Matching risk vulnerabilities with capacities for building supply chain resilience – a theoretical framework for low-probability, high-impact risks

Ming Zhou, Shu Zhou*, Tianqin Shi and Taeho Park

School of Global Innovation and Leadership,
Lucas Graduate and College of Business,
San Jose State University,
San Jose, CA, USA
Email: ming.zhou@sjsu.edu
Email: shu.zhou@sjsu.edu
Email: tianqin.shi@sjsu.edu
Email: taeho.park@sjsu.edu
*Corresponding author

Abstract: COVID-19 best reminds us of how every pain that is felt by supply chains goes to impact production. An aggregated framework of supply chain risk analysis is needed. This research endeavoured to theoretically structure the inter-relationships among supply chain vulnerabilities as well as corresponding capacity factors to mitigate supply chain risks and sustain supply chain resilience. An inter-relationship structure among risk vulnerabilities was mapped. Capacity factors were matched with each vulnerability category using anecdotal evidence found from various news and literature databases relevant to supply chain resilience concepts. The derived capacity-vulnerability typology revealed links between vulnerability and capacity factors and a structural model for risk prioritisation in managing low-probability, high-impact risks (LPHIRs). Production businesses and professionals shall find our findings a focused guideline for efficiently and effectively building risk resilient capacities. An extensive empirical study of our model with more comprehensive databases will better validate our theoretical results.

Keywords: supply chain resilience; risk management; low-probability and high-impact risks; vulnerability; adaptability; resilient strategic thinking; theory building and case studies.

Reference to this paper should be made as follows: Zhou, M., Zhou, S., Shi, T. and Park, T. (2022) 'Matching risk vulnerabilities with capacities for building supply chain resilience – a theoretical framework for low-probability, high-impact risks', *Int. J. Supply Chain and Operations Resilience*, Vol. 5, No. 2, pp.185–216.

Biographical notes: Ming Zhou is a Professor of Supply Chain and Operations Management in the Lucas College of Business at San José State University, USA. He received his PhD in SCM from University of Maryland, College Park. His research focuses on ecommerce, online auctions, online reputation systems, SCM, operations technologies, and data/empirical analysis.

Shu Zhou is an Associate Professor at Lucas College and Graduate School of Business, San Jose State University. She received her PhD in Operations Management from Cornell University, the S.C. Johnson Graduate School of Management. She received her Bachelor's degree in Management Information Systems from Tsinghua University, China, and a Master's degree in Management from Cornell University. Her research interests include SCM, inventory control, forecasting, and operations management-marketing interface.

Tianqin Shi is an Associate Professor at the Lucas College and Graduate School of Business, San Jose State University. She received her PhD degree in Operations Management from University of Illinois at Urbana Champaign, a Master's degree in Management Science and Engineering and a Bachelor's degree in Mathematics both from Shanghai Jiao Tong University. Her research interests include sustainable operations management, SCM, and operations management-marketing interface.

Taeho Park is a Professor of Supply Chain and Operations Management in the Lucas College of Business at San José State University, USA. He received his PhD in Industrial Engineering from University of Wisconsin-Madison. His research has focused on operations/supply chain management, environmental sustainability management, total quality management, enterprise risk management, and technology management.

1 Introduction

Businesses must deal with increased market fluidity in global supply chains as a result of global sourcing and globalised markets. In today's environment, supply chain disruptions are more common than ever, ranging from social and supplier/buyer uncertainty, political upheaval, and technical disruptions to natural disasters, pandemics, and so on. HMC, a South Korean automaker, ceased operations in 2003 after failing to reach an agreement with its labour unions. Its operations in Europe, Asia, Africa, and North America were halted (All Answers Ltd., 2018). COVID-19 was supposed to be a localised outbreak until it spread all over the world, wreaking havoc on the global economy. Risks surrounding business supply chains have become increasingly global and growingly complicated.

1.1 Supply chain resilience: vulnerability and capabilities

Supply chain resilience is a key concept in supply chain risk management (Pettit et al. 2010). Resilience was defined as 'the tendency of a material to return to its original shape after the removal of a stress that has created elastic strain' in engineering domains. Pettit et al. (2010) expanded the concept to SCM, in which a supply chain must not only deal with numerous uncertainties, but also return to normalcy within a reasonable time window, or even improve to a better state than before, as it recovers from risk occurrences.

