Managing complexities in the integration of supply chain risks and resilient capabilities for construction projects

By

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(NUST2018MSCEM00000274148)

A synopsis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Construction Engineering and Management

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(2022)

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ACKNOWLEDGEMENTS

Thanks to ALMIGHTY ALLAH, THE BENEVOLENT, AND THE MERCIFUL, who gave me strength and courage to complete my research.

I would like to extend my gratitude towards my advisor Dr. Khurram Iqbal Ahmad Khan for his persistent guidance that greatly motivated me for the completion of my thesis. I want to thank my family, especially my mother, for supporting me in every possible way to achieve this and every chapter of my life. I owe my gratitude to my committee members Dr.-Ing Abdur Rehman Nasir and Dr. Muhammad Usman Hassan for their support.

ABSTRACT

More complex the supply chain (SC), more difficult it becomes to mitigate its associated risks. It is, therefore, important to manage the complexities in integration of SC risks and resilient capabilities (RCs) for a resilient SC. This study investigated the complexity involved in the dynamics of effects between organizations' SC risks and RCs to overcome disruptive events. Past researchers investigated how to improve the performance of construction projects, regardless of the complexities and interdependencies associated with the risks across the entire SC. Limited work using the system dynamics (SD) approach to describe the diversity of construction SCs under risks indicated a research gap that is pursued by this study. This work aimed to analyze and establish interconnectivity and functionality amongst the construction SC risks and RCs using systems thinking (ST) and SD modeling approach. SD technique is used to assess the complexity and integrated effect of SC risks on construction projects to enhance their resilience. The risks and RCs were identified by critically scrutinizing the literature and were then ranked through content analysis. Questionnaire surveys and expert opinions (involving 10 experts) helped develop causal loop diagrams (CLDs) and SD models with simulations to assess complexity qualitatively and quantitatively within the system. Research reveals that construction organizations are more vulnerable to health pandemics, budget overruns, poor information coordination, insufficient management oversight, and error visibility to stakeholders. Further, the most effective RCs include assets visibility, collaborative information exchange, business intelligence gatherings, alternative suppliers, and inventory management systems. This research helps industry practitioners identify and plan for various risks and RCs within their organizations and SCs. Furthermore, it helps understand trade-offs between suitable

RCs to abate essential risks and develop preparedness against disruptions to improve organizational policy-making, project efficiency, and performance.

Keywords: Construction supply chain; resilient capabilities; simulation modeling; supply chain resilience; supply chain risks; system dynamics.

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LIST OF ABBREVIATIONS AND ACCRONYMS

CLD	Causal Loop Diagram
RC	Resilient Capabilities
SC	Supply Chain
SD	System Dynamics
ST	System Thinking

Chapter 01

INTRODUCTION

1.1 Brief Overview

Increased globalization and high regard for innovation has made the modern supply chains more complex, uncertain and interdependent, resulting in a great widespread of interrelated risks with respect to inter as well as intra-organizational perspective (Abidin and Ingirige, 2018a). Although this interconnectedness and advancement in global economy unfolds numerous benefits and ensures better living standard in various developed countries but have intensified the supply chains risks to the greater extent (Kosansky and Taus, 2014). Various types of risks are present worldwide including socio-economical risks, political risks, technological risks, natural disasters and other contingencies. These risks have made difficult for the organizations to understand and confront every single aspect of this global marketplace thus a small negligence can make them suffer their whole life (Swedberg, 2010). In such widespread world where every industry is interconnected with other industries in one way or the other, risks are ahead of any single organization's control. A small error by one organization will not only harm itself but can send cascading effects out into the other sectors and can become the primary cause of their disruption as well (Wildgoose, 2011).

Construction industry is one of the industries that is operated by supply chain and suffers a lot because of interdependent risks. Such risks provide basis for deviation from project objectives and thus, poor overall project performance causes other great losses in requisites of quality, time, and cost (Le-Hoai et al., 2008a, Mehdi Riazi et al., 2011). Great work has been done in the past about how to improve performance of projects in construction industry (Le-Hoai et al., 2008b, Osei-Kyei and Chan, 2017) but those studies failed to focus on the complexities associated with risks and their interdependencies across entire supply chain. Transient nature of the project-based supply chain with interrelated risks makes interdependencies of the construction supply chains unique as compared to the other industries (Loosemore and Teo, 2000). Similarly, highly fragmented construction industry is reducing the organizations' visibility to identify risks that may take place within the supply chain network.

To handle complexities and interdependencies, which are gradually increasing day by day, within the supply chain is actually a very challenging task for a single entity. Consequently, to overcome disruptions mutually it is important for an entity to carefully explore the dynamics of the effects between its prevailing risks and resilient capabilities. The main challenge is to make systems resilient enough so that they not only survive the disruptive events but continue to make progress as well in a stable state. By evaluating the supply chain risks and resilient capabilities of construction industry in developing countries we can provide better awareness regarding disruptions and necessary actions required to alleviate them in order to enhance projects performance.

1.2 Research Gap

Past researchers aimed to improve the performance of construction projects but didn't paid attention to the complexities linked with supply chain risks and their interdependencies across entire supply chain (Le-Hoai et al., 2008b, Osei-Kyei and Chan, 2017). The intersection between risk management and resilience related to supply chain is clearly indicated in the previous studies (Mandal, 2012) but are not linked with construction industry. Similarly some discussed the resilience, considering the perspective of a single organization (McManus, 2008, Pettit et al., 2013, Zsidisin and

Wagner, 2010) but only few tried to communicate value of resilience against disruptive events, reviewing cascading effects of vulnerabilities and capabilities of supply chain on entire system (Abidin and Ingirige, 2018a) but are mostly related to Malaysian construction industry. Pre-disruption risk management processes were the main concern of the construction industry in past (Goh et al., 2013, Siang and Ali, 2012). There is a clear lack of literature figuring out the sources of 'actual disruptions' in construction supply chains. Wedawatta and Ingirige (2016) presented the theoretical framework to illustrate the resilience of medium sized construction firms against extreme weather events. An experimental study to inspect the resilience of supply chain in a disruptive global event is done by Juttner and Maklan (2011) to explore the bond of resilience with the related concepts of vulnerability and risk management in supply chain. The dynamics of the complex relationships between the organizations' risks and capabilities to mitigate disruptive events collectively still demands to be deeply analyzed. Li et al. (2016) used system dynamics to analyze the effects of risks and risk mitigation scenarios in chemical supply chain transportation, Peng et al. (2014) researched the effects of post-seismic supply chain disruptions on inventory and transportation in supply chains and Keilhacker and Minner (2017) used system dynamics simulation model to test strategies to mitigate risks in different situations for a rare earth elements supply chain. Henceforth, a very little work is done to build a resilient supply chain in construction sector using system dynamics approach (Oliveira et al., 2019).

Regarding the construction and other engineering supply chain sectors disruptions and resilience in 2021, latest report issued by Business Continuity Institute clearly explains that overall supply chain disruptions faced by the organizations in 2020 were higher than any other year in the report's history and the organizations have held COVID-19 responsible for this intense upsurge. Major challenge during 2020 was logistics; transport network disruptions affected most of the organizations. However, some conventional disruptions like adverse weather, cyber-attack and natural disasters still held eminent place in the table this year (Business Continuity Institute, 2021).

There arises the need of 'Risk resilience approach' (Kinman, 2012) for construction supply chains because if organizations wanted to survive in this uncertain global marketplace, they should integrate the resilience within their risk management approach. The above discussion makes us certain that, resilience is an important aspect of supply chain management. For a single entity it is actually a very challenging task to handle the interdependencies within the supply chain because complexities are gradually increasing day by day. Therefore, to investigate the dynamics of effects between supply chain risks and resilient capabilities of an organization is very important to mutually overcome disruptive events in the construction industry.

1.3 Problem Statement

Supply chains rule most of the construction industry and if risks related to supply chain management not managed properly, as discussed above, can transmit disruptions into other related industries as well. Furthermore, resilience discipline is still being explored in the construction sector (Pettit et al., 2013, McManus, 2008, Stephenson, 2010).

Thus the fact that; a very little research work in the construction sector using system dynamics approach (Oliveira et al., 2019) to characterize the diversity, dynamism and complexity of supply chains under risks to make resilient supply chain, comes up with an important research questions that:

1. What are the complexities involved in integrating critical risks related to SC management and RCs? and,

2. How to build a resilient SC in construction industry using a SD approach?

The dynamics of complex relationships between the organizations' SC risks and RCs to mitigate disruptive events collectively still demands to be deeply analyzed in the construction industry, and this study is basically meant to target this research gap.

The novelty of this research lies in the evaluation, integration and quantification of construction SC risks associated with organizations, technology and human factors and RCs in order to make a resilient SC. A very limited literature is available regarding the understanding of interrelationships among SC risks, RCs, their complexity and dynamics. Furthermore, resilience discipline is still being explored in the construction sector (Pettit et al., 2013, McManus, 2008, Stephenson, 2010). This study investigated the complexity involved in dynamics of effects between organizations' SC risks and RCs, using ST and SD modeling approach, to enhance system's resilience and to overcome disruptive events collectively. This work aimed to analyze and establish interconnectivity and functionality amongst the risk factors and RCs qualitatively by the formation of CLDs (reinforcing and balancing loops) and later SD modeling and simulations were run to assess the complexity within the system quantitatively.

1.4 Research Objectives

The research aims to provide clear insight to the industry practitioners about the importance and interdependencies among critical risks and trade-offs between the most appropriate capabilities required to mitigate key risks to build a resilient supply chain and for continual improvement in such highly competitive industry. To accomplish the research aim, following objectives are identified:

1. To analyze the risks associated with the construction supply chain management.
2. To identify the capabilities necessary for a resilient supply chain, tailoring risks associated with supply chain management.
3. To establish the interconnectivity and functionality amongst the identified factors in SC management, through System Thinking.
4. To assess the complexity and evaluate the integrated effect of supply chain risks and capabilities for a resilient supply chain, through System Dynamics approach.

1.5 Research Significance

This research essentially bridges the literature gap in addressing criticality of construction supply chain management risks from resiliency perspectives using system dynamics approach. This study utilizes an integrated approach to evaluate SC's reaction to disruptions alongside three disruption phases considering pro-active and reactive risk management strategies to improve the construction SC performance thus adding a holistic view to the existing construction literature. It will help the construction industry practitioners to understand major SC risks. It includes their inter-connectivity and how they consequently transfer cascading impacts throughout an entire SC. It also includes the ability to get rid of them gradually, by understanding trade-offs between suitable RCs to abate essential risks, to develop their preparedness against disruptions in order to improve their decision making, project efficiency and performance and system resilience.

This research can be applied to any of the following fields of study; Supply Chain Management, Complex Systems and Dynamics, Supply Chain Risk and Resilience Management in construction industry.

1.6 Relevance to National Needs

Very limited research has been done to build a resilient supply chain in Pakistan's construction industry. Thus this work will not only highlight the key risks and resilient capabilities that really do affect efficiency and effectiveness of entire construction supply chain but, will also provide the deep understanding of their complex inter-relationships quantitatively using system dynamics approach to form a resilient supply chain, enhance organizations' performance as well as our economy, much needed by the construction industry of Pakistan and will also benefit our industry practitioners, the academic theoreticians and society as well.

1.7 Organization of Thesis

The research is structured into five chapters. Basic outline is given as follows:

Chapter 01 – Introduction: It contains the background of the research along with problem statement, objectives, research significance as well as its relevance to national needs.

Chapter 02 – Literature Review: It contains brief overview about disruptions and resilience in supply chains accompanied by the comprehensive review about various risks related to construction supply chain management, important capabilities mandatory for a resilient supply chain, the systems thinking concept to understand interconnectivity between risks and resilient capabilities and the system dynamics approach for managing complexity.

Chapter 03 – Research Methodology: The complete research design and methodology with the purpose to achieve research objectives is explained in this chapter. The research methodology consists of four major phases. Phase 01 consists of identification of research gap, problem statement and formulating the research objectives. Phase 02 consists of detailed literature review including identification of different risks confronted by supply chain management in the construction industry and capabilities required to mitigate these risks to form a resilient supply chain and enhance system performance. Phase 03 consists of formulating the final questionnaire for study, data collection and its analysis. Finally, in Phase 04 the causal loop diagrams and system dynamic model is established, along with final conclusions and recommendations.

Chapter 04 – Results and Analysis: This chapter contains in depth analysis of system dynamics approach implemented in this research. The causal loop diagram along with system dynamics model is presented and explained in detail.

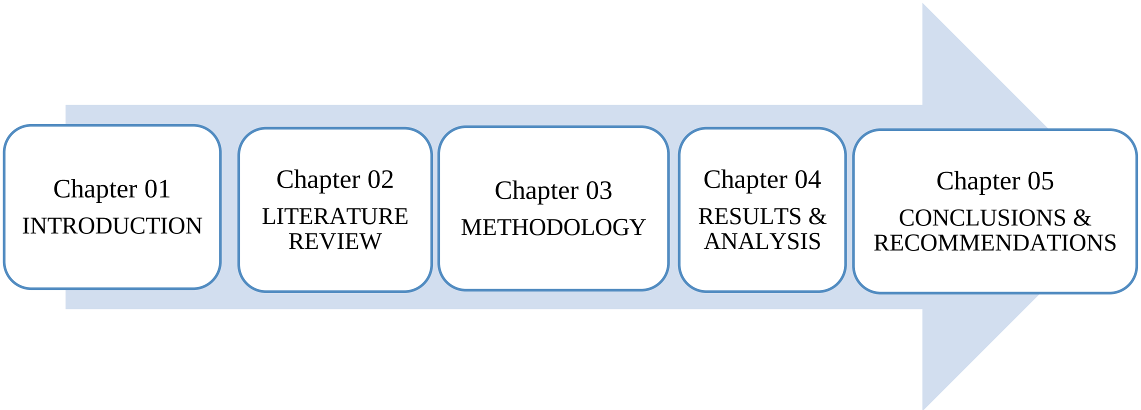

Figure 1.1 Organization of Thesis

Chapter 05 – Conclusions and Recommendations: The last chapter consists of significant findings and conclusions of whole research by revisiting its objectives along with some limitations and future recommendations for further research as well. References and appendices are presented in the end.

Chapter 02

LITERATURE REVIEW

2.1 Introduction

Chapter 02 involves a comprehensive review of different research articles meant to figure out various risks faced by the construction industry to make supply chain resilient through system dynamics approach. It begins with the literature analysis of various supply chain risks followed by explanation of term resilience and its different capabilities used to manage identified risks in construction industry. Finally, concept of complexity and system dynamics approach for managing the inter-relationships between risks and resilient capabilities is presented. This chapter fits in all the important data required for detailed and enhanced grasping of various concepts required to complete the research study.

2.2 Supply Chain Disruptions

Disruptions confronted by supply chains have created the interest of different researchers in this field. A spontaneous and unforeseen incident in supply chain which usual stream of materials and goods is interrupted is known as supply chain disruption (Svensson, 2000, Kleindorfer and Saad, 2005, Hendricks et al., 2009).

