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Identifying Supply Chain Vulnerabilities in Industrialised Construction: An Overview

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Abstract

Construction supply chains are subject to much more disruptive forces than before, and the heightened risk exposure of supply chains calls for greater resilience. Focusing on Industrialised Construction (IC), this study examines how more resilient supply chains can be better developed through a deeper understanding and clear identification of key vulnerabilities that are commonly encountered. Therefore, this study employed a systematic review of the Supply Chain Vulnerabilities (SCV) related literature and conducted a thematic analysis to categorise the variables identified. The results revealed 37 SCV in IC and mapped the trend in the research publications by the year, country, and methodological approaches adopted in previous research. This study contributes to a deep understanding of the vulnerabilities that retard the performance of supply chains through reviewing and consolidating the state -of-the-art literature on SCV in IC. The findings highlight major vulnerabilities that need to be addressed by (a) introducing appropriate capability initiatives to counter these SCV and develop value-enhanced resilient supply chains in IC and (b) developing an envisaged action framework for addressing the identified SCV in IC to provide a launchpad for further research and development.

Keywords: Industrialised Construction; Supply Chain Vulnerabilities; Supply Chain Resilience

1. Introduction

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

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

SCV

In the last few decades, the vulnerability level of many SCs have increased not only because of the external environmental factors but also due to the strategic and managerial decision making of the firms (Vecchi and Vallisi 2016). Indeed, most SCs are now characterised by complexity and extensive outsourcing. Additionally, the SCs are less vertically integrated compared to the past and are exposed to increased levels of disruptions/ vulnerabilities such as those stemming from political, social and economic disorders (Snyder and Shen 2007) which are unanticipated and unplanned events affect/disturb the normal flow (Zavala et al. 2018).

In previous literature, the aforementioned vulnerabilities are referred to as 'disruptions' (Ponomarov and Holcomb 2009), 'risks' (Chopras 2004), 'errors,' 'uncertainties', and 'crises.' Besides, vulnerability is the status or the degree of fragility of a system (Elleuch et al. 2016). In terms of SCR, vulnerabilities are the key disruptions that disturb the normal SC process.

Supply Chain Risk Vs. Supply Chain Vulnerability

However, there is a difference between risk and vulnerability. Findings of Heckmann et al. (2015) identified risk as "the fear of losing investment" or "the probability of events that result in loss", while it is characterised by the probability of happening and the impact (Elleuch et al. 2016). Referring to the SC, supply chain risk is the "variation in the distribution of possible SC outcomes, their likelihood, and their subjective values" (March and Shapira 1987). On the other hand, 'vulnerability is an exogenous variable that determines the risk through the intensity of the impact generated or caused damage' (Elleuch et al. 2016). It is the status or the level of fragility of a system (Bonnefous et al. 1997), and hence, it is the readiness to handle risk, which includes the system capacity and the system preparation to face the risk or anticipated consequences (Elleuch et al. 2016; Birkmann 2007). Vulnerability is characterised by the predisposition to risk, strength-building, and elasticity to withstand shock (Gondard-Delcroix and Rousseau 2004). Besides, SC vulnerability is exposure to the serious disturbance of the SC (Christopher and Peck 2004).

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

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

SCV in IC

Interdependencies of the SC in the construction industry is unique. It differs from other industries such as manufacturing, being project-based with overlapping risks, which are wider than the immediate contractual responsibilities of the SC members (Loosemore 2000). A typical construction SC includes both upstream linkages and downstream linkages, where upstream linkages include construction client and the design team conducting activities leading to the preparation for the production on-site, and the downstream linkages include the main contractor, sub-contractors and the suppliers commencing the tasks and the activities in the delivery of construction projects (Akintoye et al. 2000). As consequences of the context of temporary multiple organisation (Cheng and Zhu 2010); due to the difficulties arising in managing networks of a large number of different companies, supplying materials, components and multiple services (Briscoe and Dainty 2005; Dainty et al. 2001), and with adversarial relationships (Saad et al. 2002), SC management processes in the construction industry face numerous obstacles (Ekanayake et al. 2019). Further, the fragmentation of design and construction processes often results in reduced visibility to detect vulnerabilities along with the SC network (Zainal and Ingirige 2018). Therefore, it is critical to swiftly identify the vulnerabilities associated with the SC process in order to manage the supply network efficiently and effectively (Aloini et al. 2012).

As explained above, the need for uplifting building performance, the flexibility of the product, the involvement of many specialists and the higher market uncertainty, all make construction projects more complex (Bataglin et al. 2017). In this context, the advantages of Industrialised Construction (IC – the adoption of prefabricated building components and systems), have been perceived to improve the efficiency of the flow and the quality of the construction (Gibb 1999; Lawson Ogden and Bergin 2011).