This concept of resilience could be traced back to Svensson's study (2002) that defined supply chain vulnerabilities as: "unexpected deviations from the norm and their negative consequences." These deviations made a system vulnerable to unwanted consequences. Christopher and Peck (2004) proposed a framework of a resilient supply chain where vulnerabilities should be well identified and addressed through capacity building. Building resilience therefore meant instilling within a supply chain various capacities that would counter or prepare for vulnerabilities.

1.2 Research motivation and questions

The plethora of supply chain risk research built up a substantial repository of theories. But there is still work to be completed. This study aims to provide a theoretical framework that emphasises on the establishment of inter-relationships among risk vulnerabilities, followed by a typology that better links resilience capacities to risk vulnerability categories.

Fan and Stevenson's review paper (2018) concluded that a clear risk inter-relationship structure has been missing. Risks were individually categorised in existing literature, which hampered the development of a relational structure that connected risk categories into an organic entirety. A further issue with the lack of a risk inter-relationship pertained to risk assessment. Occurrence of one risk often led to rippling effects that triggered or precipitated other risks to manifest. Assessing risks individually could be misleading at least or it could even mean a complete misunderstanding of the scale, magnitude and scope of risk events. Risk vulnerabilities often struck together and their entangled impacts unfortunately hadn't been well studied.

Pettit et al. (2013) attempted to establish some links between risk vulnerabilities and resilience capacity factors. Capacity factors, which surely differed in their efficacy to deal with various vulnerabilities, seemed to be equally relevant in every vulnerability scenario in their work. Vulnerabilities were swept into a long and unstructured list without discussing their inter-relationships. Their goal of '... creating and maintaining a state of balanced resilience that mitigates risks without overly investing in excessive capacities…' was only partially achieved.

Building upon existing research, we believe that inter-relationships among risk vulnerabilities shall be a top priority. Capacities would then be holistically analysed within the framework of vulnerability inter-relationships for an efficient and more practical discussion of resilience. Capacities ranked by relevance to each vulnerability would enable a manager to allocate risk-countering resources intelligently for global, instead of local, considerations (Yadav and Samuel, 2021). Supply chain risk can be a vast topic in its entirety. Our discussion in this research is confined to low-probability, high-impact risks (LPHIRs). In summary, our research goals within LPHIRs are:

- identifying inter-relationships among risk vulnerabilities
- establishing a capacity and vulnerability typology that prioritises capacities for each vulnerability category to build balanced resilience for supply chains.

1.3 Main results and contribution

This paper employed qualitative research methods for theory building. We reviewed a large amount of literature in supply chain risk management and supply chain resilience. The research team identified and categorised over one hundred supply chain risk anecdotes based on their relevance to vulnerabilities and corresponding capacities. These anecdotes served as empirical evidence and practical inspirations for the development of our theoretical framework.

Our vulnerability inter-relationship clustered vulnerabilities into five groups, namely root macro layer, external layer, impact layer, mediating layer, and firm layer. These layers explicitly grouped vulnerabilities by their scale and scope of impacts and by their sequential relationship as suggested by current literature and anecdotes. Our layered structure specified how a vulnerability could cause or precede other vulnerabilities, which essentially sequenced and prioritised vulnerabilities. This interrelationship structure better enabled a business to focus on the key issues related to decision making and action taking for supply chain risks.

These vulnerability layers facilitated our discussion of capacities. We analysed capacities presented by current resilience literature. Our work better defined the meaning and scope of each capacity within the context of vulnerabilities. The typology could work as a to-do-list for a manager to further emphasise on the most relevant/immediate and potentially most effective capacities when dealing with a particular vulnerability. This typology takes us closer to achieve '...a state of balanced resilience that mitigates risks without overly investing in excessive capacities' (Pettit et al., 2013).

This is the first research to the best of our knowledge which explicitly and specifically tackles the issues of risk inter-relationships and resilience capacity typology. We will review existing literature in the next section. Section 3 discusses our methodology and iterative analysis. We map out vulnerability factors in an inter-relationship structure in Section 4 and develop our typology of capacity factors based on their relevance and efficacy for each vulnerability category in Section 5. Section 6 concludes this research.