Such disturbances were stated by few researchers as “risks” whereas some referred them as “disruptions, errors, uncertainty or crisis” (Chopra and Sodhi, 2004, Ponomarov and Holcomb, 2009, Mason-Jones and Towill, 1998, Loosemore and Teo, 2000, Love and Smith, 2016). This research refers these disturbances as disruptions, an unplanned or unexpected event (Barroso et al., 2008) affecting the normal working of supply chain. The disruptions in supply chain is like chain reaction where if one chain is broken it affects all the other members of that chain in one way or the other, same is the case with the supply chains; affecting the flow of materials and thus, the performance of whole system. Presence of such disturbances having an adverse effect on supply chains is obvious and certainly supply chains are at risk (Craighead et al., 2007).

In highly fragmented construction sector, supply chain is divided into upstream and downstream relations. With respect to the main contractor on site, upper stream involves relationships with client and design team, whereas downstream involves the relationship with suppliers, sub-contractors or specialty contractors (Akintoye et al., 2000). Such division is reducing organizations' visibility to identify risks within supply chain network. Whenever, a disruption occurs internally or externally, it in turn affects various nodes or links of the entire complex network (Taylor, 2000). The bull whip effect explains this phenomenon that; a little demand variation in one tier of supply chain will amplify itself from tier to tier and ultimately disturb the operational flow (Lee et al., 1997). Tier 1 involves the relationship of main contractor with client and design team. Tier 2 involves subcontractors (suppliers) having straight link with tier 1. Similarly, tier 2 subcontractors have direct relationship with tier 3 and maximum of four or five layered tiers are involved as it makes the system more complex. Although the past reports Latham et al. (1994), Egan (1998) have explained that the complex, interdependent and fragmented nature of construction industry have great influence over supply chains performance and efficiency (Abidin and Ingirige, 2018a) but still in this era developing countries, like Pakistan, are very much concerned about these issues. Therefore, this research studies the disruptions faced by the organizations' supply chain together with their partners to understand viewpoint of everyone in the field along with measuring balanced impact of each disruption on whole system.

“Supply chain risk management is the identification of potential sources of risk and implementation of appropriate strategies through a coordinated approach among supply chain risk members, to reduce supply chain vulnerability” (Jüttner et al., 2003). Great work has been done in the past about how to improve performance of the construction projects (Le-Hoai et al., 2008b, Osei-Kyei and Chan, 2017) but those studies failed to focus on the complexities linked with risks along with their interdependencies across entire supply chain. It is very important to understand how to handle such risks in order to succeed. Most of the researchers have done significant work in the fields of automotive, gas, oil (Behdani, 2013), retail (Oke and Gopalakrishnan, 2009) and manufacturing (Xiao and Yang, 2008) but the work related to the risks faced by the construction supply chains in the developing countries have not gotten much attention.

Disruption management processes are classified in 03 categories: “pre-disruption, during disruption and post-disruption.” Pre disruption is a proactive response devising ways and necessary actions in order to mitigate the known risks. Billa et al. (2006) have done work for the flood disaster management to aware people from the upcoming floods by making forecast with the help of collected data. Sheffi and Rice Jr (2005), Cockram and Van den Heuvel (2012) believes that if each participant of the supply chain develops the ability to foresee risks at pre-disruption phase, it will help the entire system to nullify or lessen the effects of crisis. This proactive approach is very much similar to the risk management approach and was the main concern of the construction industry in past (Goh et al., 2013, Siang and Ali, 2012).

Berg et al. (2008) worked on “reactive supply chain risk handling” to evaluate efficiency of risk management process during this phase by judging from the fact that how much time was taken to handle the disruption and how well the proactive plans were followed to mitigate the disruption but as the project proceeds the supply chains become more complex and its participants also increases from phase to phase thus, transfer of risks among different members makes this whole process very uncertain, complex and interdependent. Realization of prevailing risks and using the existing capacities to mitigate those risks have not gotten much consideration in literature (Abidin and Ingirige, 2018a). There is a clear lack of literature figuring out the "actual disruptions" in construction supply chains (Sheffi and Rice Jr, 2005). Thus, there arises the need for alternative measures besides the traditional procedures to tackle unexpected risks to measure supply chains competence (Camerer and Kunreuther, 1989).

Post-disruption is healing and learning phase, signifies the importance of how to resume the system as usual and how to deal with the after-effects of the disruptions (Cockram and Van den Heuvel, 2012). Corrective measures, like feedback procedures and policy reviewing, are required by any organization in order to mitigate the effects of disruption, prevent future loss or further similar disruptions. Therefore, a key step for making supply chain more resilient (Pyke and Tang, 2010). Research work of Busby and Zhang (2008) proposed that an integrated approach is very much needed in order to understand what the prevailing risks are and how to tackle them during disruption and post disruption with an effort to make system stronger and more stable. Pyke and Tang (2010) stated such an approach to improve efficiency of supply chains known as "3R framework"; that explains the relationships between three phases of disruption. The only problem in framework was; its steps were unclear with less detail and was related to a peculiar disruption (Abidin and Ingirige, 2018a), thus a study was needed to explain the inter-relationships among wide range of disruptions that can affect construction supply chains and how to deal with them collectively.

Sheffi and Rice Jr (2005) also introduced an integrated process with eight steps to manage disruptions. They have properly evaluated the performance and state in which an organization was and is before and after the disruption to analyze the consequences of disruption. But Abidin and Ingirige (2018a) indicated that the capabilities needed by the organization to improve its efficiency at different phases of disruption are not specified in this process. Consequently, still there is the need to incorporate the risks and capabilities together to help supply chain members to understand their complex and interdependent relationships and their effects on an organization; to form supply chain more resilient.

Today's complex, uncertain and interdependent construction industry is such a place where most of the risks are unpredictable, typical risk management practices seem ineffective because they merely rely on risk identification and statistical information (Fiksel et al., 2015). There is an urge to develop such effective and efficient supply chain capabilities that can help to resist as well as withstand disruptions, without losing the entire supply chain stability. In short, there is the need of integrated approach to evaluate supply chain's reaction to disruptions alongside three disruption phases. Pro-active risk management plan that is being made in pre-disruption phase is put into action during disruption and post-disruption phase involves all the necessary actions required to improve the construction supply chain performance, bring it into a better state and make it more resilient.

2.3 Supply Chain Risks

"Risk focuses on the likelihood and severity of the after-effects of disruption." It discloses such features of the supply chain that needs proper attention in order to function properly and to make system resistant and stable after disruption. Spontaneous or unexpected disruptions occurring in the supply chains that cause variations in as-per-planned tasks of the system are termed as risks (Svensson, 2000). Risks arise from the disruptive events occurring within the system as well as in its surroundings (Christopher and Peck, 2004). "Supply chain risk is a function of certain supply chain characteristics and that the loss a firm incurs as a result of a given supply chain disruption" (Wagner and Bode, 2006). More precise and comprehensive definition of supply chain risks was given by Pettit et al. (2010b): "fundamental factors that make an enterprise susceptible to disruptions." Thus, decreasing the likelihood and severity of such factors can ultimately help an organization in making supply chain more resilient and more stable (Sheffi and Rice Jr, 2005). Various supply chain risks have been very well addressed by different researchers in the past.

Supply chain risks can be divided in 03 groups: supply risks, demand risks and supply chain structure risks. The supply risks are connected to supply base and the supplier (portfolio, financial status, entire network among different suppliers). Demand risks are mainly related to the customer needs and a slight change in them can affect project performance in terms of cost and time overruns. Demand risks are elements of downstream operations in supply chain which involves the customer (financial status), the product (lifecycle, features), the distribution and transportation systems adapted to serve the end customers (Svensson, 2000, Wagner and Neshat, 2010). Finally, the supply chain structure risks arise due to the disintegrated supply chains. Modern era supply chains are very fragile (Zsidisin et al., 2005) and their urge to deal with more international markets renders them more susceptible to disturbances.

Conversely, supply chain risks have been grouped in seven main categories by (Pettit et al., 2010b) which are further divided into 39 subfactors: turbulence (i.e. natural disasters, price fluctuations, political instability); threats (i.e. theft, terrorism); connectivity (i.e. inter-relationships with external entities); external pressures (i.e. innovation and price pressures from competitors); resource limits (i.e. production and distribution capacity and suppliers availability); sensitivity (i.e. product and process reliability); and supplier or customer disruptions.

Other researchers classified supply chain risks as financial risks (i.e. price fluctuations, price pressures); operational risks (i.e. supplier disruptions, products availability); strategic risks (i.e. vast supply network, unproductive planning); hazards risk (i.e. natural disasters) (Blos et al., 2009, Perez-Franco et al., 2010); demand and supply risks (i.e. customer disruptions, demand unpredictability) (Chowdhury et al., 2012); organization risks (i.e. risks resulting due to the organization itself and are under its direct control); and external risks (ahead of company and its supply chain's control) (Einarsson and Rausand, 1998, Christopher and Peck, 2004, McManus, 2008). These factors are further discussed below.

2.3.1 Financial Risks

Financial risks arise due to the instability of market prices of different materials; the price pressures (selling same products at less prices) created by the competitors; and liquidity due to changing economic policies (Einarsson and Rausand, 1998, Pathirage et al., 2012). These factors create the basis for cost overruns, affect the project scope and performance and as a result a loss in business opportunity.

2.3.2 Organization Risks

Pettit et al. (2010b), Abidin and Ingirige (2018a) sub-divided organization risks into: strategic, management and personnel risks, the detail of each of them is given below.

Strategic risks talk about the poor planning and decision-making abilities of the organization about its services like outsourcing to different suppliers, increasing complexity within the system and depending more on the external sources. Such risks will be the source of failure for an organization in case of any disruption (Pettit et al., 2010b). Outsourcing increases complexity within the supply chains and more relationships and complex dependencies with external entities make supply chains more susceptible to risks.

Management risks are also included within the category of organization risks. They describe the capability of an organization to manage its work-related decisions (Pettit et al., 2010b). Poor information handling, inability to control or manage different stakeholders and other members, failure to control cost, time and quality constraints affecting project performance and other such deficiencies will bring supply chain at risk.

Finally, by personnel risks we meant the risks related to the workforce of any company like unavailability of trained and experienced staff, loss of lives working in dangerous situations or poor weather conditions and labor disputes or strikes (Einarsson and Rausand, 1998). Such factors have great impact on an organization.

2.3.3 Operational Vulnerability

The operational risks related to construction supply chain are subdivided into following categories (Sheffi and Rice Jr, 2005): process related risks, supplier and customer disruptions, technology related risks. The detail of each factor is given below.

Process related risks are like chain events, if one link is disturbed whole chain will be damaged. Thus, any risks that arise because of the damage in any link of supply-production-distribution chain are referred as process risks. It is necessary to mitigate such risks that highly affect the projects constraints (scope, cost, time and quality) in case of any disruption during construction. (Abidin and Ingirige, 2018a, Sheffi and Rice Jr, 2005). Supply part of chain has the responsibility of accessibility and to transfer supplies (raw materials, utilities) whenever and wherever they are needed. Production section of the chain is accountable for all the manufacturing tasks executed for the project completion and all distribution and transportation procedures (final product quality, customer satisfaction) involved to serve the end customer are in control of the distribution part of the chain.

The “supplier or customer disruptions” explain exposure of suppliers and customers to disruptions in a highly complex and inter-related construction industry (Pettit et al., 2010b). Selecting incompetent contractors or suppliers by the organization can seriously harm the supply chain and project in case of any disruption. Different risks faced by the suppliers include equipment failure, their inability to deal with unforeseen demand changes and financial crisis (Svensson, 2000). Similar is the case with the customer disruptions; unexpected and unplanned customer demands also affects the organization’s reputation. Therefore, extensive flexibility in orders and products availability must be assured by the organization to mitigate such disruptions in order to enhance the project performance (Pettit et al., 2010b).

Finally, technology related risks involve such risks that organization's supply chain suffer because of its lack of knowledge about the technology changes occurring in the modern world and unanticipated breakdowns of the machinery during operations.

2.3.4 External Risks

External risks are the pressures from external sources, that create difficulties for the organizations to proceed further through their strong influences. They include different sub-factors: Variations in government rules and authorities creates political and legal pressures for the firms, increasing their expenses; Physical damage disruptions disturb the progress of the projects by causing human or financial loss as they involve risks like accidents and theft; Different environmental risk factors that may include health pandemics like COVID in recent years and other such fatal diseases and natural disasters like floods or earthquakes that may affect the entire production and distribution system of supply chains (Abidin and Ingirige, 2018a, Pettit et al., 2010b).

Above stated all factors by different authors have somehow same intuit but wording is different thus all the factors studied through this detailed literature review were incorporated in this research for purposeful and meaningful results, to ascertain their current importance and value in industry to find ways to mitigate them and make supply chains more secure and steady. All supply chain risk sub-factors part of above stated main categories are presented in Table 1.1.

Table 1.3 Construction Supply Chain Risks Factors

Sr #	Risk Factors	Sources	Literature Score
1	Exposure to political disruptions	(Luo et al., 2019, Abidin and Ingirige, 2018a, Abidin and Ingirige, 2018b, Liu et al., 2018, Truong Quang and Hara, 2018, Badurdeen et al., 2014, Rangel et al., 2015, Chowdhury et al., 2012, Pettit et al., 2010a, Blackhurst et al., 2008)	0.5500
2	Political/regulatory changes		
3	Terrorism or sabotage		
4	Severe price fluctuations	(Zainal Abidin and Ingirige, 2018, Liu et al., 2018, Truong Quang and Hara, 2018, Badurdeen et al., 2014, Rangel et al., 2015, Chowdhury et al., 2012, Gunasekaran et al., 2011, Jüttner and Maklan, 2011)	0.4500
5	Price pressure due to competitors		
6	Social & cultural changes	(Luo et al., 2019, Liu et al., 2018, Abidin and Ingirige, 2018a, Truong Quang and Hara, 2018, Badurdeen et al., 2014, Rangel et al., 2015, Chowdhury et al., 2012, Gunasekaran et al., 2011, Juttner and Maklan, 2011, Pettit et al., 2010b, Blackhurst et al., 2008, Sheffi and Rice Jr, 2005)	0.6000
7	Exposure to natural disasters		
8	Health pandemic affecting employees		
9	Pressure from public opinion		
10	Changes in financial policies affecting assets management	(Abidin and Ingirige, 2018a, Abidin and Ingirige, 2018b, Truong Quang and Hara, 2018, Badurdeen et al., 2014) (Rangel et al., 2015) (Chowdhury et al., 2012) (Sheffi and Rice Jr, 2005, Gunasekaran et al., 2011, Ho et al., 2015)	0.2700
11	Lack of financial resources		

12	Technology changes	(Badurdeen et al., 2014, Abidin and Ingirige, 2018a, Truong Quang and Hara, 2018) (Sheffi and Rice Jr, 2005, Johnsen, 2010, Gunasekaran et al., 2011, Aloini et al., 2012, Rangel et al., 2015, Ho et al., 2015)	0.2700
13	Unforeseen failures in technology		
14	Unpredictability of demand by client	(Truong Quang and Hara, 2018, Luo et al., 2019, Dolgui et al., 2020) (Blackhurst et al., 2008, Badurdeen et al., 2014, Ho et al., 2015)	0.1800
15	Limited raw materials availability		
16	Significant members in supply chain	(Ivanov et al., 2017, Abidin and Ingirige, 2018a, Liu et al., 2018, Truong Quang and Hara, 2018, Luo et al., 2019) (Rangel et al., 2015) (Chowdhury et al., 2012, Pettit et al., 2010b) (Blackhurst et al., 2008) (Ho et al., 2015) (Aloini et al., 2012)	0.6000
17	Poor availability of utilities (electrical power, water, sewer)		
18	Products quality problems		
19	Transportation disruption during operations		
20	Limited production and distribution capacity		
21	Outsourcing to different suppliers	(Pettit et al., 2010b, Gunasekaran et al., 2011, Badurdeen et al., 2014, Rangel et al., 2015, Abidin and Ingirige, 2018a, Abidin and Ingirige, 2018b, Liu et al., 2018, Luo et al., 2019, Dolgui et al., 2020) (Blackhurst et al., 2008) (Aloini et al., 2012) (Wieland and Wallenburg, 2012) (Yao, 2013)	0.6500
22	Decentralization of suppliers/operation facilities		
23	Threats by competitive innovations		