IC, which was initially developed to address urgent rehousing needs after World War II in Europe and Russia, for example, has again become popular, if not necessary, in this age of rapid urbanisation. IC includes various approaches, including precast panels, columns, and other components, prefabricated units, and, more recently, pre-engineered modular units (Gosling et al. 2016; Gibb and Isack 2003; Jonsson and Rudberg 2014). In terms of IC, there are three phases in the SC operations, namely, prefabrication, logistics, and the onsite assembly (Zhai and Huang 2017). The disruptions such as machine breakdown, traffic jams, low efficiency of customs clearance, and damages to the modular units all appeared in each phase of the IC SC. If these situations are not managed effectively and efficiently, the time and the cost savings realised from adopting IC will undoubtedly wither away. Any disturbance at any point of the IC SC will impact the entire process since once scheduled, it is relatively unchangeable and fixed (Zhai and Huang 2017). Being resilient is also fundamental to avoiding exceptionally high costs caused by the vulnerabilities when there are no precautionary measures (Vecchi and Vallisi 2016). Therefore, the researchers Christopher and Peck (2004) presented several approaches to overcome SCV, including dual sourcing, transhipping and improved SC visibility (Zainal and Ingirige 2018).

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

To realise the research aim of this study, a comprehensive and systematic literature review was first conducted by identifying SCV affecting SCR in IC, as explicated in section 2. Second, a thematic analysis was done to categorise the SCV identified. Section 3 presents the results derived from this analysis and the discussions that followed based on the IC. Third, this study developed an envisaged action framework for addressing the identified SCV in the IC, as shown in section 4. Section 5 presents the future research directions suggested from this study, whereas section 6 conveys the research limitations of this study. Further, section 7, as the final section, includes the conclusions drawn from this research.

2. Research Methods Used

This study followed a methodical approach suggested by Yi and Chan (2013), Owusu et al. (2017) and Wuni et al. (2019) which is the systematic review of literature in a domain, namely through meta-analysis to identify, retrieve and examine the extensive output in Vulnerabilities in IC Supply Chains. The approach consisted of three phases, including desktop search, targeted publications search, and examining the selected publications. Besides, the approach is clearly illustrated in the following Figure 1.

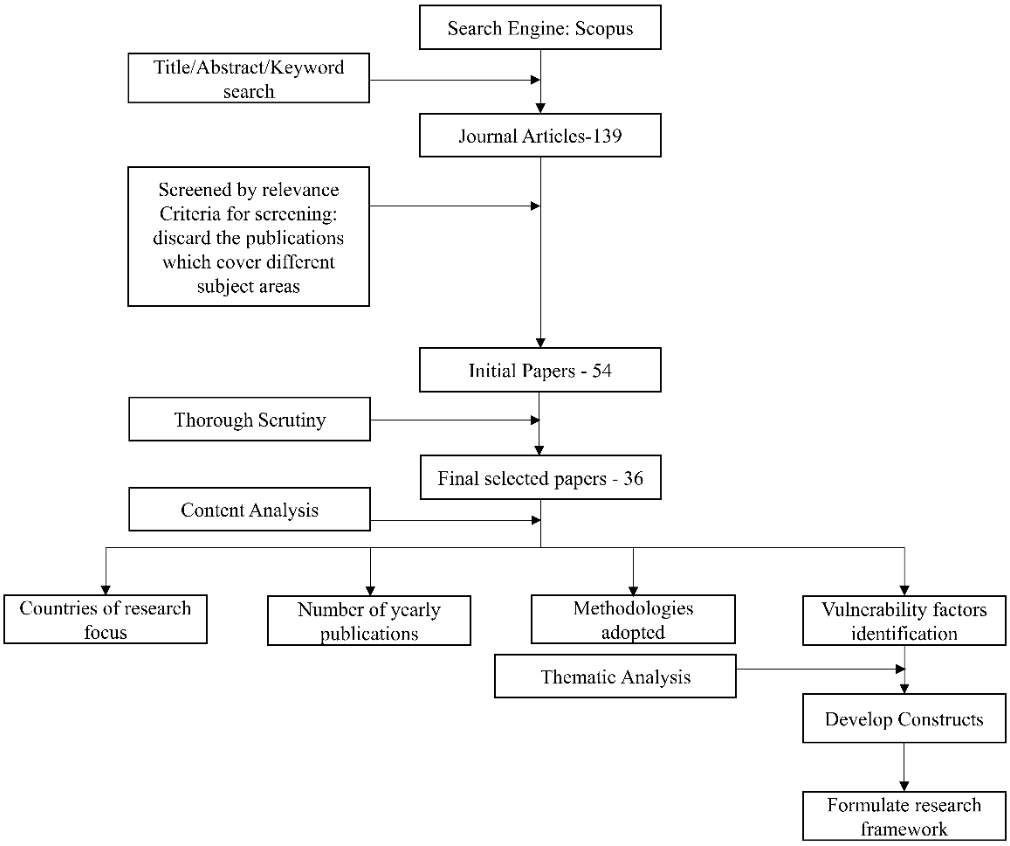

Figure 1: Research Methodology

Phase 1: Desktop Search

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

A preliminary screening was then conducted for all the retrieved 139 publications to discard the publications which cover different subject areas outside the main scope of this study. Therefore, a deep scanning of the title/abstracts/keywords, as well as a document scan, was carried out to aid selecting the publications that appeared relevant and valid for the literature review. In choosing the journal articles for further processing, this study adopted a method suggested in the studies of Osei-Kyei and Chan (2015) and Owusu et al. (2017), as explained and followed further in this study. The publications were selected after a deep scanning of the title/abstracts/keywords, as well as a document scan, of the top-ranked journals in different fields. Further, the initial study identified 54 publications, including two book publications and ten conference papers based on their relevance for this literature review (with a high number of citations) for the next phase of analysis.

