ on tasks and more experience in general. Failure prevention needs industry attention since failures are possible at any node of IC-SC operations, beginning from manufacture to onsite assembly (Li et al. 2018a). Together with inadequate information sharing and technological breakdowns, these failures result in variations in IC in HK (Ekanayake et al. 2020) and, hence, call for resilient SCs. This is clearly shown by receiving 4.25 mean score for the importance of the variable: ‘avoid variations’, and the current practice level of 3.44. Tolerance, assembly, logistics and manufacturing failures incur additional cost and time, contributing to non-value-added activities, i.e. so-called wastes

(Ekanayake et al. 2019). Although IC targets waste elimination (Jaillon et al. 2009), the focused application in current practice is considerably low (3.25). Therefore, it is encouraged to deploy the lessons learnt from previous projects to practice (Peck, 2005). However, this is not easy due to the industry's fragmented nature and the temporary multi-organizational structure of the construction projects.

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

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

FIS was ranked with the second highest mean score: 4.18 by necessitating a good financial capacity in a competitive industry, specifically in the construction sector (Ekanayake et al. 2019). However, the current financial capacity (3.55) is lower, hence compelling portfolio diversification, including self-manufacturing decisions (Han et al. 2017), having a good price margin, financial reserves and funds (Kadir et al. 2005) and good insurance coverage (Fateh and Mohammad 2017).

As the third-highest ranked SCC component, capacity received an importance index of 4.12 with a current practice index of 3.44. Capacity implies adequate resources in the SCs to enable continuous operation in IC (Ekanayake et al. 2019). This capability was highly researched within the SCR domain, as found, with justifications, in the related literature (Ekanayake et al. 2021). Moreover, the variables within this SCC component highlight the need for having reliable backup maintenance agreements with the equipment suppliers or the maintenance companies (Ekanayake et al. 2020), redundancies in SCs to bypass disruptions (Ekanayake et al. 2019), practising an effective communication strategy during disruptive situations, having a professional response team to deal with disruptions (Zainal and Ingirige 2018), the development of effective crisis mitigation techniques to surpass traditional risk management practices (Zavala et al. 2018) with the use of BIM and GIS tools (Irizarry et al. 2013) by relating specifically to IC practices in HK.

Besides, 'distributed decision making' under the SC capability component of 'dispersion' is one of the most widely practised capabilities in the industry. However, the practice level of this variable (3.89) is still slightly less than the required level (4.07), highlighting the resilience gap of SCs, even in a popularly pursued area/component. This is crucial in ensuring that the 'right' key decisions are taken after obtaining relevant inputs, i.e., taken collaboratively after consultation with the relevant SC stakeholders involved in the flow of the prefabricated components not only during problem-solving but also in the materials flow control process (Ekanayake et al. 2020). Under these circumstances, BIM can provide valuable support to SCR in facilitating decentralized decision-making (Bataglin et al. 2017). According to Ekanayake et al. (2021), among these, dispersion has received the least research interest over the years;

whereas dispersion is essential in robust decision making. Since IC-SCs are highly fragmented, quick but sound decision making is only attainable through decentralized decision making. Recent relevant developments such as in RFID (Chen et al. 2020) and blockchain (Wang et al. 2020) integrated platforms will facilitate promising opportunities in such decision making.

All of the other five SC capability components, namely, resourcefulness (collaborative, secure and resourceful approaches to enhance SCR), flexibility (the ability of quicker resource mobilization following a disruption), adaptability (ability to adapt in response to SCV), visibility (having sound knowledge of ongoing SC operations and the environment) and anticipation (ability to detect potential future SC disruptions) also received lower values for the level of current practice indices compared to their levels of importance. Therefore, it is essential to move a step further in mobilizing SCC measures to avoid turbulence from any materializing SCV in IC in HK. Developing virtual prototyping and BIM-based platforms to enhance the collaborative data interoperability in the IC supply chains (Li et al. 2011), improved personal and cybersecurity, and maintaining adequate buffer time to avoid vulnerabilities associated with tardy deliveries are the essential capabilities under the category of resourcefulness. Production postponement, vertical integration, and alternate distribution channels/multimodal transportation add flexibility to IC-SCs in HK to reduce the likelihoods of inherent disruptions and logistical delays (Ekanayake et al. 2020).

