DYNAMIC SUPPLY CHAIN VULNERABILITY ANALYSIS OF HONG KONG-ZHUHAI-MACAO BRIDGE CONSTRUCTION: A TOPIC MODELLING APPROACH

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The Hong Kong-Zhuhai-Macao Bridge (HZMB) was a challenging milestone construction project that boosted the Hong Kong construction industry participants to new heights of recognition. While industry-boosting long-term benefits arose from knowledge gained in managing specialist prefabrication processes and complex supply chains (SCs), these advances also necessarily imposed challenges, rendering the project highly vulnerable to disruptions. Therefore, higher resilience was essential to withstand higher Supply Chain Vulnerabilities (SCV) through enhanced capabilities, for which identifying dynamic SCV becomes critical. To address this, the study employed the Topic Over Time modelling approach to detect critical SCV using 1,748 unstructured official documents on the HZMB from 2003 to 2018 (project design to handover). The popularity trend analysis that was thereby conducted, enabled identifying the six most critical vulnerabilities and categorizing them among each project phase. Finally, an ex-post vulnerability evaluation map was developed by considering the vulnerabilities' popularity trend and their relevance towards the project and SC phases. Using these findings, industry practitioners could improve their ex-ante decision-making, targeting value-enhanced-resilient SCs in future prefabricated infrastructure development projects. Further, the text-mining research approach unveils an effective mechanism for researchers to extract dynamic empirical clues from a large unstructured set of documents in construction SCs.

Keywords: supply chain; vulnerabilities; prefabricated; resilience; Hong Kong

INTRODUCTION

The Hong Kong-Zhuhai-Macao Bridge (HZMB) is the longest bridge-cum-tunnel sea crossing in the world (55km) and a milestone cross-regional major transportation infrastructure project. It was constructed recently and is now in operation. This mega-project was a critical part of China's 13th Five-Year Plan, aiming to promote the economic development of the entire Pearl River Delta by developing an economic hub (Li, 2019). This massive, advanced infrastructure development boosted the Hong Kong (HK) construction industry to new heights of recognition, including an award from the UK Institution of Civil Engineers for its achievements in project

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Ekanayake, E M A C, Xue, J, Shen, G Q and Kumaraswamy, M M (2021) Dynamic Supply Chain Vulnerability Analysis of Hong Kong-Zhuhai-Macao Bridge Construction: A Topic Modelling Approach *In:* Scott, L and Neilson, C J (Eds) *Proceedings of the 37th Annual ARCOM Conference,* 6-7 September 2021, UK, Association of Researchers in Construction Management, 491-500

management and contribution to enhancing regional transportation networks. The HZMB is located at the Pearl River entrance, crosses the Chinese Lingding Bay, and connects three metropolises: Hong Kong, Zhuhai, and Macao. The design and construction of the HZMB included three navigable bridges, one immersed tunnel and two artificial islands (Hu *et al.,* 2015).

However, this project faced more serious challenges than previously encountered due to the vagaries of the weather and the marine environment at the construction site (Hu *et al.,* 2015). Hence, towing and installing activities became more difficult. The other challenging tasks included preventing serious leakages due to excessive and uneven settlement of cross-joints and avoiding settlements along the tunnel alignment due to discontinuous geotechnical conditions (Hu *et al.,* 2015). The bad weather condition around Lingding Bay itself caused serious disruptions (Zeng *et al.,* 2018). The environmental authorities kept close oversight of this HZMB construction, as the site was in a White Dolphin Protection Zone (Li, 2019). The site was also on a busy traffic shipping route at the Pearl River mouth with 4,000 vessels shuttling back and forth daily (Ming, 2017). Therefore, it had to allow for and not delay nor disrupt heavy traffic during any on-site construction processes.