Phase 2: Targeted paper search

During phase 2 of this study, a more comprehensive visual examination was conducted of the selected publications to identify the highly relevant publications on vulnerabilities in IC supply chains. This study excluded the publication categories of 'editorial,' 'letter to the editor,' 'briefing sheet,' 'introduction,' and 'forward' from the analysis. Also, the publications which did not fully express or explicate the vulnerability factors that can be related to IC supply chains were discarded in this phase. Therefore, 36 publications out of 54 publications were selected for examining in the next phase of this structured literature review. The final selection included 2 books, 7 conference papers, and 27 journal articles. An exhaustive summary of the targeted publications that were finally selected for the review analysis is presented in Table 1.

Table 1: Targeted publications in this study

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

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

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

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

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

This study followed a systematic review approach to comprehensively identify and trace the background of all the literature (Eysenck 1994) on SCV using a meta-analysis. Systematic review enabled collecting and reviewing all related literature, whereas meta-analysis helped in obtaining and combining these data to generate a summary of results including statistical analysis (Gopalakrishnan and Ganeshkumar 2013). Then, the study followed a deductive category application of research (Mayring 2000) using directed content analysis without adhering to conventional or summative content analysis techniques (Hsieh and Shannon 2005) since this method facilitates the extension of SCV related theories towards IC considering the existing theories of SCV and SCR. Determining the appropriate SCV variables and analysis of annual publication trends were completed at this stage. This study then continued with the thematic analysis of the identified variables through the three phases of; coding of text, development of descriptive themes; and the generation of analytical themes (Thomas and Harden 2008). The qualitative content analysis just provides clarification of the content of data through a systematic classification process of coding and identifying themes whereas thematic analysis enables generating new interpretive constructs and explanations based on the underlying themes of variables (Vaismoradi et al. 2013). Hence, following the thematic analysis, this study developed SCV constructs by taking their underlying themes into account, formulated the framework, and explicated the developed constructs. The forthcoming sections of this paper discuss phase 3 of this study that comprised of analysis, reporting the findings, and deriving the conclusions.

3. Findings and Discussion

This study aims to review the body of literature connected to the identification of vulnerabilities in IC supply chains, by targeting resilience, through the thematic categorisation and eventual addressing of such vulnerabilities. In order to achieve the aim of the study, 36 selected targeted publications were examined, as explained in more detail in the preceding section, and 37 vulnerabilities were identified. The authors found identical relationships between some of the vulnerability factors and hence, categorised the factors under six newly formulated constructs, which form the basis for the developed envisaged action framework of the vulnerabilities in IC

SCR. The succeeding sections explain the annual publication trends and the formulated themes in detail.

Although there was no restriction as to the year of publication in the literature search, all the screened publications were from 1998-2018. Because the concept of SCR is relatively new, and this has been broadly studied during the last decades by demarcating the importance of this concept (Bevilacqua et al. 2018). This concept is evident basically in the management sector (Ali et al. 2017) and recently emerges in the construction sector (Cui 2018). Figure 2 plots numbers of research papers on vulnerabilities in SCR related publications for the 20 years up to 2018.