24	Budget overruns/ unplanned expenses	(Ivanov et al., 2017, Abidin and Ingirige, 2018b, Luo et al., 2019, Dolgui et al., 2020) (Truong Quang and Hara, 2018, Badurdeen et al., 2014) (Rangel et al., 2015) (Gunasekaran et al., 2011) (Pettit et al., 2010b) (Blackhurst et al., 2008) (Sheffi and Rice Jr, 2005) (Ho et al., 2015) (Aloini et al., 2012) (Johnsen, 2010) (Yao, 2013)	0.7500
25	Poor information coordination and decision making		
26	Insufficient management oversight		
27	Visibility of errors/ deficiencies to stakeholders		
28	Loss of key supplier(s)	(Abidin and Ingirige, 2018a, Truong Quang and Hara, 2018) (Rangel et al., 2015) (Chowdhury et al., 2012) (Pettit et al., 2010b) (Sheffi and Rice Jr, 2005)	0.0600
29	Supplier(s) face frequent disruptions		
30	Customer(s) face frequent disruptions		
31	Shortage of skilled labor	(Abidin and Ingirige, 2018a, Truong Quang and Hara, 2018, Luo et al., 2019) (Badurdeen et al., 2014) (Rangel et al., 2015) (Gunasekaran et al., 2011) (Pettit et al., 2010b) (Ho et al., 2015) (Aloini et al., 2012)	0.2700
32	Labor disputes/strikes		
33	Operating in extreme/hazardous environments		
34	Loss of key personnel		
35	Accidents during operations (fire, workers accident)	(Sheffi and Rice Jr, 2005, Pettit et al., 2010b, Abidin and Ingirige, 2018a, Luo et al., 2019)	0.0400
36	Theft (Products stolen/vandalized)		

2.4 Supply Chain Resilience

An important capability that supplements typical risk management practices is resilience as it deals with several risks and takes in various mechanisms of risk management (Fiksel et al., 2015, Ponomarov and Holcomb, 2009). The past studies clearly indicate the intersection between supply chain risk management and resilience (Mandal, 2012). Basic theories concerning supply chain design principles, resilience and risk management are inter-related because of disruptions (Mandal, 2014). "Resilience is the heart of modern supply chain management thinking" (Melnyk et al., 2014). According to Peck (2005) ability of an organization to change and restore itself according to any disruptive event is supply chain resilience. Resilience of supply chain is mainly connected to the preparedness of the system for any uncertain environment and stability of operations in order to have a proper command over entire structure clarified by (Ponomarov and Holcomb, 2009).

Two different terms were introduced by Mamouni Limnios and Mazzarol (2011) to make it clearer that the supply chains should be adaptive as well as more resilient. When any disruption occurs, the system must be able to withstand and absorb the impact of that event or the system must adapt itself to the current situation and change it policies and procedures accordingly, in order to survive and uphold its structure. "Supply chain resilience is defined as the adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations." (Kamalahmadi and Parast, 2016)

Resilience is mostly discussed considering the perspective of a single organization (McManus, 2008, Pettit et al., 2013). A very few studies tried to communicate value of resilience against disruptive events in supply chain reviewing consequences of vulnerabilities and capabilities on entire system (Abidin and Ingirige, 2018a) mostly related to Malaysian construction industry. Realization of prevailing risks and using the existing resilient capacities to mitigate those risks have not gotten much consideration in literature. Resilience is a vast topic comprising of disruptions, risks and capabilities to mitigate the risks. According to Pettit et al. (2010b) two important components with the help of which supply chain resilience can be achieved are risks and resilient capabilities. Cutting down the risks with the help of effective capabilities, ultimately make the supply chains more resilient to the disruptions. The detailed relationship between each of them is explained in this research to identify major and actual issues of construction industry in developing countries, how they are disturbing the supply chain and what still is needed to improve the efficiency of whole system and to make it more resilient and stable.

2.5 Supply Chain Resilient Capabilities

Preparedness of the system for any uncertain environment and stability of operations in order to have a proper command over entire structure and function is supply chain resilience (Ponomarov and Holcomb, 2009). Removing risks with help of effective capabilities, ultimately make the supply chains more resilient to the disruptions. Such capabilities can either prevent or mitigate an actual disruption and its effects or can make the entire supply chain acclimatize of that disruption (Abidin and Ingirige, 2018a). Pettit et al. (2010b) researched 14 resilient capabilities: "Flexibility in sourcing and order fulfilment, capacity, efficiency, adaptability, visibility, anticipation, recovery, dispersion, collaboration, market position, organization, security and financial strength." Christopher and Peck (2004) investigated four primary resilient capabilities; risk management in organizations, agility, re-engineering and collaboration. Other secondary factors explained by the author were supply chain availability, efficiency, flexibility, redundancy, velocity and visibility. Sheffi and Rice Jr (2005) deeply explored different risks faced by the supply chains in order to pinpoint main capabilities needed to mitigate those risks. Capabilities like flexibility, collaboration, redundancy, security and customer relation management were the center of attention for the researcher. Different capabilities required to make a resilient system are identified above by different researchers in their respective works and their brief definitions are stated below:

2.5.1 Adaptability:

Because of challenges or opportunities in the widespread market, adaptability is a skill needed by an organization to adjust its processes to make their supply chains resilient to disruptions (Abidin and Ingirige, 2018a).

2.5.2 Flexibility:

One of the significant capabilities is the flexibility. Capability to quickly adjust demands/ supplies or the means of receiving inputs/ delivering outputs (Abidin and Ingirige, 2018a). Flexibility of any task is defined by its ability to consider the aftereffects of various uncertain situations it may face and prepare itself according to them (Olsson, 2006). Flexibility is further divided into two main categories: flexibility in sourcing as well as in order fulfilment by the Pettit et al. (2010b).

2.5.3 Capacity:

Capacity of an organization is defined as the accessibility of resources for non-stop production levels (Abidin and Ingirige, 2018a).

2.5.4 Visibility:

By visibility we mean having complete knowledge about working resources and environment. The management should know everything to prepare supply chain for a particular risk (Abidin and Ingirige, 2018a).

2.5.5 Anticipation:

Anticipation is an ability of an organization to predict future circumstances or events that supply chain may face (Abidin and Ingirige, 2018a).

2.5.6 Efficiency:

Ability to yield outputs with least resource requirements. System's efficiency is the capability to fulfill demands of customer keeping in mind scope, time and quality of the project but with minimum expenses and wastage (Olsson, 2006, Pettit, 2008). Thus, better efficiency will enhance supply chain performance.

2.5.7 Recovery:

Aptitude of an organization to quickly restore to its normal operational state is termed as system's recovery (Abidin and Ingirige, 2018a).

2.5.8 Dispersion:

Extensive distribution or decentralization of resources by an organization is known as dispersion (Abidin and Ingirige, 2018a).

2.5.9 Collaboration:

Collaboration is basically a skill to work efficiently with others for mutual benefit. It can further be subdivided as collaboration within the organization itself and with other organizations as well (Abidin and Ingirige, 2018a).

2.5.10 Market Position:

It is the reputation of an organization and its manufactured goods in certain markets (Abidin and Ingirige, 2018a).

2.5.11 Security:

Security of supply chains by an organization means providing protection against planned intrusion or attack (Abidin and Ingirige, 2018a).

2.5.12 Financial Strength:

It is the ability of an organization to realize and take in the cash flow variations during disruptions (Abidin and Ingirige, 2018a).

Above stated all resilient capabilities, studied through this detailed literature review were incorporated in this research for purposeful and meaningful results. These capabilities and their sub-factors as well were included in the preliminary survey explained in Chapter 3 to determine their current importance and value in construction to make supply chains more resistant and stable in case of disruptions. A summary of all the supply chain resilient capabilities and their sub-factors is presented in Table 1.2.

Table 1.4: Supply Chain Resilient Capabilities

Sr #	Resilient Capabilities	Sources	Literature Score
1	Alternative technology development	(Sheffi and Rice Jr, 2005, Ponomarov and Holcomb, 2009, Pettit et al., 2010b, Johnsen, 2010, Juttner and Maklan, 2011, Wieland and Wallenburg, 2012, Mandal, 2012, Abidin and Ingirige, 2018a) (Tukamuhabwa et al., 2015, Purvis et	0.7143
2	Learning from experience		
3	Process improvements		

		al., 2016, Liu et al., 2018) (Soni and Jain, 2011, Wieland and Wallenburg, 2013, Scholten et al., 2014, Mwangola, 2018)	
4	People, products and assets visibility	(Abidin and Ingirige, 2018a, Dolgui et al., 2020) (Pettit et al., 2010b) (Blackhurst et al., 2008) (Sheffi and Rice Jr, 2005, Ponomarov and Holcomb, 2009) (Ivanov et al., 2017) (Yao, 2013) (Wieland and Wallenburg, 2012) (Mandal, 2012) (Juttner and Maklan, 2011) (Tukamuhabwa et al., 2015) (Brandon-Jones et al., 2014) (Liu et al., 2018) (Purvis et al., 2016) (Scholten et al., 2014) (Wieland and Wallenburg, 2013) (Soni and Jain, 2011) (Mwangola, 2018)	0.9048
5	Collaborative information exchange among stakeholders		
6	Business intelligence gatherings		
7	Alternative suppliers/ sources to quickly reallocate orders	(Abidin and Ingirige, 2018a) (Pettit et al., 2010b) (Blackhurst et al., 2008) (Sheffi and Rice Jr, 2005, Ponomarov and Holcomb, 2009, Yao, 2013, Ivanov et al., 2017) (Chowdhury et al., 2012) (Wieland and Wallenburg, 2012) (Mandal, 2012) (Juttner and Maklan, 2011) (Johnsen, 2010) (Tukamuhabwa et al., 2015) (Purvis et al., 2016) (Scholten et al., 2014) (Soni and Jain, 2011) (Mwangola, 2018)	0.8095
8	Inventory management system (Fast rerouting of requirements)		
9	Alternate distribution channels		
10	Product commonality (flexible design)		

11	Monitoring early warnings (deviations, near miss analysis)	(Abidin and Ingirige, 2018a, Dolgui et al., 2020) (Pettit et al., 2010b) (Blackhurst et al., 2008) (Sheffi and Rice Jr, 2005, Ponomarov and Holcomb, 2009) (Chowdhury et al., 2012) (Brandon-Jones et al., 2014) (Liu et al., 2018) (Purvis et al., 2016) (Scholten et al., 2014) (Wieland and Wallenburg, 2013)	0.5714
12	Demand forecasting		
13	Contingency planning (drills, trainings)		
14	Recognition of new business opportunities		
15	Formal risk management culture	(Ponomarov and Holcomb, 2009, Johnsen, 2010) (Tukamuhabwa et al., 2015) (Scholten et al., 2014, Liu et al., 2018) (Mandal, 2012)	0.1714
16	Reserve (materials, equipment, labor) capacity	(Abidin and Ingirige, 2018a) (Pettit et al., 2010b) (Ponomarov and Holcomb, 2009) (Sheffi and Rice Jr, 2005) (Ivanov et al., 2017) (Chowdhury et al., 2012) (Wieland and Wallenburg, 2012) (Johnsen, 2010) (Tukamuhabwa et al., 2015) (Purvis et al., 2016) (Scholten et al., 2014) (Wieland and Wallenburg, 2013)	0.5714
17	Redundancy (alternative assets, labor)		
18	Backup utilities (electricity, water)		
19	Labor productivity	(Abidin and Ingirige, 2018a) (Pettit et al., 2010b) (Ponomarov and Holcomb, 2009) (Chowdhury et al., 2012) (Purvis et al., 2016) (Scholten et al., 2014)	0.1714
20	Waste minimization		
21	Reducing product variability (consistent quality)		
22	Preventing failure (reliable equipment)		

23	Transparent communication flow (external, internal)	(Abidin and Ingirige, 2018a, Dolgui et al., 2020) (Pettit et al., 2010b) (Ponomarov and Holcomb, 2009) (Blackhurst et al., 2008) (Sheffi and Rice Jr, 2005) (Ivanov et al., 2017) (Yao, 2013) (Mandal, 2012) (Juttner and Maklan, 2011) (Johnsen, 2010) (Tukamuhabwa et al., 2015) (Liu et al., 2018) (Scholten et al., 2014) (Wieland and Wallenburg, 2013) (Soni and Jain, 2011) (Mwangola, 2018)	0.8095
24	Order postponement willingly by clients due to disruption		
25	Risk sharing with partners		
26	Employee involvement in security (awareness programs)	(Abidin and Ingirige, 2018a) (Pettit et al., 2010b) (Tukamuhabwa et al., 2015)	0.1429
27	Cyber security		
28	Access restriction (facilities, equipment)		
29	Significant market share	(Abidin and Ingirige, 2018a) (Pettit et al., 2010b) (Ponomarov and Holcomb, 2009)	0.1429
30	Brand equity		
31	Communication and relationships with customers		
32	Distributed assets & capacity	(Abidin and Ingirige, 2018a) (Pettit et al., 2010b) (Sheffi and Rice Jr, 2005)	0.0857
33	Distributed decision-making		
34	Geographically dispersed market		

35	Decentralization of key resources (suppliers)		
36	Crisis management	(Abidin and Ingirige, 2018a) (Pettit et al., 2010b) (Sheffi and Rice Jr, 2005)	0.0857
37	Resource mobilization		
38	Consequence mitigation		
39	Insurance (facilities, equipment, personnel)	(Abidin and Ingirige, 2018a) (Pettit et al., 2010b)	0.0571
40	Financial reserves and liquidity		
41	Financial portfolio diversification		
42	Knowledge management (feedback control system)	(Pettit et al., 2010b) (Ponomarov and Holcomb, 2009) (Tukamuhabwa et al., 2015) (Scholten et al., 2014) (Juttner and Maklan, 2011, Mwangola, 2018)	0.2857
43	Encourage teamwork and creativity		
44	Various skill trainings to staff		

These all resilience strategies are interrelated (Juttner and Maklan, 2011, Wedawatta and Ingirige, 2016) and therefore it is important to understand the trade-offs between appropriate RCs to mitigate critical risks related to construction SCs. This is an under-researched area that has been overlooked by the previous researchers (McManus, 2008, Zsidisin and Wagner, 2010, Pettit et al., 2013, Abidin and Ingirige, 2018a, Rasul et al., 2021) needs proper attention.

