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Chapter 5

Construction Supply Chain Resilience in Catastrophic Events

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Additional information is available at the end of the chapter

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Abstract

In the wake of a number of catastrophic events, construction supply chain (CSC) vulnerability has become a major issue in the industry. Construction organisations today focus on strategies to minimise the impact of catastrophic events and manage risk by creating more resilient supply chains. However, there is lack of a mechanism to minimise the impact of catastrophic event on CSC. Therefore, this chapter focuses on the impact of catastrophic events on CSC and proposes a strategic framework to minimise their ultimate impact on the construction organisations. This aim is achieved through a comprehensive literature review, preliminary investigation and structured questionnaire survey. According to findings, most likely catastrophes that disrupt CSC are non-terrorist events and in fact are not always the most severe catastrophes. The aggregate effect of likelihood and severity revealed that disruption to transportation has the extreme risk level on CSC, while the most significant impact of catastrophic events is business failure and least significant impact is loss of focus to work. Thus, the catastrophic event risk minimisation strategic framework presented in this chapter will assist construction organisations to identify most suitable strategic actions to minimise the impact of catastrophic events on CSC in order to create resilient construction industry.

Keywords: construction supply chain (CSC), construction supply chain management, catastrophic events, risk analysis, severity, likelihood, strategic framework

1. Introduction

Heightened challenges due to series of catastrophic events that have disrupted economies around the world have prompted academics and practitioners to investigate new strategies to

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minimise their impact on supply chain. Supply chains are increasingly vulnerable to catastrophic events and a diverse set of risks [1]. According to Atley and Ramirez [2], there are evidence that failure to manage supply chain risks effectively may lead to a significant negative impact on organisations. Such impacts include not only financial losses but also reduction in product quality, damage to assets and loss of reputation [3]. Developing strategies to mitigate disruptions has become a necessity as systems become more complex and increasingly more vulnerable to experiencing supply chain disruptions [4]. According to Stecke and Kumar [5], it is difficult to find strategies that best suit an organisation or industry due to the nature and severity of catastrophes.

The construction industry consists of certain peculiarities such as one-of-a-kind nature of project, temporary multi-organisation, on-site production and regulatory intervention preventing the attainment of flows as efficient as in manufacturing [6]. Vrijhoef and Koskela [7] argued that due to construction peculiarities, supply chain management (SCM) has specific roles in construction. The construction supply chain (CSC) basically represents a series of serial and parallel connections between clients and suppliers leading to the delivery of one or more products to one or more end clients [8].

Some researchers have introduced strategies that can be implemented both before and after a catastrophic event in order to minimise or prevent the impact of such an event in manufacturing industry [1, 5, 9, 10]. However, there is a lack of research on the impact of catastrophic events on CSC and strategies to ensure a resilient CSC. Consequently, there is no evidence in the literature of any mechanism to minimise the impact of catastrophic event on CSC. There is therefore a necessity to investigate the impact of catastrophic events on this sector and to propose an action plan with strategies to face such events with resilience in future.

The structure of this chapter begins with a review of supply chain management, construction supply chain management, supply chain risks, impact of catastrophic events on CSC and strategies to minimise the impact of catastrophic events on supply chain. The next section presents the research methodology and conceptual framework. Research findings are presented in Section 7 followed by concluding discussions.

2. Supply chain management (SCM)

Supply chain management (SCM) originated and flourished in the manufacturing industry. Although supply chains exist in any type of organisation, the complexity of the chain seems to vary greatly from firm to firm and also from industry to industry depending on the size of the business, type of products and intricacy of the industry. The supply chain starts and ends with the customer. Despite the popularity of SCM, both in academia and industry, there is a considerable confusion as to its meaning and lack of a universally accepted definition. **Table 1** shows typical definitions of supply chain and SCM given by various authors in their publications.

References	Supply chain	Supply chain management (SCM)
Monczka et al. [11]	Supply chain is a set of three or more organisations linked directly by one or more of the upstream or downstream flows of products, services, finances and information from a source to a customer	SCM endorses a supply chain orientation and involves proactively managing the two-way movement and coordination of goods, services, information and funds from raw materials through to end user
Coyle et al. [12]	Supply chain can be viewed as a series of integrated enterprises that must share information and coordinate physical execution to ensure a smooth, integrated flow of goods, services, information and cash through the pipeline	SCM is involved with integrating three key flows across the boundaries of the companies in a supply chain: product/materials, information and financials/cash
Handfield and Nichols [13]	Supply chain encompasses all activities associated with the flow and transformation of goods from the raw materials stage, through to the end user, as well as the associated information flows. Material and information flow both up and down the supply chain	SCM is the integration of these activities through improved supply chain relationships, to achieve a sustainable competitive advantage
Lambert et al. [14]	Supply chain is not a chain of businesses with one-to-one, business-to-business relationships, but a network of multiple businesses and relationships	SCM is a philosophy which integrates key business processes from end user through original suppliers that provides products, services, and information that add value for customers and other stakeholders
Thomas and Griffin [15]	There are three traditional stages in the supply chain: procurement, production and distribution and supply chain for a particular product will cross functional or corporate boundaries	SCM is management of material and information flows both in and between facilities such as vendors, manufacturing and assembly plants and distribution centres
Ayers [16]	Life cycle processes supporting physical, information, financial and knowledge flows for moving products and services from suppliers to end users	Design, maintenance and operation of supply chain processes for satisfaction of end user needs
Mentzer et al. [17]	Supply chain is a set of three or more entities (organisations or individuals) directly involved in the upstream and downstream flows of products, services, finances and/or information from a source to a customer	SCM is the systemic and strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole

Table 1. Definitions of supply chain and supply chain management.

Although the definitions of supply chain appear similar across authors, the definition of SCM could differ. Tyndall et al. [18] and some authors defined SCM in operational terms involving the flow of materials and products, some viewed it as a management philosophy and some others viewed it in terms of a management process. Mentzer et al. [17] and Mohanty and Deshmukh [19] identified three degrees of supply chain complexity, that is, "direct supply chain," "extended supply chain," and "ultimate supply chain" as presented in **Figure 1**.

SCM integrates all organisations across supply chain, through upstream and downstream linkages. Many past researchers applied the generic concepts, methods and lessons learnt from SCM in manufacturing industry to the construction industry. The next section presents the review on construction supply chain management.