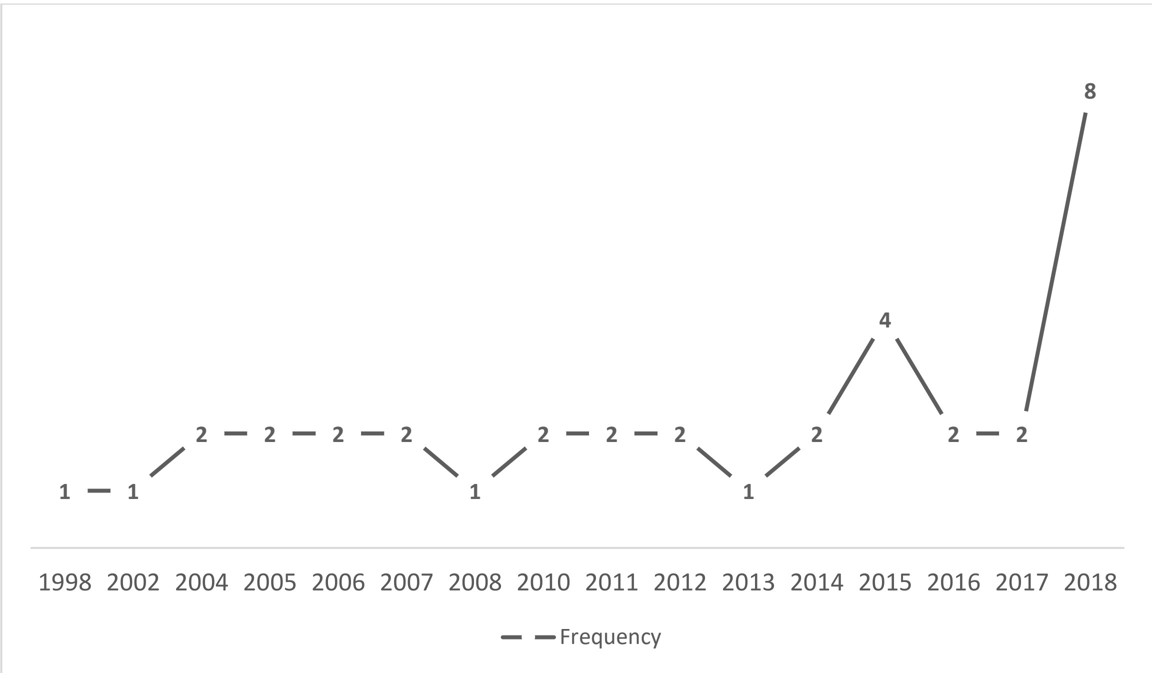

Figure 2: Research Papers on vulnerabilities in SCR related publications

As shown in Figure 2, the total number of publications from 1998 to 2014 remained steady, although a little sporadic, whereas an increment in the publications was seen in 2015. Further, the trend seems briefly steady again in 2016-2017, whereas a rapid increase in publications is evident in 2018. Before 2015, most of the papers were based on empirical studies and case studies in different industries. From 2018, the research interests have broadened towards mathematical experiments, modular analysis, and modelling such as Fuzzy-Micmac. Indeed, this pattern indicates the emerging interest in exploring better approaches to achieving SCR in project delivery. Also, this indicates that the domain of vulnerability has become more critical in SCR research.

It is also not surprising that SCR attracted more attention after four reviews published by Christopher and Peck (2004); Chopras (2004); Sheffi and Rice Jr (2005) and Tang (2006) which received 760; 860; 499 and 880 citations, respectively. From 1998-2008 the SCR concept was still at an infancy stage, and publications were only from a few countries such as the United States (USA) and United Kingdom (UK). After 2010, SCR publications originated from a broader base, also indicating the growing and maturing trend of SCR. Figure 3 denotes the vulnerabilities in SCR related research by country.

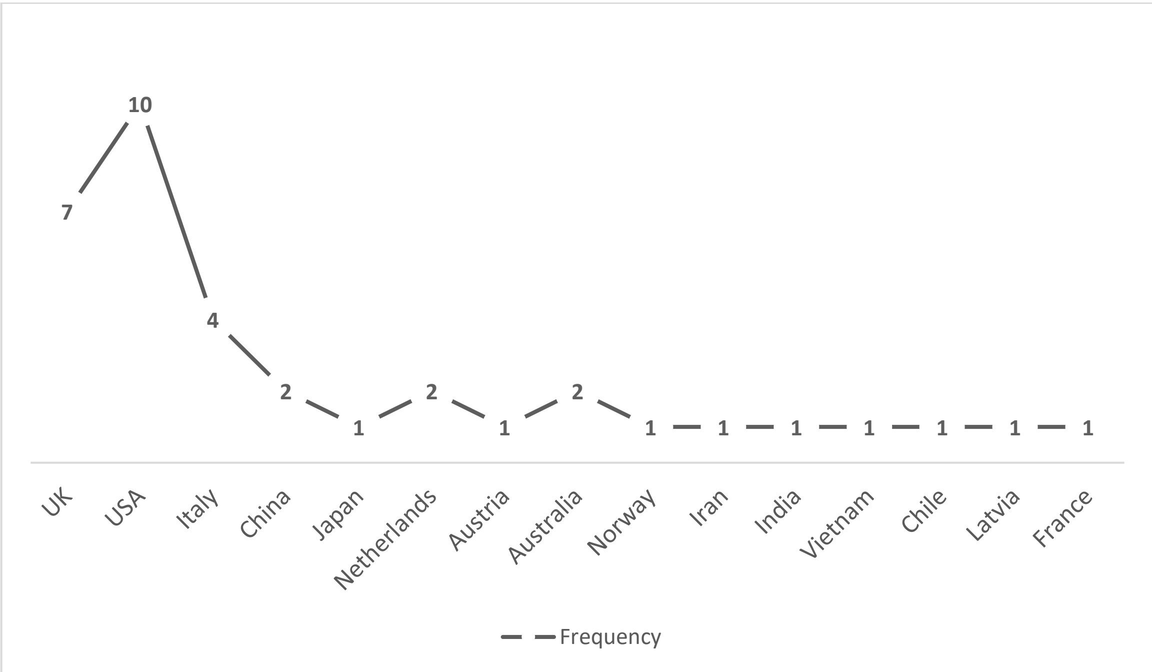

Figure 3: 'Vulnerabilities in SCR' related research publications by country from 1998 to 2018

As depicted in Figure 3, UK, USA, and Italy have the highest numbers of publications on the vulnerabilities in SCR within the selected publications. All three are developed countries and have contributed greatly to the knowledge domain of this study by identifying the vulnerabilities associated with SCs. This may indicate that more developed construction industries have already made some preliminary attempts towards SCR by identifying and addressing relevant vulnerabilities since they value the need for SCR.

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

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

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

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

Following the trend revealed in this review, it is expedient that research into vulnerabilities in SC in IC should be encouraged due to the following reasons; (a) IC supply chains are complex networks subjected to continual turbulence, creating a potential for unpredictable disruptions/vulnerabilities; (b) effective management of those disruptions will be critical for ensuring timely project delivery in IC; and; (c) although the industry utilizes traditional risk management techniques to manage these inherent disruptions (Luo et al. 2018), they cannot assess the complexities of SCs, evaluate the intricate interdependencies of threats, and prepare the industry for future unknowns. These reasons lay the foundations for exploring and addressing the vulnerabilities associated with SC in IC, so as to enhance resilience and improve performance.