2 Literature review

In this section, we attempted to cover literature relevant to supply chain risk and resilience. This review served the purpose of establishing theoretical background and identifying research opportunities. This section contained four sections, namely, types of supply chain LPHIR, stages of supply chain risk management, and supply chain resilience.

2.1 Types of supply chain risk

Tang (2006) defined supply chain risk management as 'the management of supply chain risks through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity'. He emphasised the need for more research on how to manage disruption risks rather than operational risks. Khan and Burnes (2007) reviewed extant literature on supply chain risks, focusing on how risk theory and risk management approaches might be applied to supply chains. They asserted that a concerted research effort would be needed to understand and manage risks embedded in supply chain functions. The importance of modelling interdependency between supply chain risks across many facets of a supply network was highlighted by Qazi and Gaudenzi (2016).

Supply chain risk management is often about risk types (operational accident, operational catastrophes, and strategic uncertainties) and risk stages (risk identification, risk assessment, risk management, and business continuity management) (Norrman and Lindroth 2004). Cucchiella and Gastaldi (2006) divided supply chain risks into two categories based on the source of uncertainty: internal source (such as available capacity, customs regulations, and internal organisational, etc.) and external source (such as competitor action, manufacturing yield, and supplier quality, etc.). Ritchie and Brindley (2007) developed a framework in managing supply chain risk with five major components: risk context and drivers, risk management influencers, decision makers, risk management responses, and performance outcomes. They pointed out that the five components should be interactive and dynamically related. Heckmann et al. (2015) identified three core characteristics of supply chain risk: risk affected objective, risk exposition, and risk attitude. Ho et al. (2015) classified the common supply chain risks into five types: macro risk, demand risk, manufacturing risk, supply risk, and infrastructural risk. After being identified, supply chain risks can be further assessed based on the probability-impact risk matrix (Hallikas et al., 2004, Blackhurst et al., 2008, Fan and Stevenson, 2018).

2.2 Low probability and high impact risks (LPHIR)

Risk has been generally categorised along two dimensions, probability and impact (Fan and Stevenson, 2018). Based on their alternate structural models, Ellis et al. (2010) suggested that, besides probability of supply disruption, magnitude of supply disruption was a significant determinant in the formation of overall supply risk perceptions. This categorisation may have overly simplified the actual complexity of the risk landscape, but it did offer a pragmatic framework for differentiating risks. Risk management process involves the estimation of the probability and the severity of an event, but it suffers from the inability to adequately characterise LPHIR (Pettit et al., 2010). Supply chain tsunamis (Akkermans and Van Wassenbove, 2018), defined as rarely occurring supply chain phenomena with low probability and high and sudden impact, have been overlooked by management and academia. While governments and policymakers have been concerned with low-probability disruptions such as extreme weather or widespread disease, businesses tend to care only about high-probability failures (Bhatia et al., 2013).

LPHIR often comes with rippling effects, which becomes visible only when the impact of a LPHIR event cascades downstream and cannot be held back locally, resulting in a sudden and high impact effect (Ivanov et al., 2014, Gao et al., 2019, Kinra et al., 2020). Simchi-Levi et al. (2014, 2015) developed a supply chain risk management approach with a focus on evaluating a firm’s vulnerability in order to reduce the need to estimate the likelihood of low-probability, high-impact events.

2.3 Stages of supply chain risk management

Fan and Stevenson (2018) conducted a thorough review of supply chain risk management literature, structured in line with the four main stages in the supply chain risk management process: proactive risk identification, thorough and swift risk assessment, pertinent risk treatment, and dynamic risk monitoring (Zsidisin, 2003, Jüttner et al., 2003, Neiger et al., 2009, Tummala and Schoenherr, 2011, Kern et al., 2012, Sodhi et al., 2012). They argued that risk transfer and risk sharing are more appropriate for LPHIR than risk acceptance, risk avoidance, and risk mitigation.