At the same time, the project's quality requirements and specifications were very high (Zeng *et al.,* 2018). For instance, the targeted service life of the HZMB was 120 years; hence had higher expectations than most common infrastructure development projects in China (Zeng *et al.,* 2018). Reducing on-site works through prefabricated construction methods helped in complying with these requirements and withstanding project environment-specific disruptions. These included prefabricated piers, pile caps, girders, steel box, and immersed tube tunnels (Zeng *et al.,* 2018; Zhou *et al.,* 2018) produced in factories and delivered for on-site assembly through maritime routes. With this arrangement, all the main tunnel elements were prefabricated under standardised management systems. Hence, labour, material and time on site were significantly reduced, and greater efficiency, safety and quality were achieved (Lu, 2020). For instance, it required 210 days to finish the two artificial islands, which was two years faster than in traditional construction (Lu, 2020). However, these innovative construction methods, advanced technology and equipment injected a new set of challenges, adding further complexities and vulnerabilities to the project Supply Chain (SC) (Hu *et al.,* 2015). Around one billion RMB worth of immersed tubes were prefabricated, and their factory manufacture required three billion RMB worth of specific equipment (Ming, 2017). Further, the installation of these elements was a complicated and time-consuming task as the elements were very heavy, e.g., 420,000 tons of box girders (Lu, 2020), while the installation of those heavy elements was affected by the meteorological and hydrological conditions on site (Zhou *et al.,* 2018). Under these circumstances, the project overran its timeline, and the actual budget [RMB 127 billion] exceeded the allocation of RMB 72.7 billion (Li, 2019).

The foregoing challenges demanded closer attention to effective vulnerability management mechanisms (Li, 2019). Traditional risk management strategies were inadequate in withstanding the Supply Chain Vulnerabilities (SCV) as observed in this project. Indeed, such fragmented prefabricated SCs call for advanced risk management mechanisms to cope efficiently with project vulnerabilities (Ekanayake *et al.,* 2021). Deploying stronger and appropriate capability measures would have boosted resilience by more effective withstanding of SCV (Pettit *et al.,* 2013). Besides, more resilient practices would have boosted project performance by reducing time and cost-overruns. Proper identification of dynamics of SCV is the first step in

enhancing resilience, hence project performance by proper withstanding of the identified SCV (Ekanayake *et al.,* 2021). In the first study on resilience-enhancing practices in prefabricated construction SCs, Ekanayake *et al. (*2021) identified the critical SCV associated with prefabricated construction in HK through an expert opinion survey. Accordingly, the prefabricated SCs were significantly vulnerable towards extensive skilled labour requirement, outsourcing decision, transportation of prefabricated units, on-site safety, complex on-site logistics, and 'tolerance' based issues, affecting the overall quality and delivery. Further, Ekanayake *et al. (*2021) identified 26 critical SCV under five groupings of economic, technological, procedural, organisational, and production-based.

However, the outcomes of the above-cited study were not tested using a specific case study; hence the authors have suggested case study based real-time justifications for verifying the results (Ekanayake *et al.,* 2021). This HZMB case study-specific research addresses this need. This particular case was chosen considering because: (a) mega-infrastructure development projects contribute significantly to construction output in HK (Xue *et al.,* 2020); (b) prefabricated construction is increasingly prominent in HK infrastructure development projects (Lu, 2020); and (c) projects (such as HZMB) are significantly vulnerable to SC disruptions (Lu, 2020). The HZMB case study, therefore, addresses the identified lack of attention to critical resilient practices in prefabrication based-infrastructure development projects. Hence, the current research questions were developed to explore, (a) the critical SCV associated with HZMB construction, and (b) their dynamics (changing pattern/nature of the SCV throughout each construction phase), so as to provide a basis for initiating resilient practices.

As indicated, this previous study of Ekanayake *et al. (*2021) was based on the static analysis; hence it lacks the evidence to support the dynamics of SCV throughout the project phases. Further, survey and interview data are subjective and depend on respondents' quality (Yin, 2017). Using a large quantitative dataset of official documents on prefabricated projects would address this limitation by facilitating objective and convincing empirical data analysis (Xue *et al.,* 2020). However, the literature remains silent on using such large, unstructured quantitative datasets in the SCV analysis and/or even in prefabricated construction research, thereby suggesting an option of effective text-mining based empirical studies in SC resilience and the prefabricated construction research domains.