Overview of the Methodological Approaches

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

Analysis of Vulnerabilities in the SC of IC

All the vulnerabilities identified following the comprehensive analysis of 36 publications are presented in Table 2. 37 vulnerabilities were identified in total. During the process of screening, the authors attempted to sort out the vulnerabilities which are relevant to the IC supply chains and avoided some of the vulnerability factors such as turbulence, sensitivity, and connectivity that are specifically relevant to some other industries.

(Insert Table 2 here)

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

Similarly, all the citations are highlighted for each variable resulting from the publications. Frequencies of the relevant citation counts are presented in Table 2. All the vulnerabilities were categorised into six constructs namely; Project Organizational Vulnerabilities (POV); Procedural Vulnerabilities (PRV); Supplier/customer Vulnerabilities (SCV); Technological Vulnerabilities (TEV); External Environmental Vulnerabilities (EEV); and Financial

Vulnerabilities (FIV) following a thematic analysis process, which is further described in the next section of the paper.

Categorisation and Explanation of the Variables

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

Zainal and Ingirige (2018) developed 11 constructs including strategic, management, personal, process, supplier/customer, technology, political/legal, environmental, physical damage, market pressures, and liquidity or credit vulnerabilities following a questionnaire survey in Malaysian public projects. These authors' focus was mainly on distinguishing the effects of interdependent supply chains within the public and private sector construction organisations in Malaysia. The study also recognised how critical vulnerabilities could generate direct cascading impacts across the supply chain through a layered framework. Also, the framework offered to understand the dynamics of the cascading effects of vulnerabilities when observed through several supply chain layers. However, the in-depth exploration of each supply chain vulnerability and evaluation of the effects of these vulnerabilities towards construction projects are missing. Besides, the study suggests taking their research forward by considering the dynamics and interdependencies in evaluating vulnerabilities across the supply chains in other similar industries as well.

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

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

The intensity of occurrence of these vulnerabilities, as based on the number of appearances in the literature was determined using citation frequency analysis to indicate the relative importance and the severity of each construct. Therefore, the total cited frequency, Mean Score (MS) and the Coefficient of Variation (COV) in each construct was calculated and stated in Table 2. In calculating the MS of each construct, the total of the frequencies of all the vulnerabilities within the construct was summed up and divided by the corresponding number of variables - n. For instance, the MS of the TEV construct was calculated as follows.

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

i=1,2,3,4,5

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

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

External Environmental Vulnerabilities-(EEV)

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

The second-ranked variable terrorism/war is also a subjective phenomenon since most of the countries are susceptible to terrorist attacks, especially the developing countries. According to the findings of Masood and Choudhry (2010), terrorism/war, political instability are significant external risks that tend to stop or delay construction activities. This may cause disturbances to the smooth flow of SC activities, including SC logistics. Considering the IC SC, most prefabricated units are fabricated in a manufacturing yard away from the construction site, and transportation (and the related logistics issues) plays a significant role in the timely delivery of the units produced by the factory. Also, these risks are very volatile and also often more difficult to observe, so they may go unnoticed and affect the offshore outsourcing process (Chauhan et al. 2015) Besides, extreme wind levels could compromise the use of cranes on-site and may delay the installation process (Gibb and Neale 1997). Hence, these disaster events significantly affect the performance of the IC supply chains, which suggests the need for a more resilient SC to deal with these disruptive situations.

As the third highly cited factor, political instability also significantly affects the performance of SCs. Findings of Zainal and Ingirige (2018) highlighted this factor as the first ranked vulnerability factor in the SC of Malaysian public construction projects. The reason behind the finding is that public projects depend on federal money following a set of rules and regulations hence making the process more susceptible to political and regulatory changes. Further, regardless of the procurement type chosen, this factor has shown a significant impact on SC performance. Political instability in offshore destinations is one of the significant risks related to IC due to the offshore outsourcing (Chauhan et al. 2015) and hence becomes more critical compared to the traditional construction projects. Adoption of novel technologies such as IC highly depends on the government rules and regulations (Ekanayake et al. 2019). For instance, countries and jurisdictions, including Hong Kong, Singapore, China, Australia, and the United Kingdom have their government initiatives to encourage implementation of IC (Blismas and Wakefield 2009; Tam et al. 2015; Jiang et al. 2017). The absence of these motivational policies or application of other disruptive government regulations beset the adoption of IC.

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

SCs are associated with various sorts of disruptions (Snyder et al. 2006), including natural disasters, terrorism (Christopher and Peck 2004), war, and political instability that result in serious SCV (Wedawatta et al. 2010). Also, fuel protests in the UK or France, foot and mouth disease spread in 2001 (Peck 2005); hurricane Katrina and Rita (Snyder et al. 2006); terrorist attack in Sep 2011 in the USA (Sheffi and Rice Jr 2005) are some of the examples for EEV that have created critical SC disruptions. Further, as declared by Snyder et al. (2006), these disruptions can generate significant cost impacts due to the facility/inventory/network/ infrastructure breakdowns and subsequent downtime losses. Also, stock-outs, inventory costs due to obsolescence (Christopher and Peck 2004), declines in shareholder wealth, sales growth, customer goodwill, and stock returns (Snyder and Shen 2007) are the possible important connected issues.