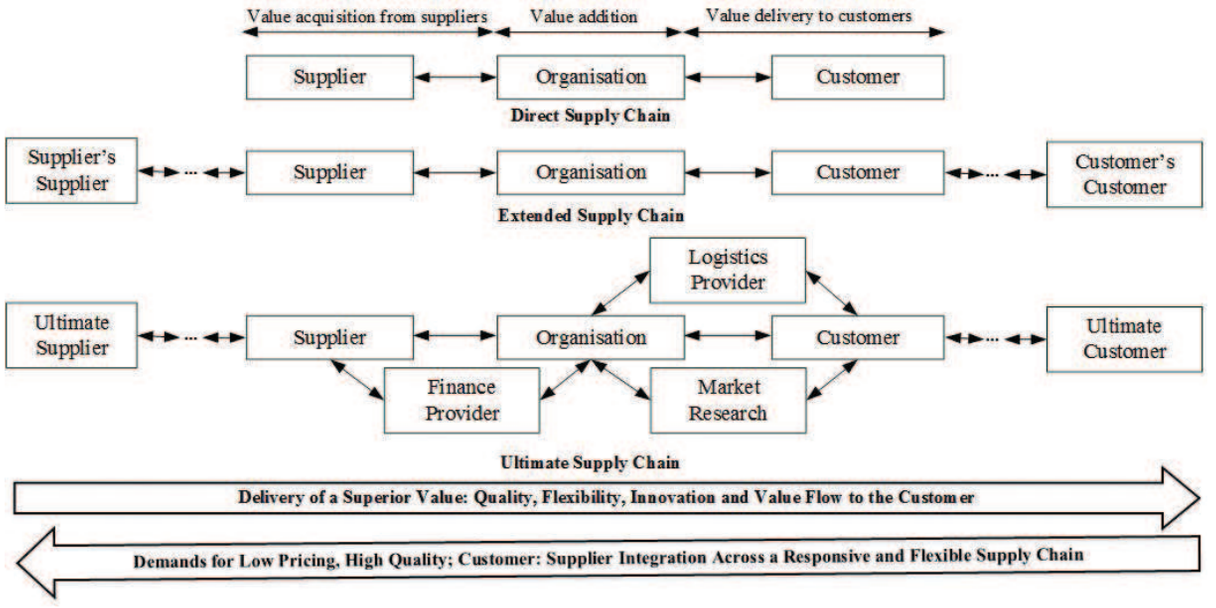


Figure 1. Types of supply chain relationships (adapted from [17, 19]).

3. Construction supply chain management (CSCM)

A major distinction between construction and manufacturing is that the construction industry is project based and of discontinuous nature, while manufacturing industry involves continuous processes and relationships [20]. The construction industry is one of the most complex industries because the total development of a project normally consists of several phases requiring a diverse range of specialised services and involvement of numerous participants. Therefore, it is difficult to control and manage construction projects effectively [21]. Production in construction is relatively disconnected and fragmented due to how demand and supply systems in construction have traditionally been organized [8]. Vrijhoef and Koskela [7] further identified four major roles of SCM in construction, dependent on whether the focus is on the supply chain, the construction site, or both. **Figure 2** presents the four areas of focus as pointed out below.

Supply chain in construction consists of all the construction business processes initiated from the demands by the client as conceptual design and construction to maintenance, replacement and eventual decommission of building [22]. According to Xue and co-workers [22], CSC is not a chain of construction businesses with business-to-business relationships, but a network of multiple organisations and relationships, which includes the flow of information, materials, services or products, and funds between client, designer, contractor and supplier. Based on three case studies conducted in the Netherlands and Finland, Vrijhoef and Koskela [7] developed a typical supply chain and make-to-order construction process as shown in **Figure 3**.

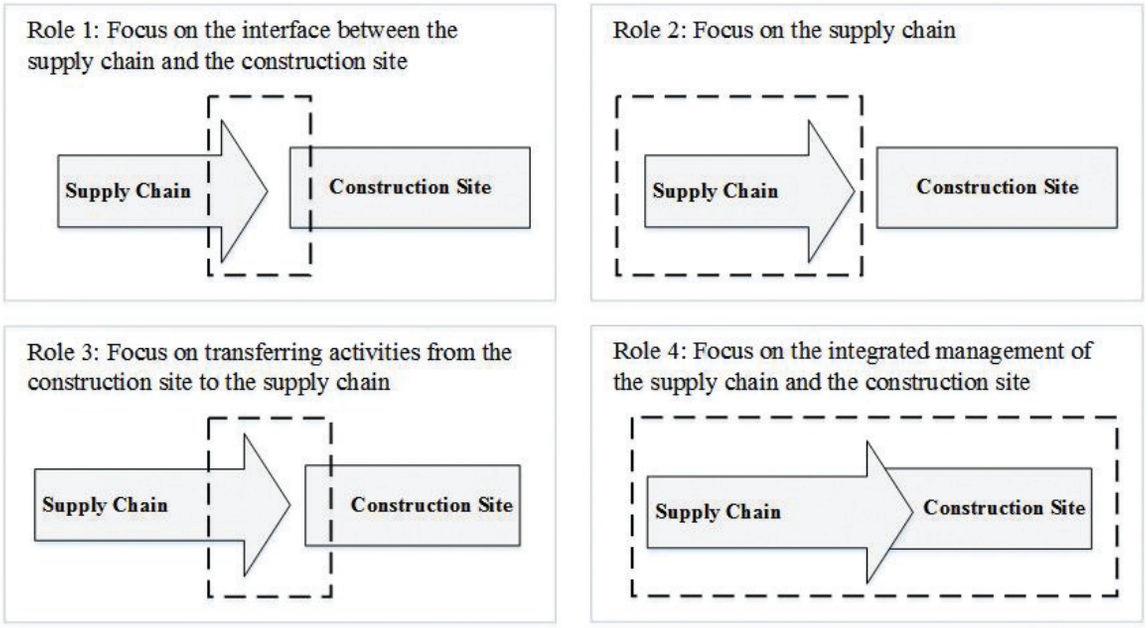


Figure 2. The four roles of supply chain management in construction (source: [7]).

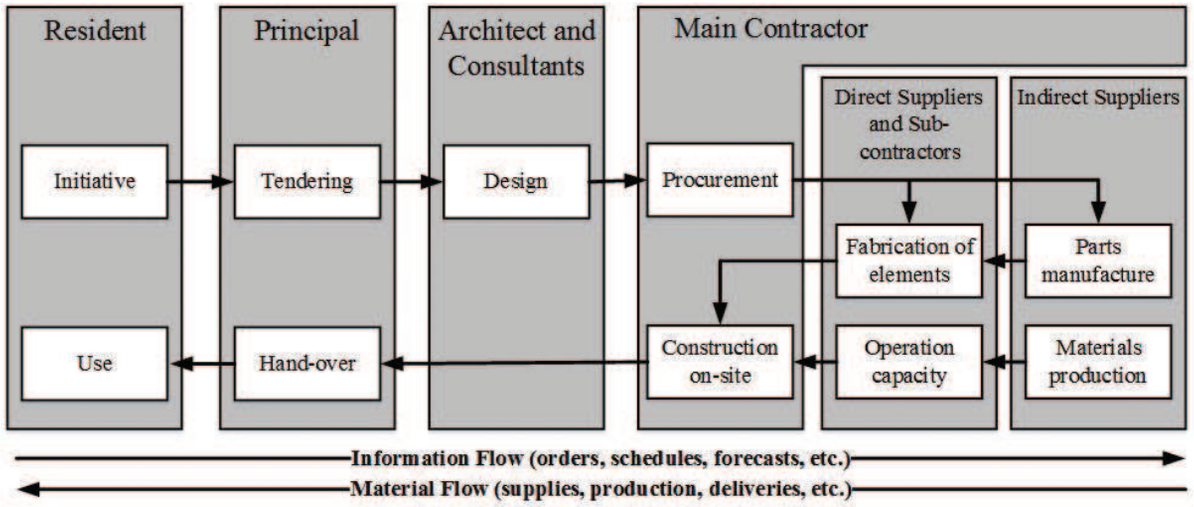


Figure 3. Typical configuration of a traditional construction supply chain (source: [7]).