'Topic modelling' is a robust tool that detects the core commonalities among a pool of texts. It has received greater prominence under the text mining research approach over recent years (Xue *et al.,* 2020). Among other topic modelling techniques such as Latent Dirichlet Allocation (LDA), PLSA and probabilistic theory, Topic Over Time (TOT) modelling is considered to be a more effective technique (Xue *et al.,* 2020). TOT is the dynamic topic modelling technique that explores both the content of core concepts and the dynamic concept patterns associated with a large set of texts (Wang and McCallum, 2006). Therefore, TOT modelling was considered appropriate to analyse SCV using the project documents of this HZMB prefabricated infrastructure development project while mining the critical SCV and presenting their dynamics over time [over the project phases of planning, construction, and handover].

Under these circumstances, this study aimed to develop an ex-post SCV evaluation map by introducing TOT modelling as a novel method for SCV analysis, using a large set of unstructured project documents of the HZMB project. First, TOT modelling

was used to analyse the official project documents of the HZMB throughout the entire project duration. As a result, the critical SCV and their annual trend could be explored under each project stage of planning, construction and handover using the project timeline. Finally, the results were appropriately mapped with SC phases, and the ex-post SCV evaluation map was developed. It is proposed as an SCV management guide for project professionals. The forthcoming sections of this paper present the research methodology, results and ensuing discussions, practical research implications and the conclusions, including research limitations and suggested ways forward.

RESEARCH METHODS

Data Collection

The research flow of this study is presented in Fig 1. The relevant data for this study was collected from the Hong Kong Legislative Council's official website. This website is accessible to the public, while the data maintained by the government is highly reliable. Therefore, all the project documents related to HZMB were downloaded from this open-source library using the search terms "Hong Kong-Zhuhai-Macao Bridge" and "HZMB". This yielded 1748 official documents on the HZMB construction spanning between 2003 to 2018, under the planning, construction and handover phases of the project.

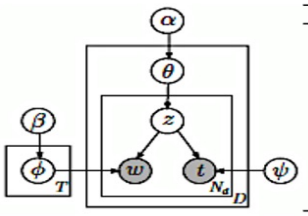
Fig 1: Research flow of this study

TOT Modelling

The collected data set was then screened through a data cleaning process by extracting the contents from the raw data files using keywords related to SCV, prefabricated construction and the HZMB. During this cleaning process, the authors used the SCV terms extracted from Ekanayake *et al. (*2021) as they were verified for prefabricated construction in HK. This approach ensured screening and selecting the highly relevant texts for this study. Thereafter, TOT modelling was employed as described below.

TOT modelling is an advance over the traditional basic text mining technique of the Latent Dirichlet Allocation model (LDA) (Xue *et al.,* 2020). The TOT model not only captures the low-dimensional data structures but also detects the structure's changes over time (Wang and McCallum, 2006). Further, meaningful results would only be generated by considering both word co-occurrences and the documents' timestamps (Wang and McCallum, 2006). Given these advances of TOT modelling over other text mining techniques, TOT models were considered effective in exploring texts and their distribution over timestamps associated with SCV analysis; hence, the decision was to use TOT modelling in this study. Fig 2 illustrates the TOT model used in Gibbs sampling for parameter estimation (Wang and McCallum, 2006), and also used in this current study. Accordingly, the cleaned data set of the HZMB project was then subjected to the mathematical modelling process [using the algorithm depicted in Fig 2] to generate the dynamic impact models (TOT graphs) of SCV. During this mathematical modelling process, timestamps were generated for all the word tokens, while all the word timestamps in a document were considered similar to the document's timestamp (Wang and McCallum, 2006). Further, fixed symmetric Dirichlet distributions of $\alpha = 50/T$ and $\beta = 0.1$ were used as the hyperparameters of α and β (Xue *et al.,* 2020) considering the simplicity of the model (Wang and McCallum, 2006). Data processing using the TF-IDF filtering was done before

running the model to enhance the texts' quality while removing frequent but meaningless texts. Then, the model was run to generate the results.