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

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

Project Organisational Vulnerabilities-(POV)

Project organisation vulnerabilities (frequency = 46) is the second-ranked construct derived by the frequency analysis consisting of 07 vulnerabilities namely; labour strikes and related disputes; communication breakdowns; loss of skilled workforce; closing/selling off the organisations; loss of trust/fraud; disruptions due to outsourcing and poor project definition. MS of the construct is 6.57, and the COV 0.45 signifies the high citation mean and the widespread within the construct.

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

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

Loss of talent and unavailability of the skilled workforce also affects SC performance and is more critical in the IC. This is because beginning from the prefabrication factory process, skilled labour is essential up to the project delivery in IC since handling the prefabricated units are not easy but require skilled labour. Chan (2001) also agreed that skilled labour is less plentiful and could slow processes. Loss of trust/fraud also need to be critically considered since the construction SC is an integrated team process and loss of trust/fraud can stop the entire project process (Owusu et al. 2017).

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

Procedural Vulnerabilities-(PRV)

PRV refer to the vulnerabilities arising from the operation at any node of the supply-production-distribution chain and can be considered as process-based disruptions. This is the construct with the third highest frequency of vulnerabilities, namely; transport disruptions; quality loss; variations/rework; utility disruptions, such as electricity, water; systems/machines breakdown; safety hazards; site inventory losses/theft; and energy scarcity. This construct shows 5.63 MS with very less 0.35 COV and hence, depicts a higher level of popularity in the literature.

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

Furthermore, machine breakdowns, inventory losses, workforce unavailability, safety hazards, including damages and accidents, are also attemptable areas of disruptions that can be expected in the assembly process of the IC supply chain (Zhai and Huang 2017). Considering the safety hazards, the most common type of danger in IC is ‘fracture’ whereas ‘fall’ is the most common cause of accidents. The underlying root cause is ‘unstable structure’ where special attention is required (Fard et al. 2017). Machine breakdown is likely with negligent maintenance (Wang et al. 2018b), and the system can fail, for instance, with the failure occurring in the manufacturing plant (Li et al. 2018). Variations/rework is the most cost significant issue in the IC supply chain (identified as the 8th ranked factor in the literature analysis). The reason behind that is, the IC supply chain is relatively fixed and unchangeable once it is scheduled (Zhai and Huang 2017). As explained earlier in this paper, variations/rework appear in the form of design changes due to the poor communication between the main contractor and the manufacturer. As a result, the manufacturer will not be able to respond quickly to design changes and continues producing precast components according to outdated design drawings, thereby engendering increased costs and delayed delivery of prefabricated components for assembly (Luo et al. 2018). In fact, the information gap between the upstream and the downstream of the IC supply chain regarding the latest delivery schedule may disrupt the production rhythm of the factory, increasing operation costs, lead to poor layout management of components, and delayed project completion.

In addition to the results generated from the meta-analysis, Wang et al. (2018b) highlighted assembly equipment problems, including periodic maintenance of assembly equipment as a disruption to the IC supply chain. Also, Li et al. (2018) indicated mechanical failures and malfunctions of cranes and misplacement of modules on storage sites as a highly disruptive event related to the IC supply chain. Hence, this study considered this variable and included it in the envisaged action framework developed in the study under the POV construct by considering its relevance to the construct. More so, the impact of risks on IC can be ‘violent’ considering the shorter schedules, difficulty in rectifying errors, inability to make design changes during installation, and the prohibitive cost of reworks. There is zero-tolerance on defects in IC projects since the production schedule becomes fixed once initiated (Hsu et al. 2018). However, given that a defect only arises when a component exceeds a specified allowed tolerance, issues may materialise between design, manufacture, and assembly in IC and increase the cost of rectification and rework (Ekanayake et al. 2019). Therefore, this construct includes highly significant disruptions related to the IC supply chain.

Technological Vulnerabilities-(TEV)

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

Considering the construction industry and focusing especially in IC, fragmentation of the sequential design-construction process (Zainal and Ingirige 2018) often results in information loss/misuse in the industry. According to their findings, technological vulnerabilities are the 6th ranked category of vulnerabilities and showed the significance of the construct.

Information sharing with the SC members are quite complicated and implementing the information systems is costly (Tran et al. 2016). Although the contemporary information systems facilitate real-time data capturing, transmitting the data, and sophisticated analysis of SC data (Li and Lin 2006), inadequate information sharing tends to aggravate operational problems in SC (Tran et al. 2016). These create costly consequences for every SC member (Madenas et al. 2015), thus highlighting needs for more effective collaboration in SCs that requires greater attention on technical and social aspects of information sharing in equal measure (Wu et al. 2014). IC supply chains are also susceptible to technological problems (Wang et al. 2018b) and hence developed Building Information Modelling (BIM) and Radio

Frequency Identification (RFID) enabled IT platforms to achieve real-time visibility and traceability of IT in IC (Zhong et al. 2017).