More importantly, considering the anticipation component, quality control (with the highest mean score of 4.41) is essential for IC to avoid tolerance issues in assembly (Ekanayake et al. 2019). This is why contractors pay for additional quality checkers assigned to oversee component manufacturing factories. However, the contractors who use their own manufacturing plants can control their quality better through BIM-enabled systems (Ekanayake et al. 2020), whereas IoT, BIM, and RFID enabled tools are proposed to enhance the real-time visibility together with traceability in the SC process (Li et al. 2018b). Further, blockchain encrypted software packages may add the expected traceability and accountability to the SC information sharing process (Wang et al. 2020). Intensive training is also essential during the onsite assembly process to avoid safety disruptions, tolerance issues, and delays (Ekanayake et al. 2019). Conducting simulations and mock-ups before the assembly process would be beneficial in this regard.

Finally, analogous to the FSE analysis results, mathematical models for evaluating the importance levels and current practices in SCC improving SCR in HK industrialized construction were developed as in Equation 13. The coefficients assigned to CSCC components correspond with the respective normalized values are shown in Table 5.

$$Overall\ Capability\ Evaluation\ Index$$
$$= [C_{RES}|CV_{RES}|] + [C_{FLE}|CV_{FLE}|] + [C_{CAP}|CV_{CAP}|] + [C_{ADA}|CV_{ADA}|] + [C_{EFF}|CV_{EFF}|] + [C_{FIS}|CV_{FIS}|] + [C_{VIS}|CV_{VIS}|] + [C_{ANT}|CV_{ANT}|] + [C_{DIS}|CV_{DIS}|] \quad (13)$$

Table 5: Overall impact calculations of SCC improving SCR in IC in HK

Capability	Level of importance			Level of current practice			
	Index	Coefficient	Ranking	Index	Coefficient	Ranking	Coefficient Symbols
RES	4.05	0.17	7	3.54	0.17	6	C_{RES}
FLE	4.05	0.15	8	3.34	0.14	9	C_{FLE}
CAP	4.12	0.12	3	3.44	0.12	8	C_{CAP}
ADA	4.06	0.12	6	3.77	0.13	2	C_{ADA}
EFF	4.19	0.12	1	3.56	0.12	4	C_{EFF}
FIS	4.18	0.10	2	3.55	0.10	5	C_{FIS}
VIS	4.00	0.07	9	3.58	0.07	3	C_{VIS}
ANT	4.09	0.12	4	3.52	0.12	7	C_{ANT}
DIS	4.07	0.02	5	3.89	0.03	1	C_{DIS}
Total		1.00			1.00		
OI	**4.11**			**3.14**			

Practical Implications

Achieving resilient and sustainable SCs is a prime goal of global organizations since it has been successfully proven that being resilient is an effective way to withstand unpredictable SCV (Sahu et al. 2017). Hence, it is essential for the professionals engaged in IC in HK to evaluate, check and compare SCC for improving the overall SC performance by developing and applying them to withstand relevant SCV. This also needs SC capability initiatives targeting organizational reforms and better management, along with plans for continuous improvements. Under these circumstances, relevant industry practitioners, especially the managerial level professionals, could be motivated to use the proposed FSE based soft computing approach in which capability assessment is established on industry experts' linguistic judgment. This approach was appropriately generalized for the IC context in HK using fuzzy triangular numbers with the use of a predefined fuzzy scale in determining the levels of importance and current practice indices of SCC of the industry.