Symbol	Description
T	Number of topics
D	Number of documents
V	Number of unique words
N_d	Number of word tokens in document d
θ_d	The multinomial distribution of topics specific to the document d
ϕ_z	The multinomial distribution of words specific to the topic z
ψ_z	The beta distribution of time specific to topic z
Z_{di}	The topic associated with the ith token in the document d
ω_{di}	The ith token in the document d
t_{di}	The timestamp associated with the ith token in the document d

Fig 2: TOT model in Gibbs sampling [Source: (Wang and McCallum, 2006)]

This modelling process led to six extracted topics, including 15 feature words with high relevant probabilities in each [Fig 3]. The extracted topics were then tested for their coherence following the method suggested by Xue *et al. (*2020). Therefore, the following formula was employed to calculate the coherence of each topic z considering the allied feature words list of $V^{(z)}$; where, D(V) represents the number of documents that feature word V appears; D(Vm, Vl) represents the number of documents that contain both feature words of Vm , Vl. Since the model passed the coherence test, then the dynamic impact models (TOT graphs) of SCV were visualised through the model, as shown in Fig 3. Finally, the ex-post SCV evaluation map was produced by mapping the impact of SCV with SC phases.

$$C(Z;V^{(z)}) = \sum_{m=2}^{15}\sum_{l=1}^{m-1} log\,\frac{D(v_m^{(z)}, v_l^{(z)}) + 1}{D(v_l^{(z)})}$$

RESULTS AND DISCUSSION

Critical SCV Associated with the HZMB Construction and Their Trend

Fig 3 presents the topics identified, feature words, topic concepts assigned by the authors, considering the common themes underlying the topics (Xue *et al.,* 2020) and their coherence values. Accordingly, the six-topic TOT model was regarded as the best valid model that interprets the project documents and evaluates critical SCV. Following the method suggested by Mimno *et al. (*2011), the TOT model was validated for its coherence and representativeness of the topics. In this TOT model, the topic concepts present the common underlying theme of each topic, which aligns with the associated feature words. Hence, the developed six topic concepts are cross-border related disruptions, disruptions due to outsourcing, communication issues, safety concerns during transport and assembly, other disruptions associated with transportation, and economic and social disruptions. These topics were considered as the critical SCV faced during the HZMB construction. Comparing the study findings with the only comparable study: that of Ekanayake *et al. (*2021), even, in this project, cross-border, transportation, safety, communication and outsourcing issues were significant. However, the dynamics of their occurrence and the nature of the disruptions are not exactly the same as discussed below. Indeed, the HZMB project faced economic and social disruptions, indicating some differences from the more general data and findings in Ekanayake *et al. (*2021). This is because this project is a strategic cross-border mega infrastructure construction project beset by several environmental, financial, and social challenges.

Therefore, drilling deeper here, Fig 3 depicts the dynamic impact of these critical SCV throughout the project duration of the HZMB from 2003 to 2018. In the HZMB project, the planning phase was between 2003-2009, the construction phase was