Financial Vulnerabilities-(FIV)

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

Supplier/Customer Vulnerabilities-(SCV)

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

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

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

4. Envisaged Action Framework for Addressing the Identified SCV in IC

The above findings from the meta-analysis of the literature were drawn upon by including all these SCV constructs in developing this envisaged action framework. All these SCV could be addressed by a set of successfully applied capabilities (Pettit et al. 2013). These capabilities can prevent, mitigate or adapt a disruption and include flexibility, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, market position, security, and financial strength that can be successfully applied in the construction projects (Zainal and Ingirige 2018). However, 'counteractive' capabilities could have dynamic impacts depending on the organisation and the product-specific vulnerabilities (Kurniawan and Zailani 2010). It is, therefore, vital for a study to investigate the dynamics of the capability effects related to the IC. In this respect, an envisaged action framework was carefully developed to address the identified SCV in IC, as shown in Figure 4.

(Insert Figure 4 here)

All these vulnerability constructs and the variables were discussed in line with IC SCs in section 3 of this study. The framework would be vital to the IC supply chain stakeholders, not just in terms of identifying vulnerabilities, but also for formulating adequate capability measures to deal with these vulnerabilities and thereby increase the resilience of these IC supply chains. However, the capabilities that have been initially proposed are preliminary examples based on an initial literature review (Ekanayake et al. 2020). Industry practitioners may seriously consider on these research findings and identify the appropriate SCV allied with their specific IC projects, further the criticalities of the identified SCV along with their groupings. Following that, the appropriate capability initiatives will be developed to adequately withstand these SCV individually or based on the developed constructs. Hence, this is the first step of accomplishing value enhanced, resilient SCs in IC. This envisaged action framework as a research and development framework will be further explored in the next phase of the current research study, after which comprehensive list of capabilities will be formulated to withstand the identified SCV in IC.

5. Future Research Directions

SCV are the critical risk events triggered by the factors that cannot be precisely anticipated (Wang et al. 2018a) and may cause simultaneous multiple disruptions, which calls for resilient supply chains (Hsu et al. 2018). According to the literature findings, ‘supply chain vulnerabilities’ has become a subject that has motivated the interest of numerous researchers and practitioners over recent years (Zainal and Ingirige 2018). However, there is insufficient attention paid to reveal the SCV in the construction industry, and the long-neglected gap of research is particularly visible within IC (Ekanayake et al. 2019). Hence, several vulnerabilities that affect SCs in IC have been determined and presented in this review. Following the findings of the study, it is essential to narrow down the areas to be researched further in greater depth in the future since there is insufficient commitment to determine the effect of vulnerabilities for SCR. Identifying vulnerabilities and categorising them by adopting a thematic analysis laid the foundations for further extensive research on the subject matter. Determination of the causes of an issue is always an initial proactive step towards dealing with the issue (Owusu et al. 2017). Similarly, determining the vulnerabilities in SC can be regarded as the first step in generating realistic solutions to overcome SC disruptions in IC.

First, the vulnerability constructs that were developed in this study may require further empirical underpinnings related to their contextual and geographical positioning (Ekanayake et al. 2019). The constructs can be further tested following a case study or with subject matter expert surveys, following empirical studies to determine the precise severity or the intensity of each construct based on the location. Second, it is suggested to conduct deep investigations of the developed constructs across the IC field to identify project-specific vulnerabilities. Third, since resilience is a relatively unexplored research area, it would be fascinating to discover the capabilities with their appropriate levels, that a firm should have or develop to cope with identified vulnerabilities In these circumstances, conducting an exploratory case study is necessitated to get a broad picture of the industry practices, such as what are the critical SCV affecting the IC field, how these are already addressed in the industry and what is lacking to improve SCR. Thereby, an assessment model or a simulation model could be developed, including appropriate SC vulnerabilities and capabilities targeting resilient SCs in IC.

6. Limitations

This study was limited to a structured review of literature under the knowledge domian of SCV; hence, no strong empirical justifications can reinforce the findings at this stage, except as already reported in the publications retrieved for the review. Therefore, the findings are necessarily generalised. The vulnerability constructs that are developed under this study depict the general categorical severity with their associated vulnerability factors, but also serve a valuable purpose in providing an important over-arching overview. The resulting mapping and prioritisation of SCV and potential counteracting capability measures are found to be an essential precursor to dipping deeper into specifics in each location. Also, there should be another detailed study to determine and deeply investigate the SC capability measures that firms should develop to enhance SCR. This will be addressed in the next phase of this study.

7. Conclusions

In recent years, several high-profile events have severely disrupted SC performance in many industries. These raised awareness among researchers and industry practitioners of the imperative to minimise the potentially devastating effects of disruptions by developing more resilient SCs (Cui 2018). Any disturbance at any point of the SC impacts the performance of the entire SC, and this issue is severe in IC because the processes are difficult to re-schedule and re-organise once scheduled. Vulnerabilities can cause significant disruptions and lower expected SC performance levels. Thus, SCs need to develop resilience capacities to withstand them effectively. The goal is to develop a resilient SC in IC, as one that can maintain and deliver the same, if not a better level of performance during and after disruptions, than it had previously.