According to Vrijhoef and Koskela [7], in a typical construction process as shown in **Figure 3**, principle (or client's representative) initiates the construction project and establishes a construction project organisation with the consultant, since the resident/client is not an expert. Based on the principles' instruction, architect and other consultants prepare drawings and tender documents. Once contracts and formalities are ready and information is available, contractor starts the physical execution of the construction project. Construction process includes

extraction of materials, manufacture of parts, engineering and assembly of elements and final construction on site. Normally, the main contractor takes care of employment of subcontractors and procurement of materials from suppliers.

Hence, CSC consists of all the construction business processes, from the client's initiation, briefing, conceptual and subsequent design and construction to maintenance, replacement and eventual decommission of building, where several stakeholders such as client, architect, consultant, contractor, subcontractor, supplier, etc. are involved [22]. Therefore, Xue and his co-authors stated that "CSC is not a chain of construction businesses with business-to-business relationships, but a network of multiple organisations and relationships, which includes the flow of information, the flow of materials, services or products, and the flow of funds between client, designer, contractor and supplier" [22]. The authors further defined CSCM as "the integration of key construction business processes, from the demands of client, design to construction, and key members of construction supply chain, including client/owner, designer, contractor, subcontractor and supplier" [22].

Today's global supply chains are highly complex networks and are increasingly vulnerable to disruption, which can have significant impact on company performance and shareholder's value. Due to the unique nature of the CSC, construction organisations face complex supply chain risks, and firms are under increasing pressure to manage, mitigate and transfer risks effectively. Hence, the following section presents the risks on supply chain.

4. Risks on supply chain

Supply chain risks and disruptions can be materialised either inside or outside of a supply chain and can be highly divergent [23]. Chopra and Sodhi [24] divided supply chain risks into nine categories, namely disruptions, delays, systems, forecast, intellectual property, procurement, receivables, inventory and capacity. Further, Kleindorfer and Saad [25] introduced two broad categories of risks affecting supply chain design and management. First category consists of problems of coordinating supply and demand and second category includes risks arising from disruptions to normal activities. Finch [26] classified supply chain risk into three broad categories, that is, application level, organisation level and inter-organisational level. Application level risks include natural disasters, accidents, deliberate acts, data/information security risks and management issues. Organisational level risks consist of legal and strategic changes in decision-making, while at the inter-organisational level, there is a possible uncertainty from the outside of the organisation, which could be risky. Wagner and Bode [23] considered five different classes of risks, namely demand side, supply side, regularity/legal and bureaucratic, infrastructure and catastrophic events. Vanany et al. [27] classified supply chain risks into three categories such as operational accidents, operational catastrophes and strategic uncertainty. While operational accidents are those affecting the operational processes or resources related to logistics/supply chain, operational catastrophes are risks associated with rare and difficult to predict events, but once occurred, have severe impact on the company. Strategic uncertainty is the type of risk that is generally difficult to address and affect the company not at the operational level, but strategically.

Reviewing different types of classifications of supply chain risks, it is obvious that some researchers have identified catastrophic event as one of the major potential risks in supply chain. This chapter therefore focuses on the impact of catastrophic events on the CSC.

5. Catastrophic events and supply chain management

Companies all around the world are increasingly vulnerable to high impact/low probable events [28]. Stecke and Kumar [5] showed that there has been a marked increase in the frequency and economic losses from natural and man-made catastrophes. But, Vanany et al. [27] highlighted that catastrophic events have received relatively less attention in the SCM literature. Catastrophic events have been identified under supply chain risks in various ways. The next sections of this chapter review literature on catastrophic events, their impact on supply chains and strategies introduced by past researchers to minimise their impact on supply chains.

5.1. Catastrophic events

Gilbertson et al. [29] defined catastrophic events as events that are beyond the ordinary or routine and are characterised by being of low probability but high consequence. Brindley [30] categorised potential supply chain risk based on probability and severity perspectives, and according to **Figure 4** developed by the author, catastrophic events are located in the bottom right corner.

Mitroff and Alpaslan [31] identified seven categories of catastrophes such as economic crises (recessions, hostile takeovers), physical crises (industrial accidents, product failures), personnel crises (strikes, exodus of key employees, workplace violence or vandalism), criminal crises (product tampering, act of terrorism), information crises (theft of proprietary information, tampering with company records), reputation crises (logo tampering, rumour mongering) and natural disasters (floods, fires). Wagener and Bode [23] recognised natural hazards,

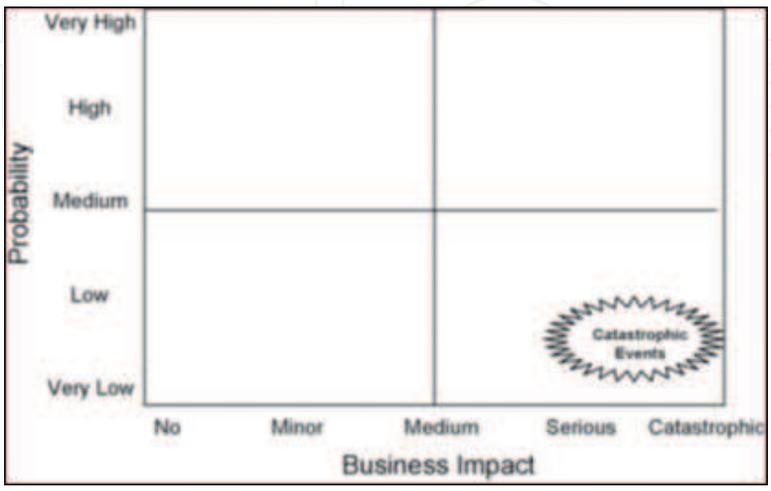


Figure 4. Risk categorisation scheme (source: [30]).

socio-political instability, civil unrest, economic disruptions and terrorist attacks as catastrophic events. Stecke and Kumar [5] broadly classified catastrophes into two main parts: man-made and natural catastrophes and further divided them into other sub groups as shown in **Figure 5**.

Gilbertson et al. [29] identified several catastrophic events that could occur during construction phase: structural collapse of permanent structure, collapse of temporary works and collapse of plant and equipment such as cranes, major fire, tunnel collapse and disruption of underground services. Further to Gilbertson et al. [29], the most significant factor, which could affect the probability of a catastrophic event in construction industry, is the failure to recognise hazardous scenarios and influencing events. Other important factors include lack of site control, interface problems with various parties, lack of checking and competent reviewing and lack of designer's involvement on site.

5.2. Impact of catastrophic events on supply chain

From time to time, frequent as well as rare catastrophes disrupt supply chain operations, and every firm's supply chain is susceptible to a diverse set of risks [1, 5]. Atley and Ramirez [2] found evidence to prove that failure to manage supply chain risks effectively may lead to a significant negative impact on organisations. Stecke and Kumar [5] found that business losses constitute a major percentage of the total losses caused by catastrophes. Cousins et al. [32] identified the wider consequences of failure to manage risks effectively. These include not only financial losses but also reduction in product quality, damage to property and equipment, loss of reputation in the eyes of customers, suppliers and the wider public and delays in delivery days. Knemeyer et al. [1] stated that if, for instance, a facility is lost due to a catastrophic event, the consequences affect supply chain operations, financial flows and possibly information flows too.