Their research highlighted the problem of a lack of studies on risk inter-relationships at several stages of risk management. First, at the stage of risk identification, risks have been classified into different categories thanks to extant literature, but researchers ‘...failed to identify inter-relationships between risks and risk categories’. Risk categorisation so far has been more isolated and segmented. Second, at the stage of risk assessment, manifestation of one risk could trigger the process of 'butterfly effect' that unfolded into materialisation of many other risks. Assessing risks/risk drivers individually or focusing on one risk/risk driver at a time would lead a manager to overlook the broader picture of the risk landscape. Acknowledging the lack of holistic approach in supply chain risk management research (Ghadge et al., 2013), Fan and Stevenson concluded that future research could look into interactions among risk drivers, risk inter-relationships, and intangible factors. This is the exact gap our research aspires to bridge.

2.4 Supply chain resilience

Pettit et al. (2010) developed a tool to measure supply chain resilience, the ability to cope with supply chain disruptions caused by a variety of sources of supply chain vulnerabilities. Through interactive discussions with focus groups, they identified seven vulnerability factors with forty specific vulnerability sub-factors and fourteen capability factors with seventy-seven specific capability sub-factors. The school of research has since then evolved (Pettit et al., 2013; Fiksel et al., 2015; Pettit et al., 2019). The latest version of vulnerability and capacity factors are shown in Appendices I and II. With those vulnerability and capability factors, they presented a supply chain resilience framework leading to supply chain resilience.

Pettit et al. (2013) showed empirical correlations between vulnerabilities and capabilities and developed supply chain resilience assessment and management (SCRAM) framework which enabled a company to identify and prioritise the supply chain vulnerabilities and capabilities. They cautioned people of applying a traditional enterprise risk management process, such as risk identification, assessment, mitigation and monitoring, because such a process identified and addressed each risk independently without recognising the hidden interactions among various risks, thus leading a company to make false or locally optimised decisions on supply chain risk management. Other supply chain capabilities discussed in existing literature include changeability, innovativeness, and sensing (Ehrenhuber et al., 2015).

Linking vulnerability factors and capability factors shall achieve the goal of balanced resilience because companies will avoid over-investing in capacities and best utilise its resources. There exist some studies on risk interrelationships. Ghadge et al. (2012) combined system engineering models with traditional risk modelling. Pettit et al. (2013) attempted to show the links between vulnerability and capacity factors, but vulnerability factor inter-relationships were not structured. Hachicha and Elmsalmi (2014) presented a structural model for risk prioritisation which illustrated a structure of supply chain risk topology that was mapped along a supply chain. Their structure greatly enhanced the understanding of SCM risks along the process of a supply chain.

We attempt to build on existing literature and directly study the inter-relationships of vulnerabilities. Vulnerability interrelationships are not trivial because they provide us with a holistic view of risks. With a clear understanding of vulnerabilities, risks can be better identified, categorised, assessed, and even monitored (Fan and Stevenson, 2018). We used the definitions of risks and vulnerability factors from the resilience literature (Pettit et al., 2019) and further elaborated on the concepts as their definitions and meanings have been obscure in current research. We theorised an inter-relationship structure of vulnerabilities. This vulnerability relationship structure therefore offered a cogent framework for resilience literature's capacity factors to be further analysed and positioned.

3 Theory building and methodology

To theorise a vulnerability inter-relationship structure and develop a typology of capacity factors on vulnerabilities, we first needed to establish a foundation of resilience theories. In this section, we also discussed the methodology and iterative analysis employed in this study.

3.1 Risk categorisation

We would like to define our focal risk category of this research before moving on to the resilience theory. In this research, our discussion of risks centred around one category, LPHIR, such as the COVID-19 pandemic. Supply chain literature normally classified risks by their occurring probability and impacts (Simchi et al., 2014; Fan and Stevenson, 2018). Four quadrants were developed along the two dimensions of probability and impacts. Each quadrant demanded different strategies. Low probability and low impact risks would normally be accepted due to their rare and uneventful nature. High probability and low impact risks could be well analysed and tamed with ample data points. Low impact nature made it uneconomical to over-invest in managing these risks, which necessitated acceptance or tolerance for this risk. High probability and high impact risks should be eliminated within a supply chain by risk avoidance. High probability combined with high impacts made this category unaffordable to almost all businesses. For example, avoidance could be discontinuing a product, cutting a tie with a vendor or quitting a geographical region entirely. LPHIRs strategies were mostly about risk transfer and risk sharing. Risk transfer meant assigning the responsibility to another party (Fan and Stevenson, 2018), which often involved insurance policies (Zhen et al., 2016). Risk sharing referred to involving another party to take risks jointly, which could mean a contract that hedged against some risks (Lai et al., 2009). Risk transfer and risk sharing have been proven valuable yet inadequate. Risk transfer and risk sharing tactics only endeavored to address some aspects of financial consequences of LPHIRs. Other aspects, including supply chain recovery and other rippling effects, have been untouched. Hence, LPHIRs seemed to be the risk category where a supply chain would be least prepared as prevailing strategies have mostly been either of less control to a business (sharing) or marginal/evasive in practice (insurance). Scholars and practitioners have been both wondering what a business could do internally and/or proactively to prepare for LPHIRs.