2.6 Complexity Science and Systems Thinking

Complex system is comprised of several different components signifying high-level of inter-connectivity (Richardson et al., 2000). "Complex systems are those systems, that self-organize themselves into states of greater complexity" stated by Merry and Kassavin (1995). Complexity science is a process through which analyzing the correlations among different components of the system describes the overall behavior and interaction of the system and its components with its surroundings (Wood and Gidado, 2008). Complexity science is related to such complex systems and troubles that are dynamic and uncertain in nature, thus is categorized by its non-linearity. Characteristics like fragmentation, adversarial relationships, project-based and transient nature have made the construction industry complex and uncertain. Different stakeholders (clients, consultants, designer, contractor, sub-contractors) are associated at different stages of construction projects making the process even more complicated (Baccarini, 1996). Moreover, factors such as scope, quality, time, cost, safety and environment increase the complexity during construction (Gidado, 1996). Though, construction process looks like a very planned and linear process, but the delays caused by various reasons makes it unpredictable, non-linear and dynamic in nature (Bertelsen, 2003).

Systems thinking is basically a route designed to understand how the sub-parts of the system affect each other. It is the science of taking into account the "problems" of whole system instead of considering the effects of a single factor (Ackoff, 2008). According to Monat and Gannon (2015) complexity science is a vast field and is almost applied to every industry to understand the non-linear behavior of the problems. A broad definition suitable for all disciplines of system thinking is given by Arnold and Wade

(2015): “Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects. These skills work together as a system.” Maani and Cavana (2007) explained four types of systems thinking: forest, dynamic, operational and closed loop thinking.

2.7 System Dynamics

There are many simulation and optimization techniques used to enhance the organization performance and most of the authors in past have done a really good work on them (Oliveira et al., 2019). Simulation cycle is meant to quantify impacts of risks or scenarios aided by different methods, such as Monte Carlo Simulation (Liew and Lee, 2012), Discrete Event Simulation (Manuj et al., 2014), Agent-Based Simulation (Wu et al., 2013, Güller et al., 2015) and System Dynamics Simulation (Peng et al., 2014, Li et al., 2016, Keilhacker and Minner, 2017). System dynamics was introduced by Forrester (1961) to model systems having great complexity and high levels of uncertainty.

To understand the dynamic behavior of complex systems one must have complete knowledge regarding complex tools and systems (Sterman, 2001, Dangerfield et al., 2010). Built on the feedback control theory system dynamics approach assesses the dynamic behavior of system using quantitative and qualitative practices (Forrester, 1999). To dynamically examines the changing trends of system that helps in making future decisions and action plans and to verify validity of working strategy and decision taken computer simulations technology is used, that works on the perspective of system modeling (Feng, 2012).

System dynamics approach uses non-linear feedback system to sort out the complicated relationships and presents the complex data in more comprehensible and simple way. Thus, it helps to reduce complexity with an intention to boost up system productivity (Khan et al., 2016). There are various causes and effects of different phenomena occurring within the system; an approach to assess such human assumptions and hypotheses through proper representing, testing and modifying is required (Metcalf and Kum, 2016). System dynamics approach helps to smooth out this decision-making process and assess the problem with different viewpoints and timelines to devise a proper strategy against that problem.

Causal Loop Diagrams: Basic tool to demonstrate system feedback structure. Causal loop diagrams quickly capture the hypothesis by understanding causes and effects of dynamics, summarizes the mental models of individuals and communicate the key feedbacks related to the certain problem (Sterman, 2000). Academicians and different organizations used these diagrams for their business purposes.

Stock and Flow Diagrams: Stocks are accumulations, describe system status and give system an inertia and memory to impart data upon which decisions are made. "Stocks create delays by accumulating the difference between the inflow to a process and its outflow" (Sterman, 2000).

Vensim®, Stella®, Powersim®, AnyLogic® etc. are the software used for simulation and modeling purposes and practice the graphical language of system dynamics. Graphical interface with unique iconography for variables, stocks, flows and loops in such software makes easy to carry out the system dynamics approach (Metcalf and Kum, 2016).

Different researchers in the past have done great work using system dynamics approach like Lee et al. (2006) have discussed about the complexity and uncertainty of construction projects due to iterative cycles of work caused due to errors and changes; Peng et al. (2014) researched effects of post-seismic disruptions on inventory and transportation rate in supply chains; Risks effects as well as their mitigation scenarios in chemical supply chain transportation were studied by Li et al. (2016); Khan et al. (2016) and Naveed and Khan (2021) used the ST and SD approach to manage the information complexity in construction projects. Keilhacker and Minner (2017) used system dynamics simulation model to test various ways to abate risks in different situations of rare earth elements supply chain. Ghufran et al. (2021) used SD approach to determine the challenges in adoption of sustainable SC Management in the construction industry. Amin et al. (2022) identified the barriers to information management and factors affecting the adoption of collaborative technologies using SD approach. A very little work regarding construction SC risks and RCs using SD approach have been done in the past. Thus, this competent approach is selected to assess the complex and interdependent relations between SC risks and RCs in this research. It essentially bridges the literature gap in addressing criticality of the construction SC management risks from resiliency perspectives using SD approach.

Chapter 03

RESEARCH METHODOLOGY

3.1 Introduction

An appropriate methodology plays vital role in achieving the objectives of the study (Grix, 2010) as well as guaranteeing the genuine input to prevailing body of knowledge. To tackle research problem emphasized in Chapter 01, different phases of the research methodology have been discussed chronologically in much detail in this chapter. Beginning from formulating the research objectives by recognizing the research gap and a detailed literature review this study adapts the system thinking and system dynamics approach as a research strategy.

3.2 Research Questions

To accomplish objectives of the research and to tackle research problem, process of data collection can be very well directed with the help of research questions. Following questions basically serve as the key drivers in order to address the issue:

1. What are the key risks related to the construction supply chain management?
2. What are the critical success factors necessary to build a resilient construction supply chain?
3. How resilient capabilities can help the industry to reduce the risks related to supply chain?
4. How system dynamics approach can be used for assessing the complexity of construction supply chains under risks to build a resilient supply chain.

Answers to the above research questions will not only help in understanding the relationship between risks and the resilient capabilities associated with supply chain management but also play an essential part in proposing a solution for enhancing the performance of entire construction industry and make it more resilient by catering all the complexities and uncertainties in supply chain management.

3.3 Research Methodology

The system dynamics approach depends on the literature as well as field data. As system dynamics approach is adapted in this research, therefore detailed literature review of different research articles was done with an aim to collect the data with respect to literature and through questionnaire-based surveys field data was collected. Research process of this study comprises of four main phases as shown in Figure 3.1 and detail of each one of them is given below.

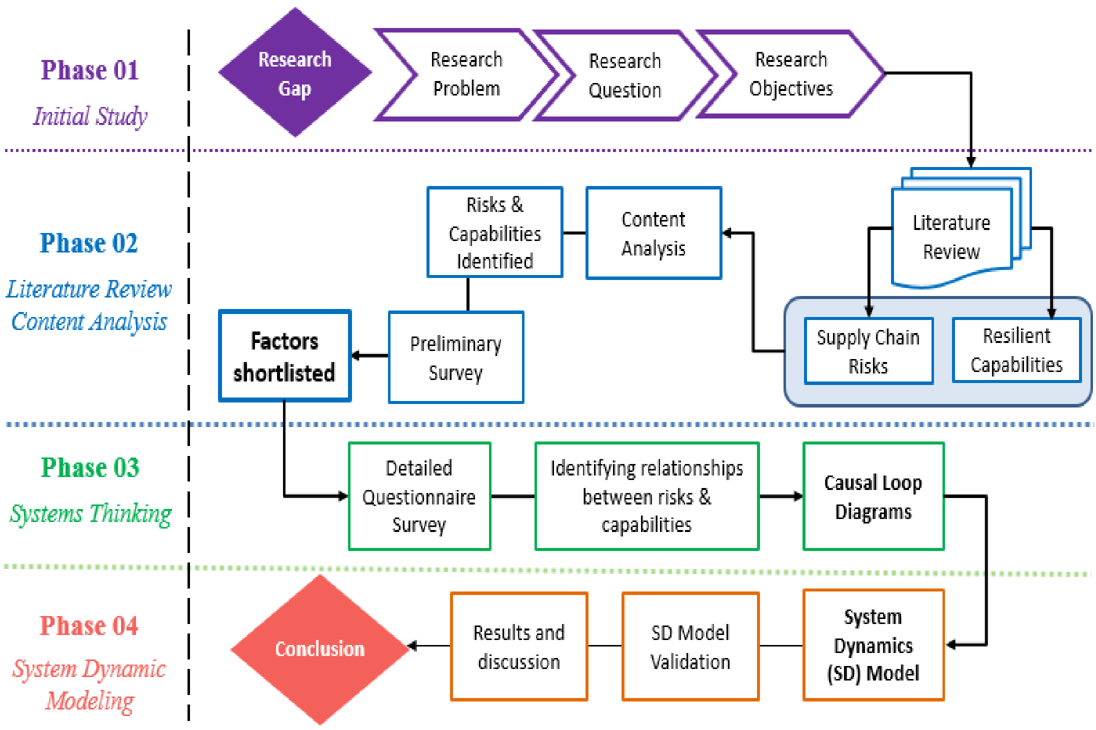

Figure 3.1 Schematic Representation of Research Methodology

3.3.1 Phase 01

In the first phase, the research gap was found after the detailed analysis of literature. Several relevant research articles, conference papers and books were accessed for this purpose. Scrutiny of literature helped to categorize different risks associated with the construction supply chains and different resilient capabilities needed to mitigate those risks. The risks and capabilities in fact highlighted the importance of need to incorporate the 'risk-resilience approach' to deal with complexities as well as uncertainties faced by supply chains in construction industry. The identification of research gap helped to refine research problems, with the help of which research objectives were planned and finalized.

3.3.2 Phase 02

In the second phase, a two-fold method was used to perform a comprehensive literature review. Firstly, the risks associated with the construction supply chain management were identified from critically scrutinizing the literature and 36 risk sub-factors were ascertained. Secondly, the capabilities required to mitigate risks and to make supply chains more resilient to disruptions were also identified from literature and a total of 44 resilient capabilities were identified. The content analysis, a qualitative as well as quantitative approach (Hsieh and Shannon, 2005), was performed to shortlist and rank the identified risks and resilient capabilities, based on their relevant importance. Content analysis consisted of the literature and preliminary survey analysis from field experts.

At first, a literature score was given to each of the identified risk and capability depending on frequency of its presence in literature as well as its impact after assessing the work of each respective author (Ullah et al., 2016) at a Likert scale consisting of three-points i.e. 1 for Low, 3 for Medium and 5 for High. Hence, the product of frequency and impact of each factor gives the final literature score of that factor.

After that a preliminary survey was conducted to take feedback from the field experts of the developing countries because the factors that were discussed in literature by the international authors may possibly not fully expose the vulnerabilities of the developing countries like Pakistan and their solutions as well. Therefore, a questionnaire was drafted and then circulated to professionals around the world. Shortlisting and ranking of factors, was the key need behind all this effort. About 50 responses were selected and their respective score was calculated and normalized. To ensure the internal consistency of collected data the reliability test was carried out through SPSS. Cronbach's alpha of the entire data comes out to be 0.94 verifying its reliability.

Basic additive weighting approach was used to analyze the literature and respondent's score differently by assessing and recommending suitable decision weights built on evidential reasoning (Ahmad, 2017). Ratios to experts and literature score respectively like 80/20, 60/40 were calculated and then analyzed using ANOVA and correlations tests in SPSS (Jahan et al., 2022). Results indicated that there was not much variation in data because the correlation value comes out within range of 0.8-0.9 and p-value from ANOVA test was 1.0. Thus 60/40 ratio was selected, giving importance to the professionals from the field. 15 risks out of 36 and 16 resilient capabilities out of 44 were chosen on simple majority principle having more than 50% cumulative impact. Table 3.1 shows the details of shortlisted risks related to construction supply chain management including their normalized score, cumulative score and ranking.

Table 3.1 Shortlisted Risk Factors affecting Construction Supply Chains

Rank	Risk Factors affecting Construction Supply Chains	Normalized	Cumulative
1	Health pandemic affecting employees.	0.03629	0.03629
2	Budget overruns/ unplanned expenses.	0.03592	0.07220
3	Poor information coordination and decision making.	0.03592	0.10812
4	Insufficient management oversight (on supply chain members)	0.03592	0.14403
5	Visibility of errors to stakeholders.	0.03592	0.17995
6	Outsourcing to different suppliers.	0.03336	0.21331
7	Decentralization of suppliers/ operation facilities	0.03336	0.24668
8	Severe price fluctuations.	0.03246	0.27914
9	Exposure to natural disasters.	0.03209	0.31123
10	Pressure from public opinion.	0.03209	0.34332
11	Poor utilities (electrical power, water, sewer) availability	0.03209	0.37540
12	Products quality problems.	0.03209	0.40749
13	Transportation disruption during operations.	0.03209	0.43958
14	Limited production and distribution capacity.	0.03209	0.47167
15	Exposure to political disruptions.	0.03081	0.50249

Table 3.2 shows the details of all selected resilient capabilities adapted to mitigate the supply chain risks including their normalized score, cumulative score and ranking.

Table 3.2 Shortlisted Resilient Capabilities

Rank	**Resilient Capabilities**	**Normalized**	**Cumulative**
1	People, products and assets visibility. (real-time data on location).	0.03389	0.03389
2	Collaborative information exchange (among stakeholders).	0.03389	0.06778
3	Business intelligence gatherings (to be aware of future trends).	0.03389	0.10168
4	Alternative suppliers/ sources to quickly reallocate orders.	0.03176	0.13344
5	Inventory management system (Fast rerouting of requirements).	0.03176	0.16520
6	Alternate distribution channels (modes of transportation).	0.03176	0.19696
7	Product commonality (flexible design).	0.03176	0.22872
8	Transparent communication flow (external, internal).	0.03176	0.26048
9	Order postponement willingly by clients due to disruption.	0.03176	0.29224
10	Risk sharing with partners.	0.03176	0.32400
11	Alternative technology development.	0.02963	0.35362
12	Learning from experience.	0.02963	0.38325
13	Process improvements (to reduce lead-times).	0.02963	0.41288
14	Monitoring early warning signals (deviations, near-misses analysis).	0.02643	0.43931
15	Demand forecasting.	0.02643	0.46574
16	Contingency planning (drills, trainings).	0.02643	0.49217

3.3.3 Phase 03

Detailed data collection and its examination was performed in the third phase. After shortlisting the final supply chain risks and capabilities as a result of content analysis, the final questionnaire survey was formulated using those selected risks and capabilities. It is basically a survey-based study because most of the results depends on the questionnaire survey. Questionnaires are used to gather information by requesting different people to respond to a same set of questions. Different computer tools and techniques are used to analyze the collected data (Saunders et al., 2011). Somehow, an online questionnaire survey is simplest way for the collection of primary data, globally. It facilitates the researcher to get to those respondents who are at a far geographical distance in a shorter time span. To prepare questionnaire survey while considering all the challenges and limitations, much time and effort was invested.

With the intention to seek reviews from experienced and skilled professionals in construction supply chain research, a formal highly organized online questionnaire survey was prepared to collect the demanded data. An influence matrix questionnaire was developed through Google™ Docs (Rasul et al., 2021) comprising of two sections. The first section requested about personal information of respondents which includes their respective qualification, years of professional experience, designation, type of organization and country of work. The second section then asked the respondents to rate the influence of relation of each construction supply chain risk with all resilient capabilities required to mitigate those risks on a three point Likert scale (1=Low, 2=Medium, 3=High) and also to identify the polarity of the same.