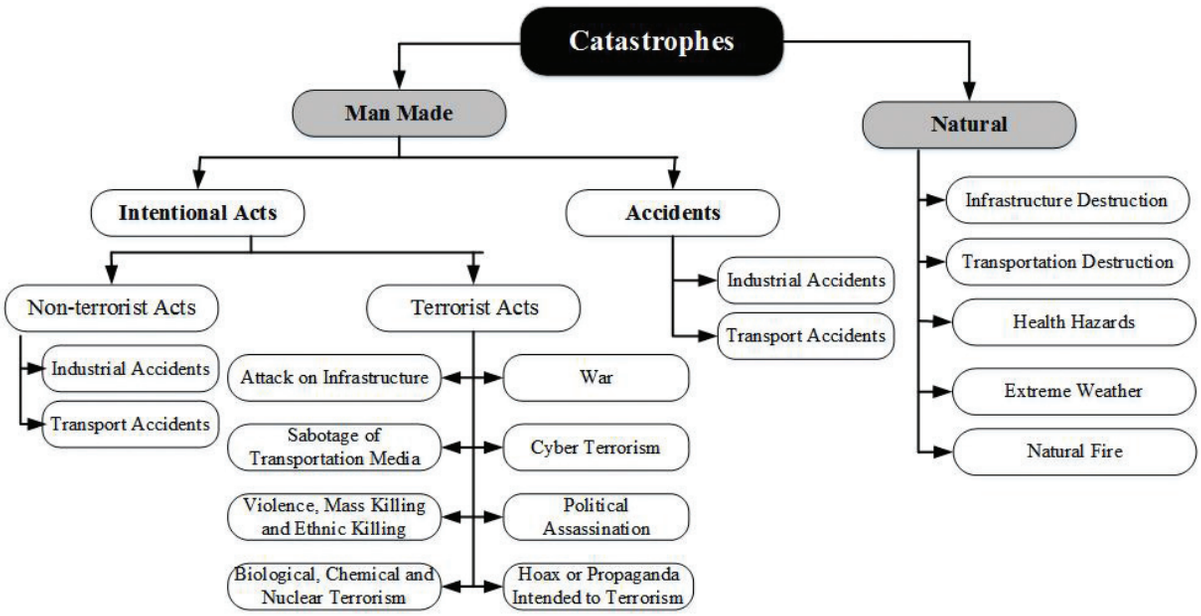


Figure 5. Classification of catastrophes (adapted from [5]).

Construction industry is also highly vulnerable to catastrophic events. The impacts of catastrophic events on construction industry include construction supply chain breakdowns, information and communication breakdowns, significant damages to property and infrastructure, increased demand for reconstruction, injuries and deaths. The aforementioned impacts lead to increase project cost and time, reduce quality and devote more management time for crisis handing. Catastrophic events may have wider implications such as extensive delay or project failure, significant business failure, loss of money and loss of reputation for all concerned [29]. Extreme weather events such as floods, hurricanes and storms have significant effects on CSC, and according to Wedawatta et al. [33], supply chain disruptions due to extreme weather events can create a substantial impact on a construction enterprise. Therefore, potential consequences of catastrophic events on CSC are wide ranging and long-lasting.

5.3. Strategies to minimise the impact of catastrophic events on supply chain

Marley [4] stated that developing strategies to mitigate disruptions has become a necessity as systems become more complex and increasingly more vulnerable to experiencing supply chain disruptions. In fact, several recent books and articles have directly focused their attention on the vulnerability of supply chains and assert the need for companies to perform a more systematic analysis of their vulnerability [1]. While many firms developed plans to protect against recurrent, low impact risks in their supply chains, there are many who ignored high-impact low-likelihood risks [24]. **Table 2** summarises the strategies introduced by researchers to minimise the impact of catastrophic events on supply chain both in manufacturing and construction industries.

Journal article	Proposed strategies
Knemeyer et al. [1]	• Identify key locations and threats • Estimate probabilities and potential loss for each key location • Evaluate alternative countermeasures for each key location • Select countermeasures for each key location
Stecke and Kumar [5]	• Proactive strategies • Advanced warning strategies • Coping strategies • Survival strategies
Tang [9]	• Postponement • Develop a strategic stock • Employ a flexible supplier base • Make and buy • Offer economic supply incentives • Flexible transportation • Revenue management via dynamic pricing • Assortment planning • Silent product rollover
Norrman and Jansson [10]	• Identify the risk • Assess the probability of risks • Assess the impact of risks • Develop strategies to implement before and after an incident

Table 2. Strategies to minimise the impact of catastrophic events on supply chain.

Norrman and Jansson [10] identified the requirement of action plan to ensure continued operations in case of a catastrophic event. Knemeyer et al. [1] proposed a proactive planning process for addressing catastrophic risks in supply chains. Researchers revealed that this method could help managers to identify key locations in their supply chain, systematically measure the risk of suffering catastrophic events at each key location and then select effective countermeasures to be adopted at selected key locations.

Stecke and Kumar [5] introduced the following four strategies to make supply chain components robust.

a. Proactive strategies—Help a company to avoid or decrease the impact of possible types of future disruptions.

b. Advanced warning strategies—Gain benefits from advance information (forecast) of a catastrophe.

c. Coping strategies—Flexibility and redundancy in various supply chain components to mitigate catastrophe.

d. Survival strategies—Aid companies to reduce losses and duration of disruptions.

Stecke and Kumar [5] stated that proactive strategies can help a company to avoid or decrease the possibility of certain types of disruptions. Researchers further emphasised that well-developed and implemented proactive strategies can reduce the need of mitigating strategies. Stecke and Kumar discussed strategies that can help in forecasting a catastrophe under the advanced warning strategies. The researchers highlighted that these advanced warning strategies can provide valuable preparation time to align its capabilities to minimise disruption effects or may allow complete prevention of a disruption. Flexibility and redundancy in various supply chain components help in defining coping strategies, which help to mitigate catastrophes [5]. A severe catastrophe and/or lack of proactive and coping strategies may result in supply chain breakdowns, which can make a company inoperative. Survival strategies can be used by companies in such situations [5]. Researchers confirm that survival strategies can be implemented in two stages: immediate response to a catastrophe (i.e. save life and property) and steps taken to recover (i.e. reorganise resources to restart supply chain operations).

Tang [9] described nine different robust supply chain strategies that aim to improve a firm's capability to manage supply and/or demand better under normal circumstance and to enhance a firm's capability to sustain its operation when a major disruption hits. The nine strategies include postponement, develop a strategic stock, employ a flexible supplier base, make and buy, offer economic supply incentives, flexible transportation, revenue management via dynamic pricing, assortment planning and silent product rollover. Tang [9] further stated that although robust supply chain strategies enable companies to deploy the corresponding contingency plans when disruption occur, these companies would become less vulnerable if they could reduce their exposure to risk. Hence, researchers proposed several possible ways to reduce the impact of disruption on the supply chain operations such as proactively form strategic alliances with other suppliers in different countries; reduce the lead time by redesigning the supply chain network and establish a recovery planning system to gain visibility of inventories, sales and shipments.