As Akkermans and Wassenbove (2018) discussed supply chain Tsunamis, LPHIRs had been so rare and infrequent that many managers never got to experience one throughout their entire career. Our era of big data seemed to make data analytics the solution for almost all problems. We realised that LPHIRs didn't lend themselves well to data analysis as they would by nature have a low probability. This meant enough data with consistent/comparable properties could be difficult to collect for a firm to learn from past experiences. Current categorisation of risks suggested that managers prioritised risks based on their expected value of loss, meaning probability multiplied by impact. LPHIRs couldn't be simply accepted like low probability and low impact risks in that the expected value of loss would be significant. On the other hand, LPHIRs ranked lower in priority than high-impact/high-probability risks given LPHIRs' lower expected loss. Yet, LPHIRs could very much be more perilous. One occurrence of such risk could mean eradicating markets, supply bases and/or even the entire business. COVID-19, other pandemics and similar events reminded us that this category deserved more of our attention. Pettit et al. (2010) saw the inability for our current risk management system to deal with LPHIRs as the greatest weakness of our systems.

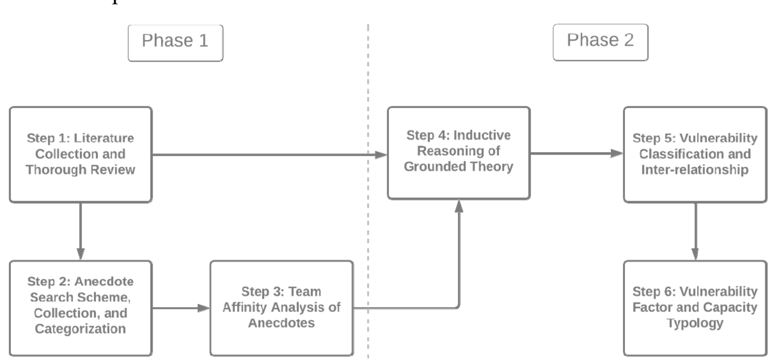
3.2 Methodology and iterative analysis

An ample dataset which supported a structural equation analysis or other empirical analysis methods would be ideal. We deliberated on many secondary data source possibilities and assessed direct data collection feasibility. A complete and robust sample to capture the full complexity of supply chain resilience theories turned out to be beyond our reach. As an exploratory research, we resorted to qualitative research methods to analyse our anecdotes and build our theoretical framework. Qualitative research methods have been often used for exploratory research (Min et al., 2013). Our research endeavored to build upon existing theories through new trends of anecdotal evidence. Eisenhardt (1989) believed that contrasting emerging trends/concepts with the current reservoir of theories could be conducive to building stronger theories, which attested to the validity and viability of our method. We employed a process based on the grounded theory method (Corbin and Strauss, 2014) to develop our theories. Inductive reasoning in grounded theory method (Handfield and Melnyk, 1998; Trochim and Donnelly, 2008) was greatly helpful in our brainstorming of theories and in coming to unanimous interrelationship results of resilience theoretical elements, as inductive reasoning involved synthesising experience, observation and anecdotes to come up with conclusions. Our analysis of anecdotes using these qualitative methods through a bottom-up approach empirically assisted us in conceptualising existing theories and contextualising their relationships.

We went through a two-phase process in our research. A flow chart of our process for conducting this research is in Figure 1.