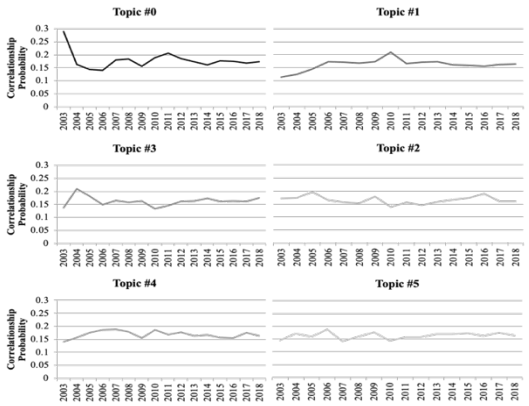
between 2010-2017, and the project was handed over in 2018. Delving specifically into the dynamic impacts of identified SCV, the project had encountered all the critical SCV during the planning phase [Fig 3]. Prefabricated construction has generally proven more beneficial than conventional construction, given the many advantages of mass production of standardised components (Goodier *et al.,* 2019). However, in mega-infrastructure development projects such as the HZMB, manufacturing of the prefabricated components is expensive, and the production cycle is much longer (Zeng *et al.,* 2018). Economies of scale were, therefore, unavailable when using customised and non-standardised elements such as immersed tubes and steel box girders (Lu, 2020). Moreover, much time was spent on planning and design. However, the project was highly disrupted by outsourcing issues in the construction phase. The cross-border related issues were also high in the construction phase because the construction phase involved the transportation of prefabricated components across customs and immigration-controlled borders. When reaching the handover phase, transportation vulnerabilities, economic and social disruptions, and communication issues were reduced because of additional efforts to reap the imminent societal benefits from the project.

Cross-border related disruptions [#0] were considered high in the planning stage since many approvals were needed from all three jurisdictions at the beginning. Mainly, because of this, the project overran its timeline until 2010 (Hu *et al.,* 2018). Further, two temporary governmental committees from the central government and three local governments were established at various levels and locations to better manage such disruptions (Hu *et al.,* 2018). Several problems still arose from many policy conflicts and uncertainties, as each jurisdiction had its own specific policies (Li, 2019).

Disruptions due to outsourcing [#1] were severe vulnerabilities on the project, as many contractors and sub-contractors were involved and responsible for different construction activities. For instance, three major suppliers were selected for the manufacturing of steel box girders. However, they initially failed to comply with product quality, specifications and production capacity requirements (Zeng *et al.,* 2018). Given the high unit price of customised prefabricated units, the suppliers were reluctant to invest in capacity improvements. Therefore, the HZMB authority had to spend much time and money to improve the suppliers' production capacities and quality through technology support programs, training, and preferential price allocation (Zeng *et al.,* 2018). To avoid quality issues, the HZMB authority had to hire an independent consultant group for the 'first-article inspection' and 'full quality inspection', which incurred more cost and time (Zeng *et al.,* 2018). Further, the outsourcing required special equipment and machinery both in manufacturing and assembly (Ming, 2017). Also, transportation arrangements arising from offsite construction demanded expensive methods by adding more vulnerabilities (Lu, 2020).

Communication problems [#2] were similarly observed throughout each phase due to the fragmented SC (Li, 2019). Multi-stakeholder involvement in such a complex mega infrastructure project required a collaborative platform for communication and timely decision making (Zhou *et al.,* 2018). The complicated environment around the HZMB site also triggered safety issues during transport and assembly [#3] (Li, 2019). Airport height restrictions, frequent typhoons, crisscross navigation, and high environmental standards were also significant (Yau and Lok-kei, 2018). Innovative prefabricated roof modules were used to tackle airport height restrictions. Pre-installed building services in these modules were also needed to reduce safety risks during the assembly at heights (Yau and Lok-kei, 2018). Single lifting and horizontal

assembly of modules were chosen to improve safety (Lu, 2020), although it was time-consuming.



Topic	Concept	Feature words	Average coherence
#0	cross-border related disruptions	crossboundari; trade; border; implement; corridor; port; increas; oper; move; pollut; region; help; delay; opportun; commenc	-68.1530
#1	disruptions due to outsourcing	enhanc; pollut; commiss; employ; million; traffic;urg; polici; estim; demand; progress; truck; apart; complet; commenc	-69.5776
#2	communication issues	facilit; logist; amend; servic; link; progress; govern; option; current; territori; worker; close; develop; construct; comment	-80.3106
#3	safety concerns during transport and assembly	Safety; cargo; crossboundari; measur; environ; west; execut; road; manpow; lantau; expediti; passeng; congest; transport; employ	-77.5507
#4	transportation associated other disruptions	transport; exist; airport; tuenmun; believ; trade; promot; comment; time; implement; freight; meet; termin; cross; tourism	-71.2842
#5	economic and social disruptions	econom; western; local; plan; impact; labour; consult; assess; region; soon; method; enhanc; resid; district; improv	-70.3662