This research was basically restrained to the developing countries therefore, the final questionnaire was distributed only among the professionals of developing countries around the world through online social and professional community platforms such as Facebook®, LinkedIn®, via Email etc. The survey was conducted from September 2021-February 2022 and subsequently a total of 60 responses from 14 different countries were collected. As generally acknowledged, a minimum sample size of 30 or above is required to satisfy the central limit theorem (Chan et al., 2018).

The accumulated data was then arranged, and responses were evaluated using basic statistic tools. To ensure the internal consistency of collected data the reliability test was carried out through SPSS. The minimum acceptable value for Cronbach's coefficient alpha is 0.7 (Wang et al., 2019). Cronbach's alpha of the entire data comes out to be 0.9 verifying its reliability. After evaluating the collected data, the most important relations were then ranked using Relative Importance Index (RII) method. The RII is a statistical method which is used to rank different factors (Hossen et al., 2015, Muneeswaran et al., 2020). Equation (1) was used to calculate the RII as follows:

$$\text{Relative Importance Index (RII)} = \frac{\sum \boldsymbol{W}}{\boldsymbol{A} * \boldsymbol{N}} \qquad \text{........................(1)}$$

where, W = weight assigned in Likert scale (varying from 1 to 3),

A = maximum weight assigned in the scale (i.e. 3 in this research),

N = total number of respondents (i.e. 60 in this research).

RII has a minimum and maximum value of 0 and 1, respectively. The value of RII is directly related to the importance of that particular relation or factor. The relation is important, if the RII value of that factor is closer to 1 and vice versa. According to (Rooshdi et al., 2018), the RII has been categorized into five levels such as RII scores ranging from 0 to 0.3 as 'Very Low', 0.3 to 0.5 as 'Low', 0.5 to 0.75 as 'Medium', 0.75

to 0.8 as 'High' and 0.8 to 1 as 'Very High'. In order to reduce the data set, relationships having RII ≥ 0.75 were considered as most important. The collected survey data revealed 29 relations between the supply chain risks and resilient capabilities as the most important having RII ≥ 0.75. These 29 important relations were then further used in this research for establishing causal loop diagram and subsequently the system dynamics model. Table 3.3 shows the final shortlisted risks and capabilities.

Table 3.5 RII Score & Polarity of Shortlisted Variables

Risks	Capabilities	Polarity	RII Score
Health Pandemic	People, products & assets visibility (real time data on location)	-	0.75
	Alternative suppliers/ sources to quickly reallocate order	-	0.79
	Inventory management system (Fast rerouting of requirements	+	0.76
	Process improvements (to reduce lead times)	-	0.76
	Monitoring early warning signals (deviations near misses' analysis)	-	0.75
	Demand forecasting	-	0.75
Budget overruns/ unplanned expenses	Process improvement	-	0.75
	Alternative technology development	+	0.75
Poor information coordination and decision making	People, products & assets visibility (real time data on location)	-	0.77
	Collaborative information exchange (among stakeholders)	-	0.81
	Business intelligence gatherings (to be aware of future trends)	-	0.76

	Transparent communication flow (external internal)	-	0.75
	Learning from experience	-	0.75
Insufficient management oversight on supply chain members	People, products & assets visibility (real time data on location)	-	0.75
	Collaborative information exchange (among stakeholders)	-	0.77
	Alternate distribution channels (modes of transportation	-	0.76
	Learning from experience	-	0.76
Visibility of errors/ deficiencies to stakeholders	Collaborative information exchange (among stakeholders)	-	0.78
Suppliers/ operation facilities are concentrated at same area	Alternative suppliers/ sources to quickly reallocate order	-	0.76
	Inventory management system (Fast rerouting of requirements	-	0.76
Exposure to natural disasters	People, products & assets visibility (real time data on location)	-	0.77
	Collaborative information exchange (among stakeholders)	-	0.77
	Alternative technology development	-	0.76
Transportation disruption during operations	Asset visibility	-	0.75
	Alternate distribution channels (modes of transportation	-	0.78
Limited production and distribution capacity	Business intelligence gatherings (to be aware of future trends)	-	0.77
	Process improvements (to reduce lead times)	-	0.76

	Monitoring early warning signals (deviations near misses' analysis)	-	0.81
	Demand forecasting	-	0.76

3.3.4 Phase 04

The conclusive phase of this research was the development of system dynamics model. The final shortlisted 29 relations (as shown in table) were used for establishing the causal loop diagram representing the specific loops. VENSIM® software was used to develop the causal loop diagram. The causal loop diagram (CLD) developing process was a trial and error, repetitive and frequentative practice where all variables were positioned and linked to each other using professional insight. All nine construction supply chain risks shortlisted in the 29 relations, were used as top variables and were related to the resilient capabilities based on the trend of their respective influence. Either a positive (+) or negative (-) polarity is carried by each arrowhead, indicating a direct or indirect relation of that particular variable with its immediate next variable in the loop, respectively. The closed chains of cause and effect known as feedback loops were identified as reinforcing (R) or balancing (B) loop.

The development of CLD paved way for creating system dynamics model. Using the VENSIM® software, the CLD was first transformed into stock and flow diagram (SFD) and then finally into a SD model. The model consists of five stocks governed by the flow rates (inflows and outflows) and by the variables used in CLD. The inflow and outflow equations were also developed for these five stocks with the help of the data obtained through survey. After establishing SD model, simulations were run to check the behavior over time graphs (BOTGs) for all the respective stocks. The model was also validated using different validation tests (Qudrat-Ullah and Seong, 2010) such as boundary adequacy test, structure verification test, parameter verification test and extreme condition test. Furthermore, the SD model results were also presented to construction industry professionals, belonging to the supply chain management and construction industry, for expert opinion. Lastly, the conclusions were derived in the view of system dynamics analysis performed and the research objectives.

3.4 Demographics of Survey

The questionnaire survey collected 60 responses with the demographic details given in the Table 3.4

Table 3.6 Respondents Demographic Details

Profile	**Frequency**	**Percentage**
Total No. of Responses = 60		
Education		
B. Tech	1	2%
BSc/B.Engg	19	31%
MSc/M.Engg	27	45%
PhD/D.Engg	13	22%
Experience (years)		
1 to 5	15	25%
6 to 10	17	28%
11 to 15	10	17%
16 to 20	11	18%
21 and above	7	12%
Type of Organization		
Client	9	15%
Consultant	5	8%
Contractor	13	22%
Sub-Contractor	7	12%
Supplier	15	25%

Academician	11	18%

3.4.1 Geographical Distribution

The survey collected a total of 60 responses including 41% national and 59% international responses. Responses were received from countries that include Pakistan (41%), Bangladesh (16%), UAE (11%), India (6%), Malaysia (5%), Iran (4%), Jordan (3%), Saudi Arabia (2%), Morocco (2%), Brazil (2%), Kuwait (2%), Qatar (2%), Turkey (2%), and Oman (2%) as shown in Figure 3.2. As the main emphasis of this research was on developing countries, all the responses were collected accordingly.

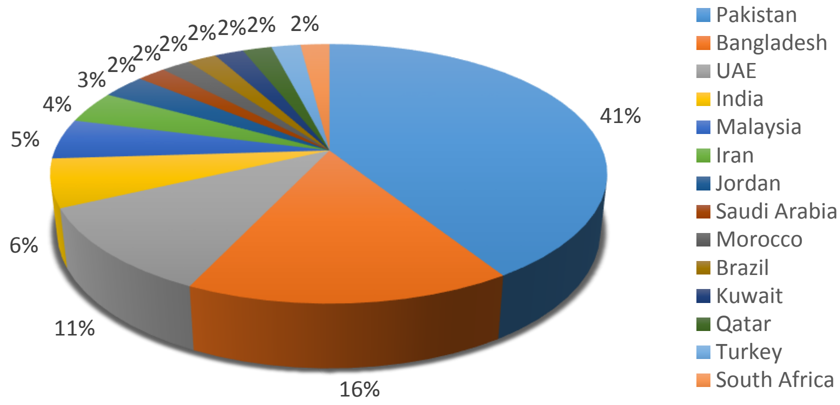

Figure 3.1 Geographical Distribution of Respondents

3.4.2 Educational Background

The respondents of different educational backgrounds participated in this detailed survey. Figure shows the distribution of educational background of respondents. The maximum response was from professionals having master's qualification i.e. 27 (45%). 19 responses (31%) were given by professionals having bachelor's degree, 13 responses (22%) by professionals having doctorate degree and only 1 response (2%) by diploma holders. The educational distribution of respondents is a good mix integrating feedback from all.

3.4.3 Professional Experience

The respondents had varying years of professional experience. Figure shows the distribution of professional experience of respondents in years. 15 respondents (25%) had experience of 2 to 5 years, 17 respondents (28%) had experience of 6 to 10 years, 10 respondents (17%) had experience of 11 to 15 years, 7 respondents (12%) had experience of 16 to 20 years and 11 respondents (18%) had experience of 21 year and above. The distribution of professional experience in survey indicates the incorporation of input from all categories.

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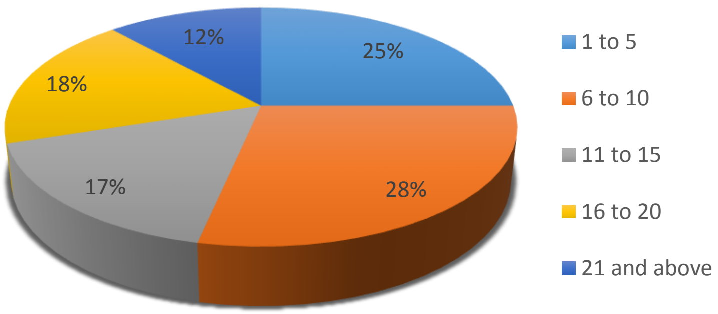

Figure 3.2 Professional Experience of Respondents

RESULTS AND ANALYSIS

This chapter portrays and describes the results and analysis of models developed using system dynamics approach in this research. The causal loop diagram established with all its reinforcing loops and balancing loops as well as the system dynamics model with all its components and simulation graphs both are explained here.

4.1 Causal Loop Diagram (CLDs)

The CLD is built on basis of the results collected through the surveys conducted in this research and demonstrates a total of nine significant loops (Figure 4.1) representing the interdependencies among RCs and SC risks affecting the system. CLD consists of two balancing (negative) loops labelled as 'B' and seven reinforcing (positive) loops labelled as 'R'. The CLD consists of two types of variables: construction SC

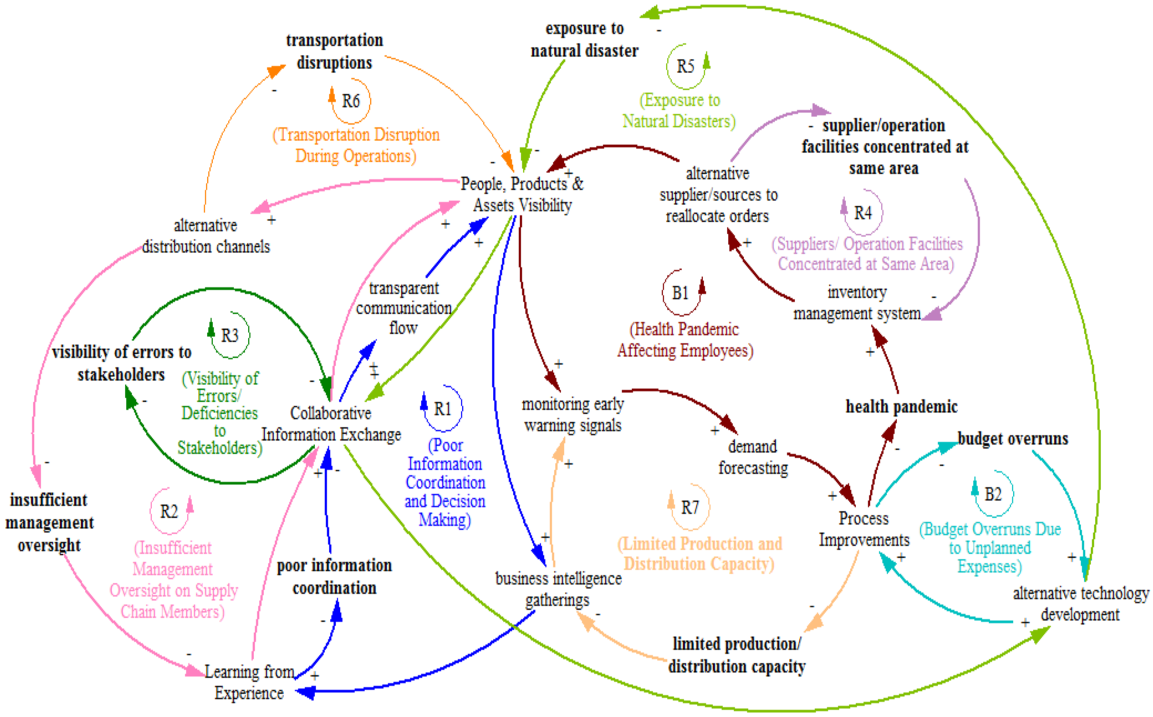

Figure 4.1 The Causal Loop Diagram

management risks and SC resilient capabilities and all the loops are identified and explained below.

4.1.1 Balancing Loop B1: Health Pandemic Affecting Employees

The balancing loop (B1) as shown in Figure 4.2 indicates that the more health pandemic affects employees and the supply chain the greater it disturbs the whole inventory management system, poor inventory management decreases reallocation of alternative sources and suppliers hence decreases the people, product and assets visibility. The decrease in visibility reduces the monitoring of early warning signals which ultimately decreases demand forecasting. With the poor demand forecasting system there will be less attention paid to the process improvement techniques to reduce lead times and delays which eventually increases more sufferings to the employees because of heath pandemic.

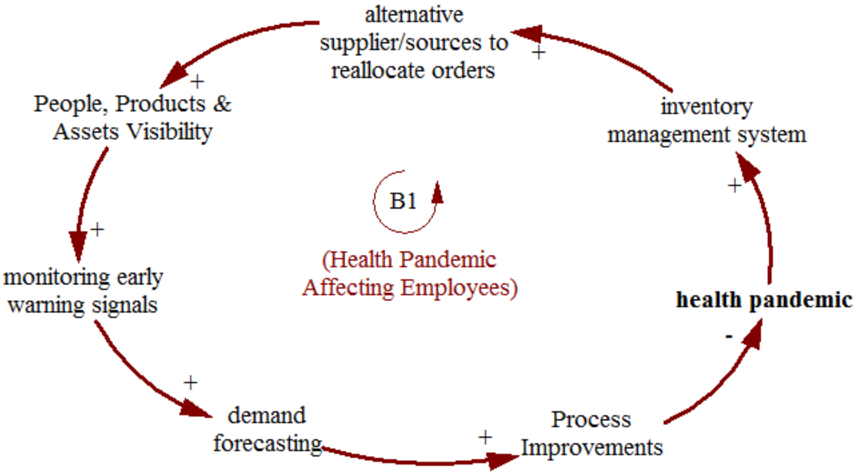

Figure 4.2 The Loop B1

4.1.2 Balancing Loop B2: Budget Overruns Due to Unplanned Expenses

The balancing loop (B2) as shown in Figure 4.3 indicates that the increase in budget overruns due to unplanned expenses leads to increase in alternative technology development by an organization to improve system efficiency. The increase in technology development increases the process improvements techniques to reduce lead times. The increase in process improvements techniques decreases the budget overruns.