Gilbertson et al. [29] identified key factors to prevent or reduce catastrophic events in construction industry. The most effective control in reducing catastrophic events is the presence on site of knowledgeable, fully qualified, trained and competent individuals who could recognise and act upon any hazards. Another significant control is to be proactive about hazards, since many projects are complex, requiring effective teamwork, careful management and coordination. Other key controls identified by Gilbertson et al. [29] include managed interfaces, communication and cooperation and adequate resources (time and money). Researchers further confirmed that processes for diagnostic check on site as another key control factor. Most of the above controls play a significant role in minimising the impact of catastrophes [29].

In summary, the strategies developed by Stecke and Kumar [5], Tang [9] and Norrman and Jansson [10] minimise the impact of catastrophic events on supply chain in the manufacturing industry, while the strategies identified by Gilbertson and his co-workers [29] reduce the impact of catastrophic events on whole construction industry rather than construction supply chain. There is therefore a necessity to identify the strategies to minimise the impact of catastrophic events on CSC. Having considered the strategies identified by aforementioned authors, those of Stecke and Kumar [5] were used as a basis to develop a strategic framework to minimise the impact of catastrophic events on construction supply chains.

6. Research methodology

This section presents the methodology used to achieve the following objectives:

a. Identify likelihood and severity of catastrophic events and their level of risk on CSC.

b. Investigate the impact of catastrophic events on CSC and its performance.

c. Develop a strategic framework to minimise the impact of different catastrophes on CSC.

The research started with an extensive review of literature to develop a research framework to gather data for an empirical study. Different types of catastrophes affecting CSC, their impact and strategies to minimise the impact were initially identified using a literature review. The study then conducted a preliminary investigation with five construction industry experts to evaluate the applicability and suitability of literature findings to CSC context in order to develop a detailed questionnaire. Five construction project managers who have more than 20 years of experience in managing CSCs were interviewed during the preliminary investigation.

Subsequently, a research framework was developed for the empirical study incorporating the aforementioned three objectives, literature review findings and feedback given by experts during the preliminary investigation. The research framework is shown in **Figure 6**.

Catastrophic events, their impacts and impact minimisation strategies identified through literature review and preliminary investigation are summarised in **Figure 6**. Further, a detailed list of strategies identified under the aforementioned four different strategic dimensions is tabulated in **Table 3**.

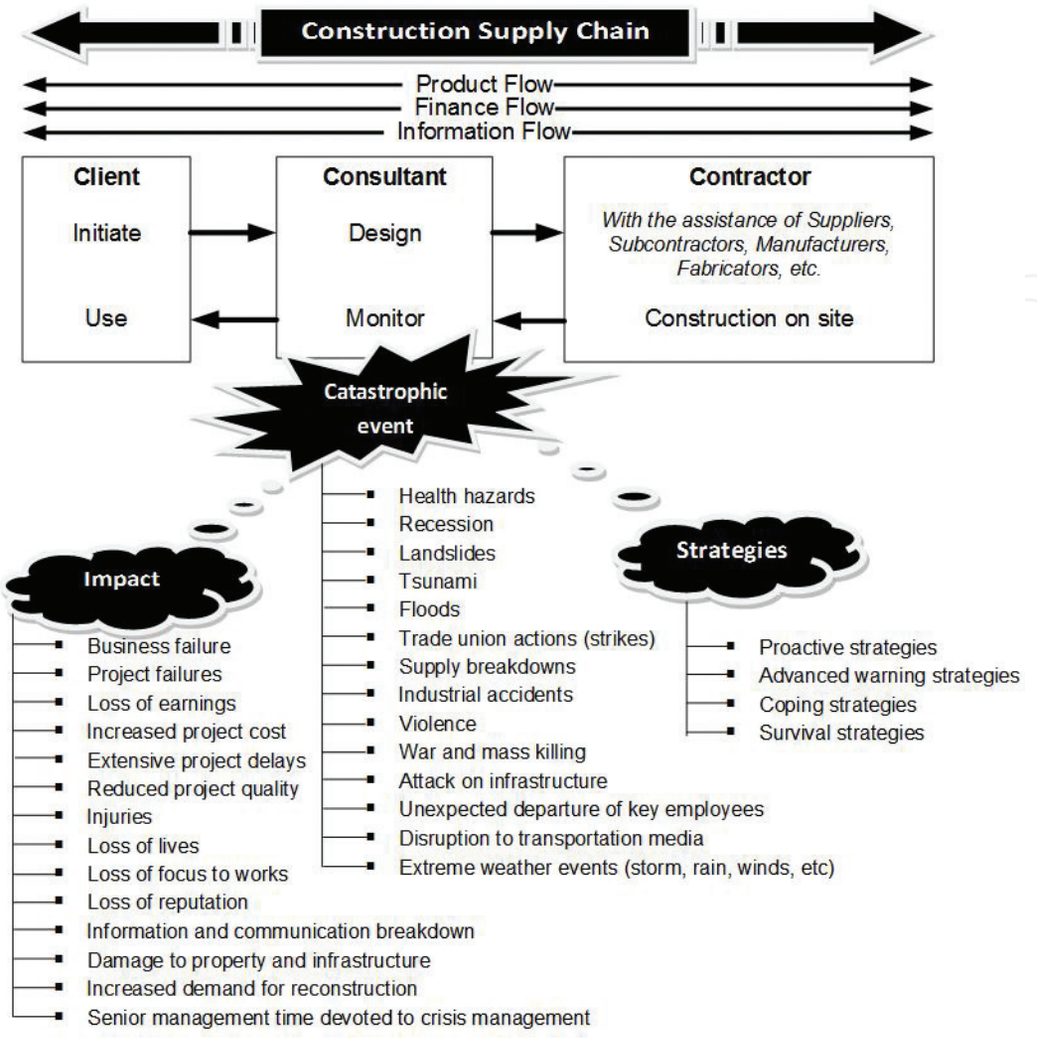


Figure 6. Research framework.

Above identified catastrophic events, impacts and strategies were used to develop a structured questionnaire for this study. The structured questionnaire was subsequently distributed among the construction industry experts in order to identify the likelihood and severity of the catastrophic events that disrupt CSC. The questionnaire survey was extended to identify significant impact of catastrophes and strategies that can be implemented to mitigate the impact of each identified catastrophes.

Construction industry experts were selected from among CS1 and CS2 grade contracting organisations in Sri Lanka, due to the complex nature of supply chain activities carried out by those companies. CS1 and CS2 are the two highest grades that can be achieved by a contractor according to the categorisation of Construction Industry Development Authority (CIDA), the regulating authority of construction in Sri Lanka. During the study, researchers requested assistance from the initial respondents to identify professionals with similar experience and/or expertise. The questionnaire was distributed among new respondents nominated by existing experts. Hence, snowball sampling method is used for this study. The questionnaires

Main strategies	Sub strategies
Proactive strategies	Identify and avoid vulnerable locations and threats Assess probabilities and impacts of risks Choose robust suppliers and manage communication and cooperation Enforce security Maintain efficient human resource management practices Maintain adequate and suitable resource base
Advanced warning strategies	Enhance visibility and coordination of supply chain Increase transportation visibility Monitor weather forecasts Monitor catastrophic trends (e.g., terrorist threat levels, strikes, recession) Monitor the progress of on-site processes
Coping strategies	Maintain flexible and alternate sourcing arrangement Choose flexible transportation Keep standardised and well-documented processes Insure against various risks Maintain redundant critical components
Survival strategies	Implement organisational emergency plans Maintain communications Keep control of the organisation at all times Identify needs to resume operations

Table 3. Strategies to minimise the impact of catastrophes on construction supply chain (adapted from [1, 5, 29]).