Fig 3: TOT model of supply chain vulnerabilities

Owing to unpredictable weather patterns, high and strong waves, component control during floating, towing and installing became more vulnerable (Hu *et al.,* 2015). On the other hand, disruptions due to marine traffic added considerable delays despite the requested special pontoons for transportation [#4] (Hu *et al.,* 2015). To prevent worker falling, mechanical collision and other safety accidents, advanced safety protection apparatuses and sensors were required (Zhou *et al.,* 2018). On-site assembly was carried out in an optimal time window by adjusting the production plans as the process was significantly affected by the environmental vulnerabilities (Zeng *et al.,* 2018). The long span [about 153m] and heavy [350t] element installation caused safety issues too (Lu, 2020). Besides, huge floating cranes with a lifting capacity of over 4000t were required for the assembly. Furthermore, prefabricated units and piers had to be divided into sections due to transportation difficulties (Lu, 2020); hence re-assembled again on-site.

In terms of economic and social disruptions [#5], the HZMB had to deal with significant direct and indirect influence from the community and the environmental authorities (Li, 2019). Besides, some political groups' involvement added uncertainties to the project implementation (Li, 2019). As the site was located at the core of the White Dolphin Protection Zone, relevant authorities raised significant queries and concerns during the initial project phases until the project passed the environmental impact assessment by using novel methods that caused less disturbance to the environment (Li, 2019). On the other hand, economic disruptions were observed throughout the project due to the use of advanced technology, the requirements of skilled and trained labour, as needed for advanced and specific machinery, laser cutting tools, robots, specifically designed pontoons and assembly cranes, with longer production and assembly cycles than expected (Lu, 2020). These economic implications also led to budget overruns.

The Ex-Post SCV Evaluation Map and Its Practical Implications

The six topics and their popularity trend outputs generated from the TOT modelling were mapped with the prefabricated SC phases of manufacturing, logistics and on-site assembly to develop the ex-post SCV evaluation map [Fig 4]. The vulnerabilities were positioned under each construction phase [Fig 4], according to their dynamic impact levels in each phase, as derived from Fig 3. According to Fig 4, considering the vulnerability dynamics, the on-site assembly was the most vulnerable SC phase in the HZMB development. The logistics phase was also associated with significant

vulnerabilities, as there were specific disturbances due to prefabricated elements' transportation. The outcomes depicted in the map provide a managerial guide to the industry professionals. The industry practitioners would benefit from prior knowledge of potential SCV and their dynamic impact on each project and SC phase, so they may prioritise how to address SCV better through appropriate capability development in each SC phase.