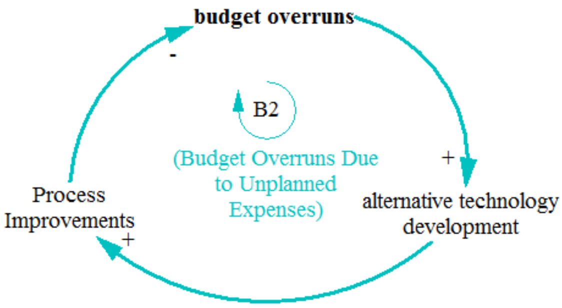

Figure 4.3 The Loop B2

4.1.3 Reinforcing Loop R1: Poor Information Coordination and Decision Making

The reinforcing loop (R1) as shown in Figure 4.4 shows that poor information coordination and decision making is due to the decrease in collaborative information exchange among stakeholders. This decrease in information exchange reduces the transparent communication flow of an organization, both externally as well as internally. The decrease in transparent communication flow decreases the people, product and assets visibility and decreases the awareness about future trends and practices collected through business intelligence gatherings and it can be gained

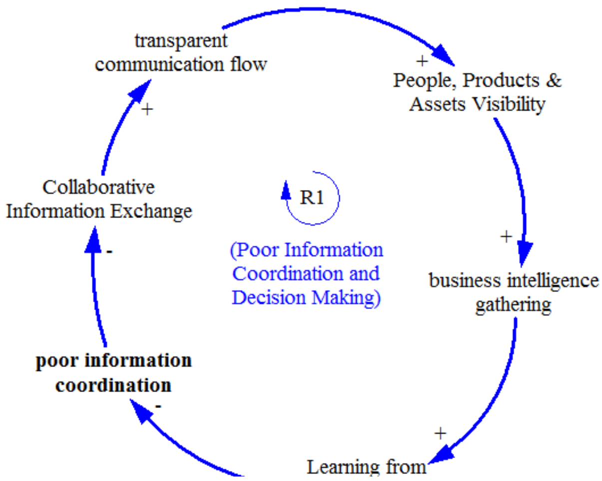

Figure 4.3 The Loop R1

through more learning from experience thus decreasing poor information coordination and decision making.

4.1.4 Reinforcing Loop R2: Insufficient Management Oversight on Supply Chain Members

The reinforcing loop (R2) as shown in Figure 4.5 indicates that insufficient management oversight on supply chain members is because of low learning from experience by an organization. Decrease in learning from experience decreases the collaborative information exchange among stakeholders and this decrease in information exchange decreases the visibility of people, products and assets on site. This reduced visibility reduces the chance for alternate distribution channels and modes of transport during any disruption. The more alternates available for distribution channels and modes of transport, the less will be the insufficient management oversight.

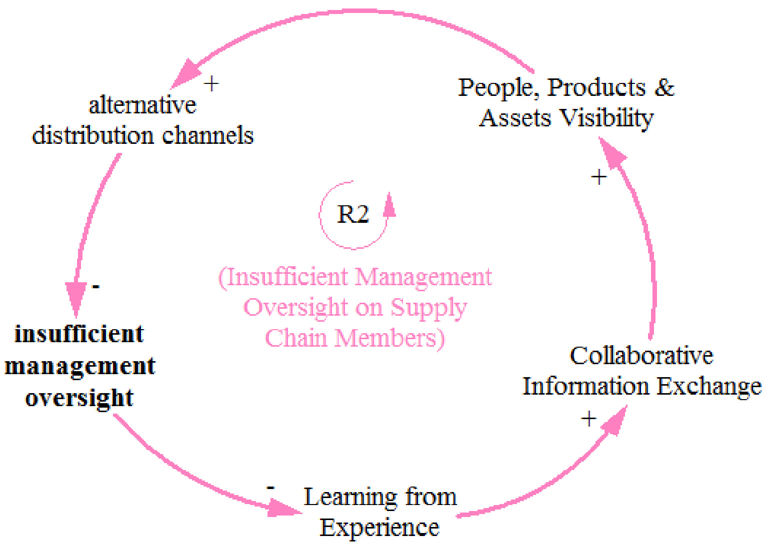

Figure 4.4 The Loop R2

4.1.5 Reinforcing Loop R3: Visibility of Errors/ Deficiencies to Stakeholders

The reinforcing loop (R3) as shown in Figure 4.6 shows that the visibility of errors to stakeholders decreases when collaborative information exchange among stakeholders increases.

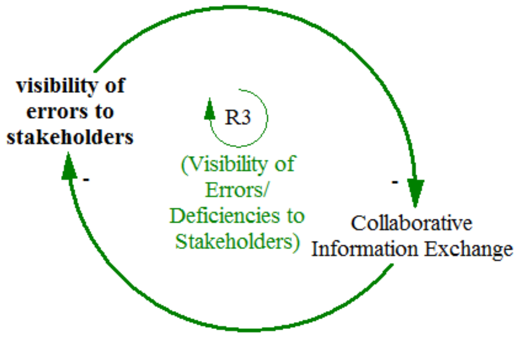

Figure 4.6 The Loop R3

4.1.6 Reinforcing Loop R4: Suppliers/ Operation Facilities Concentrated at Same Area

The reinforcing loop (R4) as shown in Figure 4.7 shows that if more suppliers/ operation facilities are concentrated at the same area it indicates poor inventory management system, the more enhanced inventory management system will ultimately assign more alternative suppliers or facilities to reallocate orders in case of disruption. Hence, increase in alternative suppliers or facilities decreases the concentration of supplier facilities at the same area.

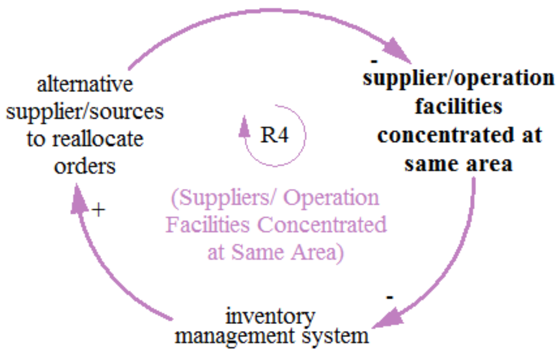

Figure 4.7 The Loop R4

4.1.7 Reinforcing Loop R5: Exposure to Natural Disasters

The reinforcing loop (R5) as shown in Figure 4.8 shows that the exposure to natural disaster increases when the people, product and asset visibility decreases. When visibility decreases collaborative information exchange among stakeholders decreases. The reduced information exchange decreases the alternative technology development programs within an organization and this decrease in alternative technology development increases more exposure to natural disasters.

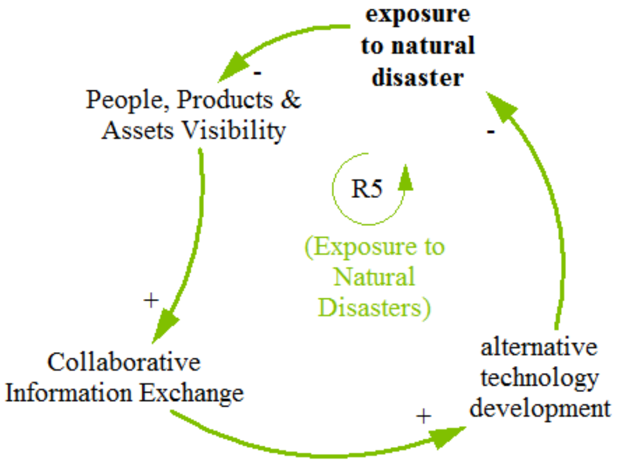

Figure 4.8 The Loop R5

4.1.8 Reinforcing Loop R6: Transportation Disruption During Operations

The reinforcing loop (R6) as shown in Figure 4.9 shows that the transportation disruption during operations decreases when the people, products and assets visibility increases on site. The increase in visibility results in better and enhanced distribution channels and mode of transportation in case of any disruption. Thus, the better alternate distribution channels solution decreases the transportation disruption during operations.

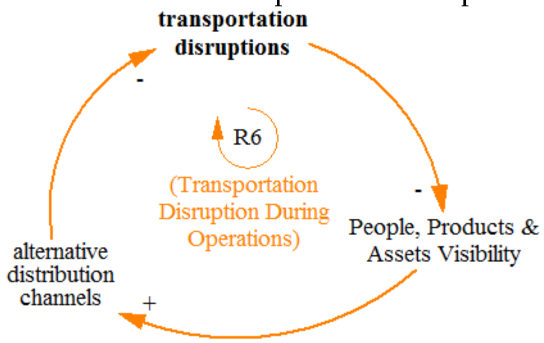

Figure 4.9 The Loop R6

4.1.9 Reinforcing Loop R7: Limited Production and Distribution Capacity

The reinforcing loop (R7) as shown in figure 4.10 shows that the limited production and distribution capacity increases when there is less knowledge about future trends and behavior in industry through business intelligence gatherings. The decrease in the knowledge gathered through business intelligence gatherings decreases the monitoring of early warning signals, which ultimately decreases demand forecasting. With the poor demand forecasting system there will be less attention paid to the process improvement techniques to reduce lead times and delays which eventually increases the limited production and distribution capacity of an organization.

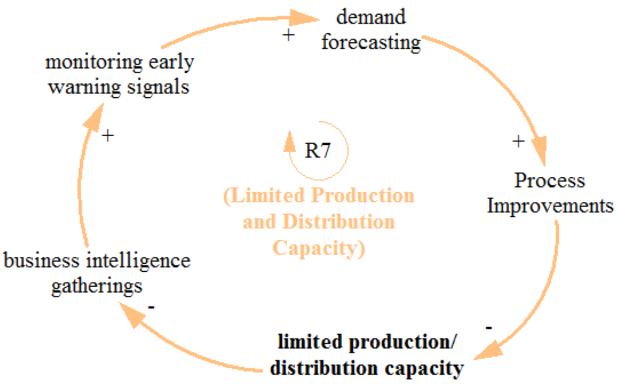

Figure 4.10 The Loop R7

4.2 System Dynamics Model

After the development of causal loop diagram, the system dynamics model was developed using VENSIM® software. The system dynamics model consists of four main components (stocks): (a)**People, Products and Assets Visibility**, (b)**Collaborative Information Exchange**, (c)**Process Improvements** and, (d)**Learning from Experience** governed by inflows and outflows. The equations (2) -

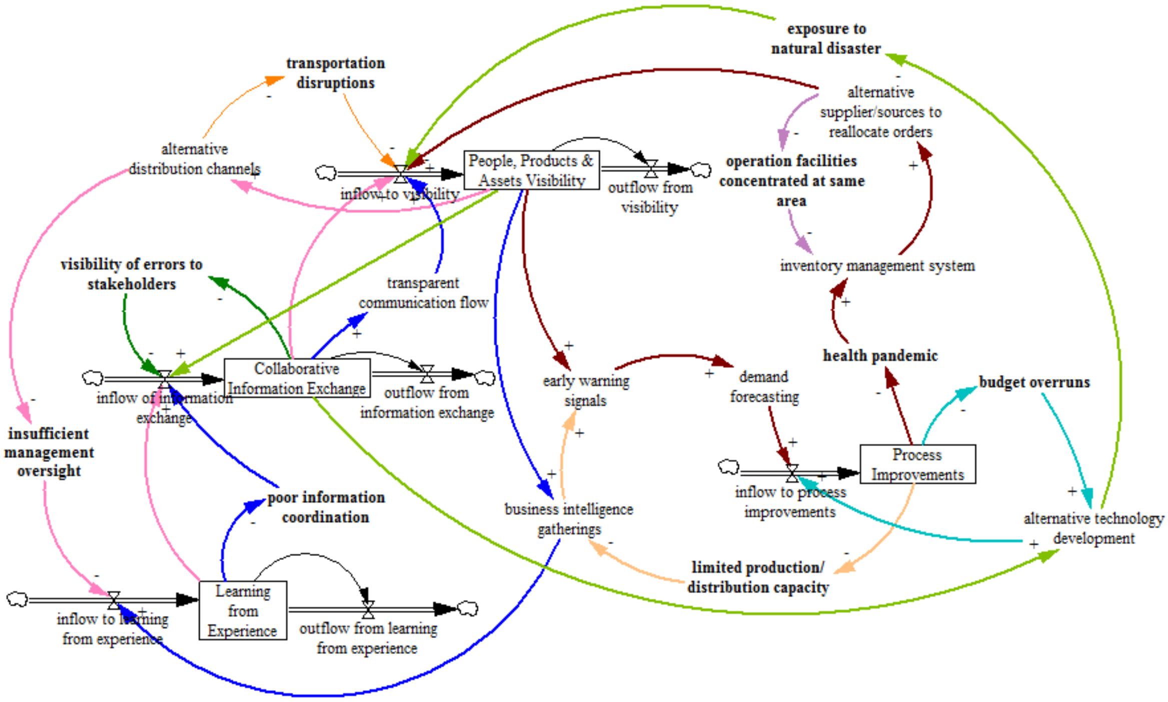

Figure 4.11 System Dynamics Model

(5) used in the system dynamics model were developed using the data collected through different surveys. The system dynamics model is shown in Figure 4.11.

$$\text{Stock-C1} = (0.034 \times C2 + 0.035 \times C3 + 0.036 \times C4 - 0.034 \times R1 - 0.035 \times R2) \quad (2)$$

$$\text{Stock-C3} = (0.035 \times C1 + 0.035 \times C5 - 0.037 \times R3 - 0.035 \times R4) \quad (3)$$

$$\text{Stock-C5} = (0.034 \times C9 - 0.035 \times R5) \quad (4)$$

$$\text{Stock-C6} = (0.7 \times C7 + 0.9 \times C8) \quad (5)$$

Where the related variables include people, product and asset visibility (C1), transparent communication flow (C2), collaborative information exchange (C3), alternative sources to reallocate orders (C4), learning from experience (C5), process improvements (C6), alternative technology development (C7), demand forecasting (C8), business intelligence gatherings (C9), transportation disruptions (R1), exposure to natural disaster (R2), poor information coordination (R3), visibility of errors to stakeholders (R4), insufficient management oversight (R5).