Designation	Number of questionnaires distributed	Number of responses received	Response rate (%)
Senior managers	7	7	100
Project managers	18	15	83.3
Planning engineers	6	6	100
Purchasing managers	4	4	100
Total	**35**	**32**	**91.4**

Table 4. Composition of participants.

were given to 35 construction industry experts and 32 responded. Composition of participants and their response rates are shown in **Table 4**.

The questions in the questionnaire were based on Likert scale format and mean weighted rating was calculated for each catastrophic event in order to identify the likelihood and severity level of catastrophic events. Furthermore, same calculation was conducted to investigate the significance of the impacts of catastrophes on CSC and to identify the strategies to mitigate the identified impact.

7. Research findings

The key findings of the survey are summarised in the discussion section, supplemented by a series of tables. Severity and likelihood of different catastrophic events that affect CSC are

discussed first, followed by risk analysis of catastrophic events and the results pertaining to the impact of those events. Finally, strategies to minimise the identified impact are presented.

7.1. Likelihood of catastrophic events

All catastrophes do not pose the same type or amount of risk to CSC. For example, war may have severe consequences such as large number of human and facility losses, while a disruption to transportation media may only affect supplies. Catastrophes such as extreme weather events and landslides may have different consequences on CSC making it difficult for construction organisations to plan their projects to face different catastrophes. Therefore, identification of severity and likelihood of catastrophes may facilitate the construction project planning process.

First part of the questionnaire is focused on the identification of likelihood and severity of catastrophic events that threaten or disrupt the CSC. The likelihood and severity corresponds to "how likely" and "how much" a catastrophe might affect the CSC.

The questionnaire used Likert scale to receive the opinion of respondents regarding the likelihood of each catastrophic event that disrupts CSC. In the particular question, respondents were asked to give their opinion about the level of likelihood based on the scale that indicates most likely—4, very likely—3, somewhat likely—2, little likely—1 and unlikely—0. The data range of this five point Likert scale is 4. Therefore, the researcher set the cut-off point at intervals of length 4/5, which is 0.8. The new guide to indicate the likelihood of a catastrophic event is unlikely (0.00–0.80), little likely (0.81–1.60), somewhat likely (1.61–2.40), very likely (2.41–3.20) and most likely (3.21–4.0). Likelihood survey findings are given in **Table 5**.

Catastrophic event	Mean	p-value	Rank	Likelihood
Unexpected departure of key employees	3.094	1.000	1	Very
Floods	2.906	1.000	2	Very
Trade union actions (strikes)	2.719	1.000	3	Very
Disruption to transportation media	2.688	1.000	4	Very
Supply breakdowns	2.531	1.000	5	Very
Health hazards	2.250	0.946	6	Somewhat
Recession	2.250	0.946	6	Somewhat
Landslides	2.000	0.500	8	Somewhat
Tsunami	1.625	0.002	9	Somewhat
Extreme weather events (storm, rain, wind, etc.)	1.625	0.002	9	Somewhat
Industrial accidents	1.594	0.001	11	Little
Violence	1.531	0.000	12	Little
War and mass killing	1.406	0.000	13	Little
Attack on infrastructure	1.313	0.000	14	Little

Table 5. Likelihood of catastrophic events that disrupt construction supply chain.

According to the survey findings given in **Table 5**, unexpected departure of key employees, floods, trade union actions, disruption to transportation media, supply breakdowns, health hazards, recession and landslides received p-values greater than 0.05. Therefore, the aforementioned catastrophic events are identified as likely catastrophic events that disrupt CSC. Most of the likely catastrophes that disrupt CSC are non-terrorist events, except disruption to transportation media. The most likely catastrophe that affects the CSC is unexpected departure of key employees followed by floods, trade union actions, disruption to transportation media and supply breakdowns. According to the ranking list, it is evident that terrorist events have very low likelihood to disrupt the CSC. Further to respondents, catastrophes such as violence, war and mass killing and attack on infrastructure are unlikely events in many countries.

7.2. Severity of catastrophic events

The survey used 1–5 Likert scale to get the respondents' opinions on the severity level of the identified catastrophic events. In the particular question, respondents were asked to give their opinion about the severity level based on the scale that depicts very high severity—5, high severity—4, average severity—3, little severity—2 and very little severity—1. This Likert scale has five severity levels and the range of the data is 4. In order to prepare a guide for indicating the severity of catastrophic events, the researchers set the cut-off point at intervals of 4/5, which is 0.8. Therefore, the severity of catastrophic events are categorised based on the guide as very little severity (1.00–1.80), little severity (1.81–2.60), average severity (2.61–3.40), high severity (3.41–4.20) and very high severity (4.21–5.00). Severity survey findings are given in **Table 6**.

Catastrophic event	Mean	p-value	Rank	Severity
Disruption to transportation media	4.406	1.000	1	Very high
War and mass killing	4.375	1.000	2	Very high
Attack on infrastructure	4.000	1.000	3	High
Tsunami	3.844	1.000	4	High
Supply breakdowns	3.719	1.000	5	High
Violence	3.656	1.000	6	High
Floods	3.625	1.000	7	High
Trade union actions (strikes)	3.625	1.000	7	High
Recession	3.563	1.000	9	High
Health hazards	3.188	0.882	10	Average
Unexpected departure of key employees	3.031	0.585	11	Average
Extreme weather events (storm, rain, wind, etc.)	2.938	0.380	12	Average
Landslides	2.844	0.096	13	Average
Industrial accidents	2.781	0.177	14	Average

Table 6. Severity of catastrophic events that disrupt construction supply chain.

All the p-values shown in **Table 6** are greater than 0.05. Therefore, all the catastrophic events that were identified from literature survey and preliminary investigation remained as severe catastrophic events that disrupt CSC. According to the ranking, terrorist events such as disruption to transportation media, war and mass killing and attack on infrastructure are moved to top of the list. It is obvious that those terrorist events have very high potential of disrupting the CSC than any other. Among the natural catastrophes, tsunami is the only catastrophe that has been selected as the severe catastrophe within the top five severe catastrophes. Industrial accident is the least severe catastrophic event that disrupts CSC.

7.3. Risk analysis of catastrophic events

Risk levels of aforementioned catastrophes are different due to the combined effect of likelihood and severity of the event. Risk analysis matrix is a way to focus managerial attention on the high priority catastrophic events that have a high possibility to occur and a high severity, if disrupt construction supply chain. The study used risk analysis matrix introduced by Scottish Government under the NHS Scotland Model for Organisational Risk Management as shown in **Figure 7** to analyse the combined effect of likelihood and severity of catastrophic events.

Table 7 shows the aggregate effect of severity and likelihood of catastrophes. This table helps to identify the risk level of each catastrophic event on CSC. The risk analysis matrix identifies suitable actions to mitigate the impact of a catastrophe based on the risk level of a catastrophe.