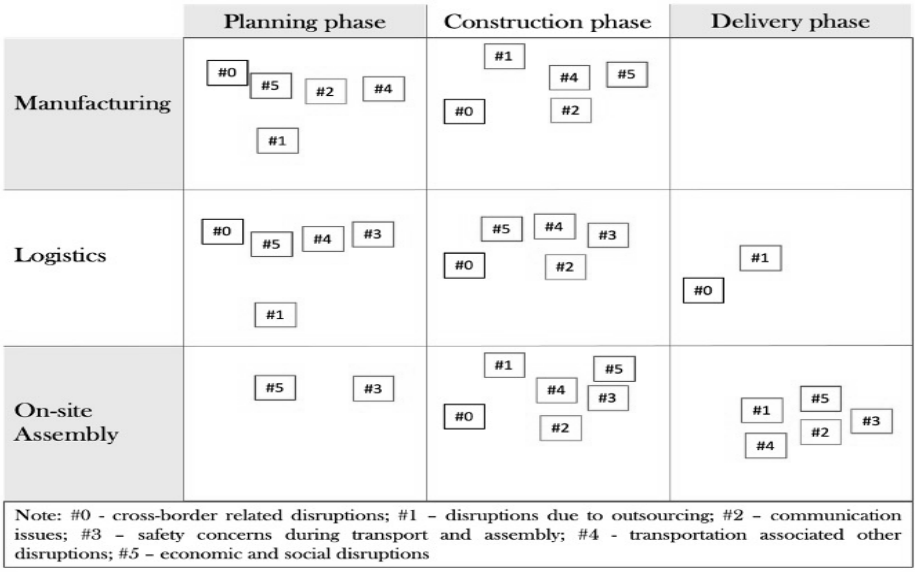


Fig 4: The ex-post SCV evaluation map

Although this is an ex-post mapping here, ex-ante decision making is also possible with this tool. The findings could then be applied in the early risk management stage of prefabricated infrastructure development projects. Significantly, the results are already validated through previously published case-study findings (Ming, 2017; Li, 2019; Lu, 2020), i.e., when comparing model predictions with actual outcomes. Therefore, this study's strengths include its representative case choice, reliable information source and a large set of text documents. Indeed, no two projects are ever the same, so as in all case studies, there will not be another identical HZMB project in future. But the findings could be necessarily generalised and adapted by comparing the prefabricated SC specific vulnerabilities in many similar mega-infrastructure development projects.

This is the first known study that developed an SCV evaluation map using the TOT modelling approach. Also, this is the first study that attempted to evaluate SCV associated with infrastructure projects targeting resilience. Hence, the novel research method employed, and the key research outcomes generated in this study significantly contribute to the construction and SC resilience research domains. The research methodology can be applied to other jurisdictions and projects based on the availability of a reliable, large set of project documents. This methodology could also be extended to explore the project-specific SC capabilities, which are the counter balancers of SCV and help develop essential capacities to achieve resilience.

CONCLUSIONS

This study employed the TOT modelling approach to detect critical SCV faced by the mega-prefabricated infrastructure development project of HZMB. Six critical topics of vulnerabilities were identified and described as resulting from the popularity trend analysis of texts. A decision-making map was also developed by considering the

popularity trend of vulnerabilities and their relevance to the project and SC phases to visualise the dynamic vulnerability impact on the HZMB construction. The identified critical SCV of HZMB included cross-border, safety, transportation, outsourcing, communication, economic and social disruptions. Deviating from the literature findings, economic and social disruptions were more critical and specific in the HZMB project, given its complexity and special challenges. Also, comparing with previous related studies, being the first study that explored the dynamic vulnerability impact in prefabricated construction SCs, this study revealed the dynamic impact of SCV during each project and SC phase.

Accordingly, the decision-making map was developed based on both theoretical knowledge and its practical feasibility and potential usefulness. Therefore, industry practitioners would benefit from such collective prior knowledge of SCV and their dynamic impact on each project phase, to prioritise addressing them adequately through appropriate capability development, targeting value-enhanced-resilient SCs in future prefabricated infrastructure development projects. The map was generated as an ex-post model; hence, it may be considered a necessary research limitation in the first attempt. However, this ex-post map could be adapted to suit any special contextual differences in future prefabricated mega-projects; and then help encourage and facilitate proactive decision-making in future ex-ante scenarios. Finally, and more significantly, the text-mining approach adopted in this study unveils and applies novel vulnerability analysis methods while pointing academia to an effective mechanism to extract empirical clues from a large unstructured set of documents in the construction domain in general. As a way forward in further research, the developed SCV evaluation map could be strengthened using several other case studies and/or more empirical data. Further, the map could be necessarily generalised for other project contexts following this robust topic modelling approach. Indeed, the TOT model could be further verified for its consistency with sentiment analysis in the text mining to derive more advanced research implications.

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