4.2.1 Simulation Results and Discussion

The simulation represents the system's behavior over a time period. In this research study 6 months' time duration is considered, which is generally accepted as project duration of a small-scale construction supply chain. The decrease and increase in the curve of simulation graphs are also explained. The simulation presents behavior over time graph of all variables in Figure 4.12

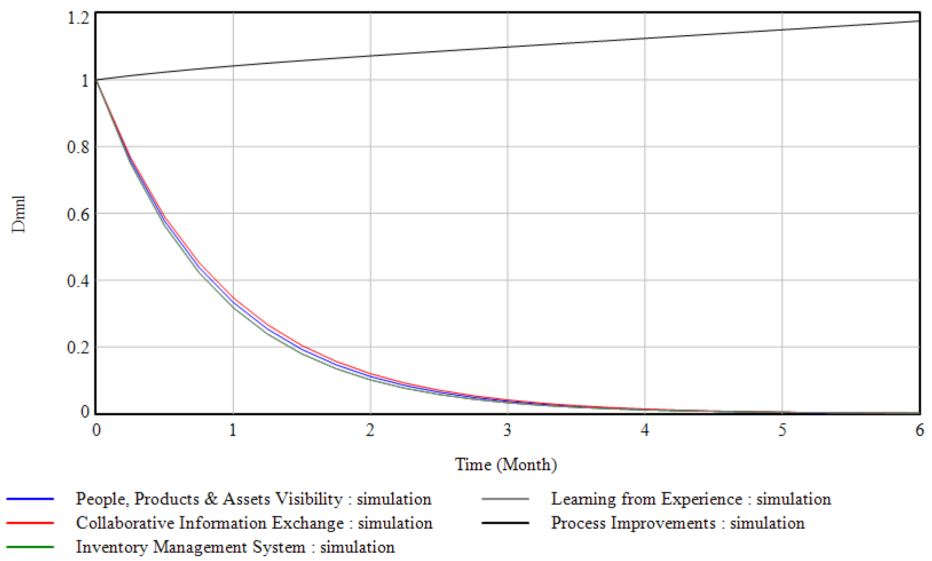

Figure 4.12 Simulation Results of all Variables

The behavior over time graph of ‘People, Products and Assets Visibility’ shows a draining process which implies that the factors in the loop are playing a negative role. People, Products and Assets Visibility is maximum at first but with the passage of time it is decreasing; rapidly in initial days and then slowly with the passage of time, decreasing till the end. The inflow of people, products and assets visibility consisting of risk factors; transportation disruptions and exposure to natural disaster are decreasing the visibility of the system. In order to increase people, products and assets visibility, the impact of these resilient capabilities involved in inflow; transparent communication flow, collaborative information exchange, alternative sources to reallocate orders will have to be catered for. The impact of capabilities must be increased in order to decrease the effects of supply chain risks on whole system. The simulation result for people, products and assets visibility is shown in Figure 4.13

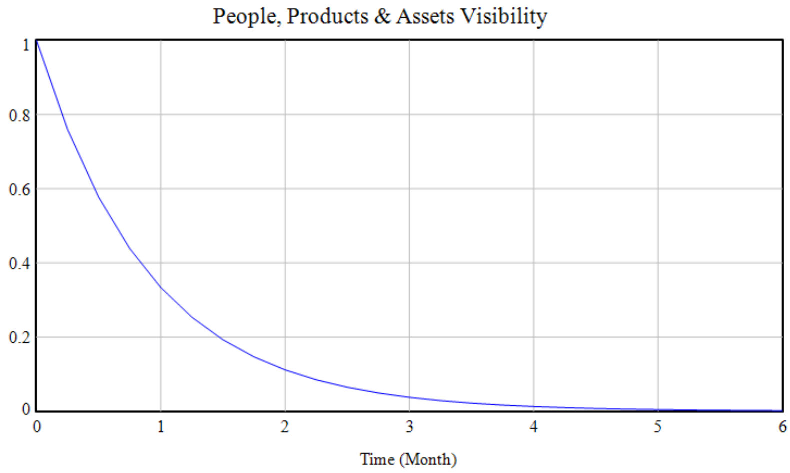

Figure 4.13 Simulation Result of ‘People, Product and Asset Visibility’

The graph of ‘Collaborative Information Exchange’ shows a draining process which implies that the factors in the loop are playing a negative role. Collaborative Information Exchange is maximum at first but with the passage of time it is decreasing; rapidly in initial days and then slowly with the passage of time, decreasing till the end. The inflow of collaborative information exchange consisting of risk factors; poor information coordination and visibility of errors to stakeholders are decreasing the information exchange in the system. In order to increase collaborative information exchange, the impact of the resilient capabilities; people, products & assets visibility and learning from experience will have to be catered for. The impact of resilient capabilities must be increased in order to decrease the effects of supply chain risks on whole system. The simulation result for collaborative information exchange is shown in Figure 4.14

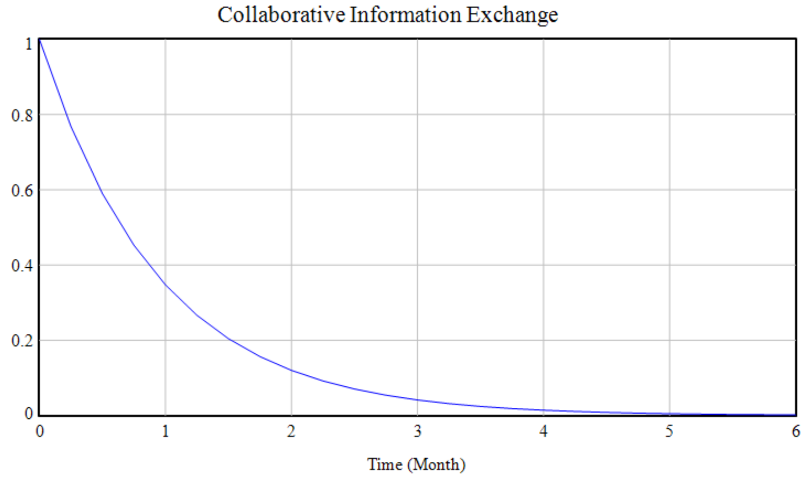

Figure 4.14 Simulation Result of 'Collaborative Information Exchange'

The graph of 'Process Improvements' shows a compounding process which implies that the factors in the loop are playing a positive role. Process Improvements is minimum at first but with the passage of time it is increasing till the end. The inflow of process improvements consisting of resilient capabilities; alternative technology development and demand forecasting are increasing the process improvements in the

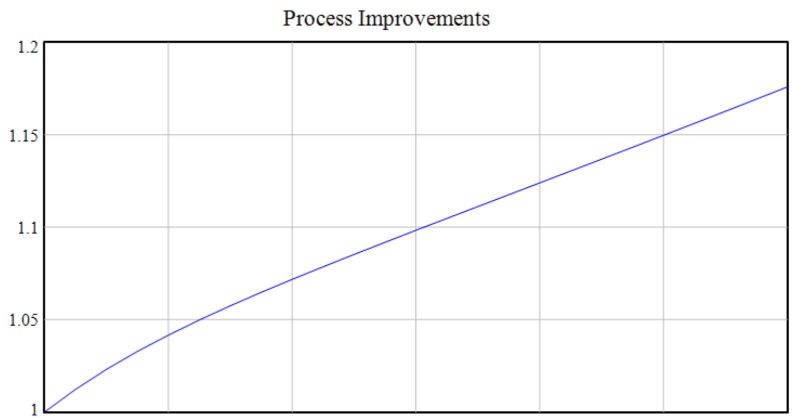

Figure 4.15 Simulation Result of 'Process Improvements'

system. This shows the strong impact of resilient capabilities on whole system to decrease the critical risks effects. The simulation result for process improvements is shown in Figure 4.15

The graph of 'Learning from Experience' shows a draining process which implies that the factors in the loop are playing a negative role. Learning from experience is maximum at first but with the passage of time it is decreasing; rapidly in initial days and then slowly with the passage of time, decreasing till the end. The inflow of learning from experience consisting of risk factor; insufficient management oversight is decreasing the learning experience in the system. In order to increase it, the impact of the resilient capability; business intelligence gatherings will have to be catered for. The impact of resilient capabilities must be increased in order to decrease the effects of supply chain risks on whole system. The simulation result for learning from experience is shown in Figure 4.16.

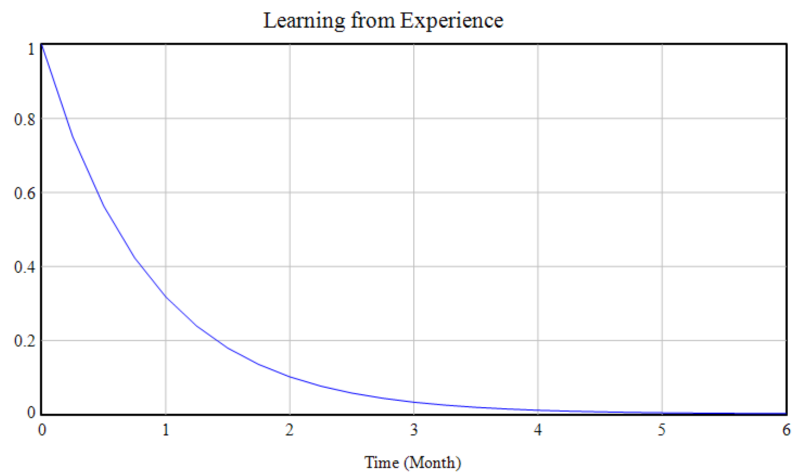

Figure 4.16 Simulation Result of 'Learning from Experience'

4.3 Model Validation

A system dynamics model addresses the problem and provides a solution to a complex system. In order to put confidence in a simulation model so that it shows right behavior for the right reasons, it is necessary to validate it using different validation tests (Qudrat-

Ullah and Seong, 2010). The model validation is a continuous and repetitive process, and hence this model was validated from beginning of its development till completion. Furthermore, to its validation the model and its results were presented to different construction industry professionals for expert opinion. The model was validated, and positive feedback was obtained from 10 experts of construction industry b0elonging to different organizations.

4.3.1 Boundary Adequacy Test

This test is used to authenticate that whether the essential concepts and structures addressing the problem are endogenous to the model or not (Qudrat-Ullah and Seong, 2010). The model must include all important variables which affect the behavior of interest. After examining the SD model, it was found that all variables were important and had been identified from literature.

4.3.2 Structure Verification Test

This test is used to confirm that whether the model structure is consistent with the relevant descriptive knowledge of the system being modeled or not (Qudrat-Ullah and Seong, 2010). The developed CLD and SD model depends on variables identified from literature and with the input of experienced industry professionals. Moreover, the influencing relationships used were also shortlisted with the help of input from experienced industry professionals. Thus, the model structure was considered as rational, logical and closely represented the actual system in the industry.

4.3.3 Parameter Verification Test

This test is used to verify the consistency of parameters developed in the model with the descriptive and numerical knowledge of the system (Qudrat-Ullah and Seong, 2010). The mathematical functions which were developed for linking variables were based on responses from field experts that ensure the empirical and theoretical foundations. The simulations developed also showed that model exhibited results related to the studies.

4.3.4 Extreme Condition Test

The test is used to ratify the logical behavior of the model when extreme values are assigned to selected variables (Qudrat-Ullah and Seong, 2010). Extreme values were assigned to the selected variables and then the model generated behavior was compared to the reference behavior of the system. Simulation results showed that even if the values were increased to 50%, the model showed meaningful results.

Chapter 05

CONCLUSIONS AND RECOMMENDATIONS

On the whole, the outcomes of this research have clearly portrayed a comprehensive image to the construction as well as supply chain professionals that if interrelationships not administered and dealt appropriately, how they could gear up a chain reaction in order to challenge and disrupt the whole supply chain. The data regarding the key supply chain risks and their current resilient capabilities has been presented to the construction organizations' and their respective supply chain partners' in this study. The interdependencies among the supply chain risks and resilient capabilities acknowledged through research surveys certainly makes us clear about the fact that one can never achieve resilience against supply chain risks and disruptions in isolation ignoring their interrelationships. The slightest ignorance by any member in the supply chain can radically worsen the whole supply chain situation.

The developing countries around the world are facing numerous supply chain risks in the field of construction industry. The supply chains have different tiers and to manage various parties and risks from those tiers is clearly a tough task. Many researchers (Ahmad Nawi et al., 2012) worked on this supply chain issue but there is a clear lack of literature figuring out the 'actual disruptions' in construction supply chains. The dynamics of the complex relationships between the organizations' risks and capabilities to mitigate disruptive events collectively still demands to be deeply analyzed. When gradually arising various risks, get through the level of networks there arises the need to develop resilience within organizations and their supply chains through deep analysis and investigations beyond the organizational boundaries.

5.1. Summary of Research

The purpose of this research work is to enhance the resilience within supply chains of construction organizations of developing countries so that they can accomplish their projects more efficiently and competently by introducing a risk resilience approach. This research aims to provide clear insight to the industry practitioners about the importance and interdependencies among critical risks and trade-offs between the most appropriate capabilities required to mitigate key risks to build a resilient supply chain and for continual improvement in such highly competitive industry. This research has accomplished its aim by fulfilling the following objectives:

1. To analyze the risks associated with the construction supply chain management.

This study has focused on the various current supply chain risks and disruptions that were faced by the construction industry of the developing countries. Various shortcomings recognized through literature in construction supply chain demands enhancements in project performance. Therefore, to improve efficiency of supply chains and to deal with the various supply chain risks confronted by the construction organizations, this study focused on to develop the appropriate resilience strategy in response to those risks. Detailed literature review was carried out in this research, to ascertain the current importance and value of various supply chain risks in industry to find ways to mitigate them and make supply chains more secure and steady. The disruption in supply chain is like chain reaction where if one chain is broken it affects all the other members of that chain in one way or the other, affecting the flow of materials and thus, the performance of whole system (Craighead et al., 2007). Furthermore, the three phases of disruption; pre-, during, and post-disruption were also studied to become familiar with how supply chains prepare, respond to and recover from the disturbances caused by various risks. The integrated approach to evaluate supply chain's reaction to disruptions alongside three disruption phases is discussed in this study to beware of various problems ascending from them and to improve the construction supply chain performance, bring it into a better state and make it more resilient.

2. To identify the capabilities necessary for a resilient supply chain, tailoring risks associated with supply chain management.

Detailed literature review was carried out in this study to understand the concept of resilience and to identify various resilient capabilities required to manage current construction supply chain risks. Preparedness of the system for any uncertain environment and stability of operations is supply chain resilience according to (Ponomarov and Holcomb, 2009). Removing risks with help of effective capabilities, ultimately make the supply chains more resilient to the disruptions. (Abidin and Ingirige, 2018a). This research study basically highlights the importance of resilient capabilities through the comprehensive literature and categorized them in proper list which were further used to make questionnaire to collect data from the supply chain professionals around the world.

3. To establish the interconnectivity and functionality amongst the identified factors in SC management, through System Thinking.

To shortlist the current construction supply chain risks and resilient capabilities collected from extensive literature review, the questionnaire survey was made and distributed among the professionals. It was identified from the survey that currently the organizations are significantly more vulnerable to health pandemics. Overall, the top five critical vulnerabilities of the supply chains of construction organizations that were identified from the survey, as Health pandemic, Budget overruns/ unplanned expenses, Poor information coordination and decision making, Insufficient management oversight on supply chain members, Visibility of errors/ deficiencies to stakeholders. Furthermore, those shortlisted factors were again sent to the experts through another questionnaire survey to find out the interrelationships between risks and capabilities, their causes and cascading effects on the projects' performance. The survey results show that these risks and capabilities are highly linked.

4. To assess the complexity and evaluate the integrated effect of supply chain risks and capabilities for a resilient supply chain, through System Dynamics approach.

The final system dynamics model in this study was developed from the findings of the questionnaire surveys and literature on the critical vulnerabilities, disruptions, and resilient capabilities of the supply chains of construction organizations. The set of resilient capabilities categorized to alleviate these critical risks were based on the literature and survey data. The system dynamics model presented in this study was justified by the field experts, on their understanding and clarity of the proposed model. This model will help the organizations to pay more focus on their critical risks in order to reduce the disruptions, to improve resilience and build better preparedness in the system. This system dynamic model clearly highlights the importance of risks and their relationship with capabilities to make entire system more resilient and to foresee, investigate and manage system's behavior accordingly.