When comparing the rankings of likelihood and severity, it is obvious that catastrophes which have high severity are not all the time likely catastrophes that disrupt the CSC. For an example, although war and mass killing, tsunami and recession ranked among highly severe catastrophes, they are little/somewhat likely catastrophes that disrupt the CSC. According to **Table 7**, disruption to transportation media has an extreme risk level on CSC. Supply breakdown, trade union actions, floods, war and mass killing, tsunami, recession and unexpected departure of key employees have high risk level on CSC, where all the other catastrophes have medium risk level. Key catastrophes that require managerial attention are the events that ranked top of both the

	SEVERITY				
	Very Little	Little	Average	High	Very High
Most Likely	Medium	High	High	Extreme	Extreme
Very Likely	Medium	Medium	High	High	Extreme
Somewhat Likely	Low	Medium	Medium	High	High
Little Likely	Low	Medium	Medium	Medium	High
Unlikely	Low	Low	Low	Medium	Medium

Figure 7. Risk analysis matrix (source: [34]).

Event	Likelihood	Severity	Risk level
Disruption to transportation media	Very	Very high	Extreme
Supply breakdowns	Very	High	High
Trade union actions (strikes)	Very	High	High
Flood	Very	High	High
War and mass killing	Little	Very high	High
Tsunami	Somewhat	High	High
Recession	Somewhat	High	High
Unexpected departure of key employees	Very	Average	High
Health hazards	Somewhat	Average	Medium
Extreme weather event (storm, rain, wind, etc.)	Somewhat	Average	Medium
Landslides	Somewhat	Average	Medium
Violence	Little	High	Medium
Attack on infrastructure	Little	High	Medium
Industrial accidents	Little	Average	Medium

Table 7. Risk analysis matrix for catastrophes.

catastrophes, which are likely to disrupt a CSC and have a severe impact. Stecke and Kumar [5] established this idea by stating that managers should focus on mitigating catastrophes that have a high possibility and severity of affecting critical components of a supply chain. Nevertheless, it does not mean that management should not look into other catastrophic events.

7.4. Impact of catastrophic events on construction supply chain

The second objective of this research is to investigate the impact of catastrophic events on CSC. Respondents' opinions regarding the significance of the impacts of catastrophic events were collected using the 0–4 Likert scale. Survey findings are given in **Table 8**.

According to **Table 8**, all p-values are greater than 0.05, except for two impacts, that is, information and communication breakdown and injuries, which are not significant. Therefore, all the other impacts that were identified from the literature survey and preliminary investigation have significant effect on CSC. The highest significant impact that could make by a catastrophic event is a business failure followed by loss of earnings and extensive project delays.

According to **Table 8**, the impacts of catastrophic events on CSC are not only limited to financial losses. The other impacts such as senior management time devoted to crisis management, damage to property and infrastructure, increased demand for reconstruction, reduced product quality and loss of reputation are identified as significant impacts on CSC. This confirms the findings of Cousins et al. [32], where they concluded that wider consequences of a failure to manage catastrophe risks not only include financial losses.

Impact	Mean	p-value	Rank
Business failure	3.031	1.000	1
Loss of earnings	2.906	1.000	2
Extensive project delays	2.875	1.000	3
Project failures	2.875	1.000	4
Senior management time devoted to crisis management	2.781	1.000	5
Damage to property and infrastructure	2.688	1.000	6
Increased project cost	2.625	1.000	7
Increase demand for reconstruction	2.594	0.998	8
Reduced project quality	2.500	0.999	9
Loss of lives	2.406	1.000	10
Loss of reputation	2.156	0.904	11
Loss of focus to work	2.156	0.904	12
Information and communication breakdown	1.688	0.012	13
Injuries	1.438	0.000	14

Table 8. Impact of catastrophic events on construction supply chain.

7.5. Strategic framework to minimise the impact of catastrophic events on CSC

The last objective of this research is to investigate strategies and develop a framework with actions to successfully face catastrophic events to minimise their impact on CSC. The impact of catastrophes can mitigate using different strategies. Therefore, construction organisations must concentrate on different strategies to overcome the impact of different catastrophes on their supply chain. In order to develop a strategic framework, the respondents were asked to give their opinion about the effective level of each identified strategy to minimise the impact of each identified catastrophic event. Responses were based on the scale of 0—4 where 0 is very low/no effect and 4 is very high effect, and the results are given in **Table 9**.

In preparation of strategic framework to indicate the effectiveness of a strategy, the researcher set the cut-off point at intervals of length 4/5, which is 0.8. The guide to effectiveness of a strategy is very low/no effect (0.00–0.80), low effect (0.81–1.60), medium effect (1.61–2.40), high effect (2.41–3.20) and very high effect (3.21–4.00). The strategic framework developed to minimise the impact of each identified catastrophic event on CSC is shown in **Table 10**.

Depending on the type and nature of catastrophe that a company faces, managers in the construction organisations can use the findings summarised in **Table 10** as a guide to choose strategies that best fit their needs to minimise the impact of those catastrophic events on CSC. For an example, construction organisations can adopt strategies such as enhancing visibility

and coordination of CSC, maintaining flexible and alternative sourcing arrangements and identification of needs to resume operations to minimise the impact of disruption to transport media caused by catastrophes on CSC. Further, construction organisations can implement (a) proactive strategies such as maintain adequate and suitable resource base, (b) advanced warning strategies such as enhance visibility and coordination of supply chain, (c) coping strategies such as maintain flexibility and alternate sourcing arrangement and maintain redundant critical components and (d) survival strategies such as identify needs to resume operations to minimise the impact of catastrophes on construction supply breakdowns.

Construction organisations can further strengthen their CSCs with advanced warning strategies such as monitoring weather forecasts on extreme weather events, floods, landslides and tsunami to successfully face disasters or minimise the post disaster impact on CSC. As coping strategies, this study highly recommends the construction organisations to obtain insurance policies to minimise the impact of catastrophes such as attack on infrastructure, war and mass killing, violence, tsunami, extreme weather events, floods, landslides and industrial accidents and to recover quickly the aftermath of disasters. Further, advanced identification of basic needs to resume construction operations aftermath of a disaster can be recognised as a highly effective survival strategy, which construction organisations must concentrate in order to successfully commence their businesses after catastrophes.