Moreover, the developed multi-stage fuzzy assessment models would facilitate successful decision-making and problem-solving tools by identifying the appropriate levels of SCC practices and determining the current practice gap. The performance indices are mostly subjective and introduce some ambiguities and vagueness into the decision-making (Sahu et al. 2017). However, fuzzy set theory helps to overcome such subjectivity and uncertainty in decision-making. Hence, this study proposed the aforesaid hierarchical evaluation models with multiple performance indices to estimate the extent of SCR. These evaluation models will further point industry practitioners towards implementing appropriate strategies to remain adaptive in the turbulent IC-SCs by improving the SC network's overall performance. Therefore, it is emphasized that this constitutes a significant milestone in the journey to establish FSE models to evaluate the overall performance of SCC in achieving SCR in IC in HK.

Conclusion and Further Research

This study proposed and demonstrated the mathematical modelling of SCC for improving SCR in IC by applying statistical analysis and fuzzy set theory to data collected for this purpose. This study further ascertained the perceived importance level of each SCC and compared it with the corresponding level in current practice. Using a list of 57-variables extracted from an exhaustive literature review, this study solicited experienced IC experts' professional judgments to evaluate the level of importance and the current practice level of SCC in improving the SCR of IC in HK. Forty-one measurement items remained critical and were considered in the factor analysis after data normalization and the necessary statistical analysis. Thereby, the factor analysis resulted in the well-justified grouping of these measurement items into nine CSCC components. A soft computing approach - FSE was then applied, and multi-stage fuzzy mathematical models were separately developed to assess the criticality and current SCC practice in IC in HK. An importance index of 4.11 showed that the identified capabilities are critical in achieving resilient SCs. In contrast, the current practice index of 3.54 indicated a wide gap to be bridged in realizing the benefits associated with SCR in IC in HK. The efficiency component (importance index: 4.19) has the highest impact among all the SCC, while dispersion is the highest in practice (3.89). However, there is a gap between the current practice and importance levels in each SC capability component.

The sample size of 76 was fully justified in the research method section, so it cannot be considered a research limitation. However, bigger sample size may facilitate more sensitive models as the optimal sample size cannot be precisely determined. However, this study lays a fruitful foundation for the study purpose by establishing the FSE theory for SCC analysis and demonstrating a successful and useful application. Although the selection of fuzzy numbers was done by the researchers and accepted by the experts in this study, it is worth examining and deploying the fuzzy numbers allied with the most reliable results. The models developed here are generic to the IC-SCs in HK without focusing on specific IC types, such as modular integrated construction. Hence, future studies may especially focus on specific IC types. Also, reliability testing of these decision-support models is encouraged as a further study direction. Besides, future studies can deploy more rigorous computational methods to generate these SCC importance and practice indices. Also, specific SCC together with underlying measurement items could be explored, further evaluated, and amended/adjusted in future to enable some continuity during particular epidemics or pandemic crises such as from the COVID-19 virus, which drastically disrupted global supply chains, including in construction.

Given HK's specific socio-economic background, the parameters and calibration of these models cannot be directly generalized for other cities. However, the research methodology developed and deployed here may be adapted and applied elsewhere, targeting similar or different research findings in other regional or national industry contexts. Besides, a multi-stage decision support model can be developed to achieve SCR by balancing unavoidable vulnerabilities (Ekanayake et al. 2020) with existing, especially extended and further 'expandable' capability levels. Hence, the most influential capabilities can be mapped against appropriate SCV, using a structural equation modelling approach to generate an impact analysis model of the SCC by discarding the least influential SCC measures. This is expected to assist industry practitioners to boost SCR in increasingly turbulent and uncertain times.

Finally, this study contributes to the body of knowledge by comparing and evaluating the perceived importance *vs* current practice levels of SCC in IC projects in HK, thereby empowering practitioners to plan and utilize suitable strategies at appropriate levels to boost SCR in IC in HK. On the other hand, academic and industry researchers and practitioners are encouraged to explore more comprehensive SCR evaluation models based on their specific regional or industry contexts. Hence, this study fulfils its original purpose of developing and demonstrating an evidence-based and viable methodology for strategic and operational decision-makers to assess and improve SCC in IC in HK, with the over-arching aim of developing more resilient, sustainable and performance-enhanced SCs.

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