5.2. Research Implications

5.2.1. Research Contributions to Theory

This research contributes to the existing literature by presenting a holistic view of managing construction supply chain risks in developing countries. The novelty of this research lies in the evaluation, integration and quantification of construction SC risks associated with organizations, technology and human factors and RCs in order to make a resilient SC.

So far, the main focus of the researchers was to manage risks at pre-disruption stage using traditional methods during construction projects. Realization of prevailing risks and using the existing resilient capacities to mitigate those risks have not gotten much consideration in literature. In short, this study utilizes an integrated approach to evaluate supply chain's reaction to disruptions alongside three disruption phases considering pro-active and reactive risk management strategies to improve the construction supply chain performance thus adding a holistic view to the existing construction literature. This research essentially bridges the literature gap in addressing the dynamics of complex relationships among 'actual' construction supply chain management risks associated with organizations, technology and human factors from resiliency perspectives using System Dynamics approach, which have not been considered by previous researchers.

5.2.2. Research Contributions to Practice

In terms of practical contribution, this research recommends the organization administrators to have complete check and balance of various risks and capabilities inside their organizations' as well as their supply chains'. It helps the construction industry practitioners to understand what the major risks are, their inter-connectivity regarding supply chain management, how these risks consequently transfer cascading impacts throughout the entire supply chain and how to get rid of them gradually. It helps to understand the trade-offs between suitable capabilities to abate essential risks, to develop their preparedness against disruptions in order to improve project efficiency and performance; a key towards the continual improvement and a more resilient supply chain. It is important to mention here that this research does not prevent the stakeholders, like clients or contractors in the construction industry from risk-taking, however it assists them to be careful of all the prevailing risks and capabilities and recognize them effectively.

In terms of the policy making, this study contributes by providing an input to the policy makers about the current competencies and critical risks faced by the construction supply chains. With the help of results of the research, the policy makers can take into account which areas need more attention and how to improve resilience by establishing various policies accordingly like use of Building Information Modelling (BIM), an advanced solution to increase the collaborative information and communication flow, which will in turn improve the visibility and productivity of the entire construction supply chain.

5.3. Research Limitations and Future Research

For this research, about 60 responses were considered enough for each questionnaire. Thus, for extensive analysis more responses could be collected to get more in-depth analysis. Additionally, case studies can be conducted to explore how these supply chain risks hinder the project performance during its different phases.

Future research might incorporate the supply chain risks and resilience assessment in other related industries like manufacturing and services sectors. For future researchers it would be thought provoking to examine that how the blockages across different tiers of supply chain network have cascading effects on other interdependent industries and to study their dynamics and interdependencies between supply chains. While using the risk resilience approach, future research could also consider the scale of disruption in terms of its severity and frequency. It will assist to decide the most appropriate resilient capabilities needed to counter disruptions having different level of magnitude.

5.4. Conclusions and Recommendations

Overall, the thesis has discussed the relevant research problem, the vulnerability of the construction supply chain to disruption. This research helps the industry practitioners and organizations to realize the importance and interdependencies among critical risks and trade-offs between the most appropriate capabilities required to mitigate key risks to strengthen their preparedness and supply chain resilience for continual improvement in such highly competitive industry.

The following recommendations can be made to diminish the existence of risk factors in the construction supply chain:

1. Set up the effective communication with suppliers to improve trust.
2. A risk management team can integrate suppliers with other parties and inform them about expected risks during the project. Previous projects review, particularly the risks, can assist the existing project to have preventive and corrective actions.
3. A useful problem-solving strategy should be exercised, to set apart the problem, its source, and seek out the workable solutions. Documentation as well as mitigation of the problems is mandatory for continuous improvement.

It must be kept in mind that these qualitative models can only ease the decision-making process by permitting the interdependencies and relationships to justify the complex system's behavior. These models cannot deliver any project specific advice to specialists. Therefore, to get detailed advice and practical solution for it one should practice the model in relationship and collaboration with a case-based or expert system to experience real time problems occurring in the construction supply chain.

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APPENDICES

Appendix 1 Preliminary Questionnaire

Respected Sir/Madam,

This survey is being carried out as part of Masters' Research titled "Complexities associated with supply chain risks and resilience in construction industry using a Systems Dynamics approach." This work aims to provide the clear insight to the industry practitioners about the importance and interdependencies among critical risks and the trade-offs between the right capabilities to mitigate those critical risks for building a resilient supply chain and continual improvement in such a highly competitive industry by using Systems Dynamics approach.

The main part of this research study relies on the questionnaire survey. The **objective** of the questionnaire is to investigate two main factors: **Risk factors** - important factors that make an organization susceptible to disruptions and **Resilient Capabilities** - qualities that enable an organization to anticipate and overcome disruptions

I would be grateful if you could spend a few minutes to complete this survey as your professional views and opinions are very important to the research. Please be assured that your response will be treated confidentially and with anonymity as the data obtained will be used for the purpose of this research only. If you have any question or concern about completing this survey, or more generally about my study, you may contact me through my contact details below. Please remember to click **SUBMIT** at the end.

Thanking you in advance for your time and input.

Regards,
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SECTION A: Respondent's Profile

1. **Name ***
2. **Email ***
3. **Please indicate your country ***

4. Please indicate your highest academic qualification *

BTech

BSc/BEng

MSc/MEng/MTech/PG Dip

PhD/DEng

Other:

5. Please indicate your respective organization *

Client

Consultant

Contractor

Sub-Contractor

Specialty Contractor

Supplier

If Other please specify;

6. **Current Designation ***

7. Please indicate your years of professional experience *

0 to 1

2 to 5

6 to 10

11 to 15

16 and above

SECTION B: Risk Factors effecting the Supply Chain

There are many risk factors that challenge the supply chain operations in construction industry. A total of 11 risk factors have been identified from a thorough literature review and are stated below. According to your experience and best opinion, mark the relative importance of each risk factor effecting the construction supply chains.

1. Political/ Legal Pressure	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
Our operations are vulnerable to Exposure to *political disruptions.*					
Our operations/products are susceptible to Strict or *fluctuating political/ regulatory policies*.					

2. **Market Pressures**	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
Our operations often face severe price fluctuations.					
Our services/products confront strong price pressure due to competitors.					

3. Environmental Factors	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
Social & cultural changes have significant impact on our ability to deliver our services.					
Our facilities/ operations are often exposed to *adverse weather events* or exposure to *natural disasters.*					
Our operations are susceptible to a potential *health pandemic* affecting our employees.					
Pressure from Public opinion/ reputation can exert significant pressure on our operations.					

4. Liquidity/ Credit Vulnerability	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
Changes in financial & economic policies extremely affect our money and assets management.					
We have *lack of financial resources* to cover all potential requirements.					

6. Technology Vulnerability	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
The *technology changes* in the industry greatly affect the design and performance of our services/ products.					
We regularly face *unforeseen technology failures* in our operations.					

7. Process Vulnerability	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
Our supply chain has *large number of members* in supply chain.					
Our products/services face *unpredictability of demands by client shifts* by client.					
limited *Raw material availability* for our product/ design are *scarce or in high demand.*					
P*oor availability of utilities* (electrical					

power, water, sewer) for production.					
Some equipment/ product used in our operations are use of failure-prone equipment.					
We have *limited production and distribution capacity to distribute* products/services.					
Our products/services often face *quality problem.*					
We frequently face *transportation disruption* during operations.					

8. Strategic Vulnerability	**Not Very Importan t (1)**	**Minor Importan ce (2)**	**Moderately Important (3)**	**Importan t (4)**	**Critical (5)**
Degree of outsourcing to different suppliers We *outsource* our operations to many different suppliers.					
We rely on *specialty sources* in delivering our products/ services.					
Our products/ services are threat by *competitive innovations*.					
Concentration of suppliers/ operation *facilities are* geographically concentrated at the same area and *highly co-dependent*.					
We provide *complexity of services*/ production operations.					

9. Management Vulnerability	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
R2.1 We have *insufficient management control* (over supply chain members)					
R2.2 *Poor information coordination and decision making* frequently affect our operation progress.					
R2.3 *Visibility of errors to stakeholders* in our operations.					
R2.5 We often incur *budget overruns* and unplanned expenses during operation/ production *due to improper planning.*					

10. Supplier/ Customer Disruption	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
R5.1 Our *suppliers* frequently face significant *disruptions*.					
R5.3 We often face the *loss of key supplier(s)* during operations.					
R5.4 Our *Customers* frequently face frequent *disruptions.*					

11. Personnel Vulnerability	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
R3.1 We have *shortage of* highly *skilled workers*.					
R3.2 We regularly face *labor disputes or strikes* during our operations.					
R3.3 *Potential safety hazards* for workers operating in extreme/ hazardous environments.					
R3.4 We often face the *loss of key personnel* during operations.					

12. Physical Damage Disruption	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
R9.1 Our products are regularly *stolen or vandalized*.					
R9.2 We often *face accidents* during operations. (i.e. fire, workers accident).					
R9.3 Our employees may be the target of *terrorism or sabotage.*					

Any other risk factor in your opinion (Not mentioned in this list)? *

SECTION C: Supply Chain Resilient Capability Factors

Resilience is defined as the ability for the supply chain to outlive, adjust and grow in the face of disruptions. Resilient capabilities help to prevent or mitigate an actual disruption and its effects to create resilience in supply chain. A total of 13 capabilities have been identified from a thorough literature review and are stated below. Based on your experience and best opinion, rate the level of importance of each capability that enables an organization to anticipate and overcome disruptions.

1. Adaptability	Strongly Disagree (1)	Disagree (2)	Neither Agree nor Disagree (3)	Agree (4)	Strongly Agree (5)
C5.4 We continually strive to further and process improvements to *reduce lead-times*					
C5.1 We excel *at seizing advantages from disruptions changes* in the market (by fast re-routing of the requirements.)					
C5.2 We use *innovative technology development* to improve our operations.					
C5.3 We effectively employ *continuous improvement programs* to (learning from experience.)					

2. Visibility	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
Business intelligence gathering (to be aware of future trends and technology) We are *highly aware of* future *trends* in industry and behavior of our *competitors*, *technologies & markets*.					
People, products and assets visibility We have *effective information systems* to track (*real-time data on location*) and status of supplies, finished goods, equipment and employees.					
C2.2 We have *regular interchange of collaborative information* exchange (among stakeholders) departments, suppliers, clients and other external sources.					

3. Flexibility	**Not Very Important (1)**	**Minor Importance (2)**	**Moderately Important (3)**	**Important (4)**	**Critical (5)**
C3.4 Our finished products/ *designs are flexible* to changes. product commonality (flexible design)					
C3.5 Our *supply contracts can be easily modified* to change specifications, quantities and terms.					

C3.1 We have many *alternative suppliers*/ sources for key inputs and can to *quickly reallocate orders*					
C3.2 We have a sophisticated *inventory management system* that combines demand projections and current orders, to keep the track of storage *capacity* and distribution services. fast re-routing of requirements (proper *inventory management system)*					
C3.3 We can *quickly change the route and mode of transportation* of the materials/ products. alternate distribution channels					
4. Anticipation	Strongly Disagree (1)	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
C4.1 We consistently monitoring early warning signals of possible disruptions or deviations from normal operations, including near miss analysis.					
C4.2 We effectively employ demand forecasting methods.					
C4.3 We have detailed contingency planning (drills, trainings etc.) to deal with possible disruptions.					
C15 We have a formal risk management culture.					

C6.6 We recognition of new business opportunities and take immediate steps to capitalize on them.					

5. Capacity	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
C5.1 We have significant *excess reserve capacity of materials, equipment and labor* to quickly boost output if needed.					
C5.2 We maintain redundancy (assets, labor) *access to alternative facilities and equipment for back up* in the event of disruption at the main facility.					
C5.3 We have reliable *back-up utilities* (electricity, water) for operation when the primary sources are disrupted.					

6. Efficiency	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
C6.1 We have effective *preventative measures to minimize the waste* of unnecessary production.					
C6.2 Our *labor productivity* is very high.					
C6.3 Our *resources* (labor, plant or material) *are consistently asset utilization* with no limiting bottlenecks.					

7. Collaboration	Strongly Disagree (1)	Disagree (2)	Neither Agree nor Disagree (3)	Agree (4)	Strongly Agree (5)
C7.1 Our *information flows* transparently between supply chain members to facilitate *collaborative decision-making*. Transparent communication flow (external, internal)					
C7.3 Our *clients are willing to delay their orders* when our production capacity is hampered by disruptions. Order postponement by clients due to disruption.					
C7.2 We have *proactive product life-cycle management* programs that strive to reduce both costs and risks.					
C7.4 Our firm invests directly t*o* share risks with partners (suppliers' or customers' operations) Risk sharing with partners.					

11. Recovery from disruptions	Strongly Disagree (1)	Disagree (2)	Neither Agree nor Disagree (3)	Agree (4)	Strongly Agree (5)
C11.1 We effectively *deal with crises and* take speedy measures to mitigate the *effects of disruptions*. Crisis management					
C11.2 We can quickly organize a *formal response team o*f key personnel, both onsite and at the corporate level to deal with disruptions.					

Resource mobilization (quick response team formation)					
C11.3 We have an *effective strategy for communications* in a variety of extraordinary situations.					

10. Dispersion	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
C10.1 Our organization empowers *on-site experts to make key decisions*, regardless of level of authority. Distributed decision-making					
C10.2 Our operation/ *production facilities are distributed* at various locations. Distributed assets & capacity					
C10.3 Our key inputs are sourced from a *decentralized network of suppliers. Decentralization of key resources (suppliers)*					
C10.4 Our *senior leaders* are based at a variety of *different locations.*					
C10.5 Our products are sold to *customers in a variety of geographic locations*. Geographic dispersion of market.					

9. Market Position	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**

C9.3 Our products/ services control a *significant share of the market.* *Significant market share*					
C9.2 Our products/ services have excellent customer recognition and a *strong reputation for quality*. Brand Equity.					
C9.1 Our firm has strong, *direct long-term relationships with* each of *our clients*. Customer relationships					
C9.3 Representatives of our firm *communicate effectively with* our *customers*. Customer communications					

8. Security	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
C8.1 We employ *layered defenses against deliberate threat* and do not depend on a single type of security measure.					
C8.3 We employ *strict restrictions of access* to our facilities and equipment. Access restriction (facilities, equipment)					
C8.2 We have a high level of *information systems security* to protect stored digital information. Cyber security					

12. Financial Strength	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
C12.1 We have considerable *insurance coverage* for facilities, equipment and personnel.					
C12.3 Our *financial portfolio diversification* is very *diverse.*					
C12.2 We have significant *financial reserves and liquidity*/ funds to cover all potential needs.					

13. Organization	**Strongly Disagree (1)**	**Disagree (2)**	**Neither Agree nor Disagree (3)**	**Agree (4)**	**Strongly Agree (5)**
C13.1 We as an organization have learning attitude, regularly using *feedback and benchmarking tools. Knowledge management (feedback control system)*					
C13.2 We strongly *encourage teamwork* and creative problem solving. Encourage teamwork and creativity.					
C13.3 We from time to time *train our employees* with variety of skills. Different skills training					
C13.4 We are *capable of filling leadership voids* very quickly at times of crises.					

Any other Resilient capability in your opinion (Not mentioned in this list)? *