Strategies	Catastrophic Events													
	Attack on infrastructure	War and mass killing	Violence	Disruption to transportation media	Health hazards	Tsunami	Extreme weather events	Floods	Landslides	Industrial accidents	Trade union actions	Recession	Supply breakdown	Unexpected departure of key employees
Identify and avoid vulnerable locations and threats	2.50	3.13	3.00	2.25	2.50	2.50	1.75	2.50	3.50	2.50	1.06	1.28	2.25	1.69
Assess possibilities and impacts of risks	2.75	2.00	2.00	1.75	1.75	1.50	1.25	1.50	0.75	1.25	1.59	1.75	2.28	1.78
Choose robust suppliers & manage communication & corporation	1.75	1.75	1.75	2.00	0.63	1.25	1.06	0.41	0.25	1.06	2.00	1.75	2.06	2.00
Enforce security	3.25	2.75	3.38	1.25	0.13	0.19	0.16	0.16	0.13	1.25	1.50	0.13	0.16	0.16
Maintain efficient human resource management practices	0.28	0.16	0.72	0.13	2.00	0.09	0.25	0.25	0.22	0.59	3.28	0.53	0.28	3.63
Maintain adequate and suitable resource base	1.81	0.31	0.22	1.75	1.94	0.94	0.75	0.53	0.41	1.28	2.00	3.00	3.25	2.63
Enhance visibility and coordination in a supply chain	0.13	0.19	0.22	3.38	0.38	0.19	0.19	0.19	0.16	0.19	0.16	0.19	3.75	0.16
Increase transportation visibility	0.00	0.00	0.00	2.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.06	0.00
Monitor weather forecasts	0.00	0.00	0.00	0.38	0.91	3.66	3.81	4.00	3.09	0.00	0.00	0.00	1.25	0.00
Monitor catastrophic trends	0.00	0.00	0.00	1.22	0.00	0.00	0.00	0.00	0.00	0.00	0.38	1.50	1.68	0.75
Monitor the progress of on-site processes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.09	1.38	0.16	1.50	0.47
Maintain flexible and alternate sourcing arrangement	2.34	1.75	1.75	3.25	3.75	1.25	1.59	1.59	1.25	1.75	3.63	2.19	3.84	3.84
Choose flexible transportation	0.25	0.97	0.41	3.03	0.09	0.66	0.50	1.06	1.00	0.25	0.00	0.00	2.59	0.00
Keep standardised and well documented processes	1.00	0.75	0.75	2.72	2.00	0.41	0.50	0.38	0.25	1.75	1.25	1.25	1.47	2.50
Insure against various risks	3.75	3.78	3.72	1.63	2.75	3.78	3.78	3.78	3.75	3.75	1.16	0.75	1.50	0.03
Maintain redundant critical components	1.31	0.00	0.00	3.72	1.06	0.00	0.00	0.06	0.00	0.91	2.31	2.00	3.88	1.13
Implement organisational emergency plans	2.75	2.88	2.63	1.75	2.50	2.25	2.16	2.47	2.22	3.00	2.84	1.91	2.56	2.44
Maintain communications	2.81	2.50	2.50	1.66	0.34	2.75	2.06	2.56	1.72	1.66	1.25	1.38	1.69	1.25
Keep control of the organisation at all times	0.25	0.50	0.53	1.75	1.50	0.44	0.44	0.44	0.41	3.00	3.25	1.81	2.25	3.41
Identify needs to resume operations	2.25	3.47	3.31	3.25	3.41	3.59	3.47	3.56	3.28	3.88	3.88	3.09	3.41	2.84

Table 9. Mean values of effectiveness of the strategies to mitigate the impact of catastrophic event on construction supply chain.

			Catastrophic events													
			Attack on infrastructure	**War and mass killing**	**Violence**	**Disruption to transportation media**	**Health hazards**	**Tsunami**	**Extreme weather events**	**Floods**	**Landslides**	**Industrial accidents**	**Trade union actions**	**Recession**	**Supply breakdown**	**Unexpected departure of key employees**
Strategies	Proactive strategies	Identify and avoid vulnerable locations and threats	H	H	H	M	H	H	M	H	VH	H	L	L	M	M
		Assess possibilities and impacts of risks	H	M	M	M	M	L	L	L	VL	L	L	M	M	M
		Choose robust suppliers & manage communication & corporation	M	M	M	M	VL	L	L	VL	VL	L	M	M	M	M
		Enforce security	VH	H	VH	L	VL	VL	VL	VL	VL	L	L	VL	VL	VL
		Maintain efficient human resource management practices	VL	VL	VL	VL	M	VL	VL	VL	VL	VL	VH	VL	VL	VH
		Maintain adequate and suitable resource base	M	VL	VL	M	M	L	VL	VL	VL	L	M	H	VH	H
	Advanced warning strategies	Enhance visibility and coordination of supply chain	VL	VL	VL	VH	VL	VL	VL	VL	VL	VL	VL	VL	VH	VL
		Increase transportation visibility	VL	VL	VL	H	VL	VL	VL	VL	VL	VL	VL	VL	M	VL
		Monitor weather forecasts	VL	VL	VL	VL	L	VH	VH	VH	H	VL	VL	VL	L	VL
		Monitor catastrophic trends	VL	VL	VL	L	VL	VL	VL	VL	VL	VL	VL	L	M	VL
		Monitor the progress of on-site processes	VL	VL	VL	VL	VL	VL	VL	VL	VL	M	L	VL	L	VL

		Catastrophic events													
		Attack on infrastructure	**War and mass killing**	**Violence**	**Disruption to transportation media**	**Health hazards**	**Tsunami**	**Extreme weather events**	**Floods**	**Landslides**	**Industrial accidents**	**Trade union actions**	**Recession**	**Supply breakdown**	**Unexpected departure of key employees**
Coping strategies	Maintain flexible and alternate sourcing arrangement	M	M	M	VH	VH	L	L	L	L	M	VH	M	VH	VH
	Choose flexible transportation	VL	L	VL	H	VL	VL	VL	L	L	VL	VL	VL	H	VL
	Keep standardised and well-documented processes	L	VL	VL	H	M	VL	VL	VL	VL	M	L	L	L	H
	Insure against various risks	VH	VH	VH	M	H	VH	VH	VH	VH	VH	L	VL	L	VL
	Maintain redundant critical components	L	VL	VL	VH	L	VL	VL	VL	VL	L	M	M	VH	L
Survival strategies	Implement organisational emergency plans	H	H	H	M	H	M	M	H	M	H	H	M	H	H
	Maintain communications	H	H	H	M	VL	H	M	H	M	M	L	L	M	L
	Keep control of the organisation at all times	VL	VL	VL	M	L	VL	VL	VL	VL	H	VH	M	M	VH
	Identify needs to resume operations	M	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	H	VH	H

Effectiveness guide: Very low/no effect (VL), low effect (L), medium effect (M), high effect (H), and very high effect (VH).

Table 10. Strategic framework to minimise the impact of catastrophic event on construction supply chain.

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8. Conclusions and recommendations

Catastrophic events are unique among other supply chain risks due to low probability of occurrence, difficulty in prediction and severity of impact. Vulnerability of CSC for various types of catastrophic events has been substantiated in the literature.

Majority of the catastrophes, which were ranked among the most likely catastrophes to disrupt CSC, are non-terrorist events. Findings corroborated the fact that most likely catastrophes to disrupt the CSC are not always the most severe catastrophes. Among the likely catastrophes, unexpected departure of key employees in construction organisations was identified as the most likely catastrophic event to disrupt CSC, and disruption of transportation media was identified as the most severe catastrophic event, which has high impact on CSC. The aggregate effect of likelihood and severity revealed that disruption to transportation media has the extreme risk level on CSC, whereas violence, attack on infrastructure and industrial accidents have medium risk level. All the other catastrophes have high risk level on CSC.

The study further identified that the impact of such catastrophes is highly diverse and has different effects on CSC performance. According to the findings, the most significant impact of catastrophic events is a business failure and least significant impact is loss of focus to work.

The research finally established the need to implement strategies not only after catastrophe occurs but also before the catastrophe in order to avoid severe consequences on construction organisations. This chapter hence presented the strategic framework developed with four strategic dimensions: (a) proactive strategies, (b) advanced warning strategies, (c) coping strategies and (d) survival strategies in order to minimise the impact of each identified catastrophic event on CSC of construction organisations. The catastrophic event risk minimisation strategic framework developed in this study would be useful for construction organisations to identify suitable strategic actions according to the risk level that they faced. The organisations in construction industry can use the proposed strategic framework to minimise the impact of future catastrophic events on CSC for creating resilient construction industry.

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