Therefore, this study conducted a systematic review of the various identified SCV over the past 20 years. 37 vulnerability factors were identified by analysing 36 publications that were screened out under the study. These publications were thoroughly examined and analysed in terms of annual publication trend, the trend of publications by the country, methodological approaches adopted in previous research exercises, and thematic categorisation of the variables.

The results found that 2017-2018 was the year with the highest number of related publications, and the USA was the country that had the highest publication frequency. Following the thematic analysis process, this study developed an envisaged action framework for addressing the identified SCV in IC consisting of six constructs, namely; Project Organizational; Procedural; Supplier/customer; Technological; External Environmental; and Financial

Vulnerabilities and suggesting the capabilities to withstand them. With the substantial advancement of SCR research, this study should inspire further research that could continue to unearth other clandestine, dormant, or less obvious vulnerabilities in IC supply chains; and to develop the effective capability measures to withstand these six constructs of vulnerabilities. The envisaged action framework provided in this study should prove vital to the stakeholders of IC supply chains and other industry practitioners in formulating appropriate and adequate capability measures needed by resilient SCs. This paper also delivers a package of useful information and basic new knowledge for academia and industry to instigate deeper research and focused development (R&D) of capacity development initiatives for SCR in IC.

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Table 2: Citation frequency analysis of general vulnerability variables for SCR

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

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

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

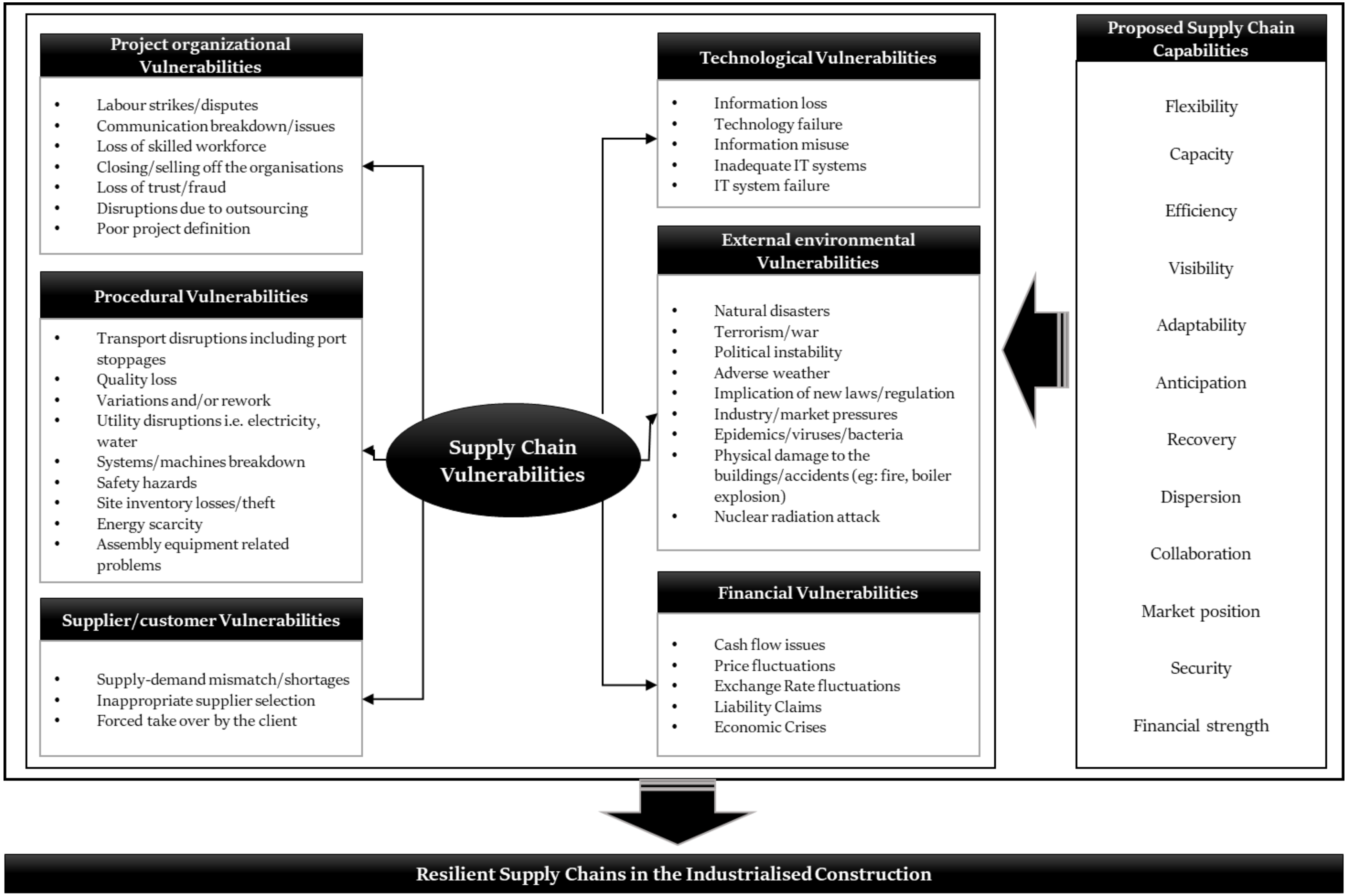

Figure 4: Envisaged Action Framework for Addressing the Identified SCV in IC