In phase one, all four researchers were tasked with two items, familiarising ourselves with resilience and supply chain risk literature and collecting anecdotes related to supply chain risks. All four researchers were trained specifically in the field of SCM with years of research (varying from 10–30 years) and consulting experiences (varying from US and international small businesses to large US and International corporations).

Figure 1 Research process



In our literature collection, we traced back to the original works of supply chain resilience and reviewed most of the resilience research following the founding paper. We also expanded our review to major categories of supply chain risk articles as documented by Fan and Stevenson (2018). This familiarisation process took about six months. Meanwhile, following the structure of supply chain resilience literature (Pettit et al., 2010, 2013, 2019), our team searched various news and literature databases for anecdotes that were relevant to supply chain resilience concepts.

At the beginning, our team selected various literature research portals, including Lexisnexis, ABI/Inform, Google/Google Scholar, Harvard Business Review, Sloan Management Review and so on. Usual academic, business and news media were all included in order to come to as inclusive a collection as possible. Supply chain risks and resilience were initial keywords for these searches. We quickly came to the realisation that such keywords were overly broad and lacked efficiency. The team came together for keyword refinement by reviewing first round results. Our original plan was to gather a large set of search results and then categorise them by vulnerability factors. It turned out that direct searches with explicit usage of vulnerability keywords produced much more efficient results. This experimentation encouraged us to proceed with vulnerability keyword search and bypassed general keywords. Next, the team simultaneously conducted content analysis of all searched anecdote results (Kolbe and Burnett, 1991). Extensive attention was paid to content uniqueness and information clarity. Many anecdotes quoted the same risk event where such duplication of information content was removed to keep our anecdotal content parsimonious. Major risk events were often exorbitantly covered by multiple news media and outlets. We decided to keep the article that most extensively covered a risk event as the unique anecdote in our record. In the third step, everyone had to thoroughly and independently review all collected anecdotes and come to their own categorisation of where each article belonged. We followed affinity analysis steps for analysing unstructured text data (Sanida and Varlamis, 2017). Each member then presented their own categorisation to other team members and repeated deliberations of categorisation were conducted. Anecdotes gradually converged to categories over time. Disagreements were resolved with team discussions and iteration. An article could mention more than one anecdote. Each anecdote could reveal information belonging to one or multiple vulnerability factor categories. This process led to one hundred and nine anecdotes classified into different groups of vulnerability factors. Their categorisation was summarised in Table 1.

We specifically focused on the sub-factors of each vulnerability as these keywords would be more relevant and specific in search. Result noises were significantly reduced through sub-factor search. Another benefit of sub-factor search was that sub-factors facilitated anecdote classification. Not all anecdotes were unique in sub-factor categories. The team conducted content analysis to further label an anecdote by all of its relevance (Kolbe and Burnett, 1991). The team then had iterative reviews of anecdotes to verify and conclude on their relevance to each vulnerability category. The team collected 109 anecdotes and their classification was presented in Table 1:

In phase two, equipped with a high level of familiarity with current literature and a large set of anecdotes, the team started the process of theory building. All four researchers were asked to develop their own theoretical framework and interrelationships. Versions of theories were compared and contrasted during regular meetings. The team further defined and elaborated on resilience vulnerabilities and capacity factors based on literature and anecdotes. The original work of resilience literature was mostly high level in theory, manifestation and practical meanings of vulnerability and capacity elements were mostly unclear. Our team took the liberty and characterised them (Appendices A and B). Such clarification for better granularity made relating resilience theory to real life examples possible and assisted us in further proposing interrelationships.

Table 1 Anecdote summary

Vulnerability factor	*Industry anecdotes*
Turbulence	22
Deliberate threat	12
External pressure	15
Resource limits	19
Sensitivity	15
Connectivity	16
Supplier/customer disruptions	11
Sum:	109

Validity of our theoretical structures has been continuously examined based on theories, anecdotes, experiences and intuitions. We were able to come to agreement on 75% or 80% of interrelationship frameworks after a couple rounds of meetings. Further disagreements were resolved based on reviewing literature and anecdotal evidence. Final disagreements were finalised by senior members of the team after thorough and extensive deliberations (Hussain et al., 2010; Rask and Kragh, 2004). Our initial version of interrelationships was validated and refined after rounds of agreement reaching and deliberation. The final theoretical framework was developed as presented in later sections of this research.

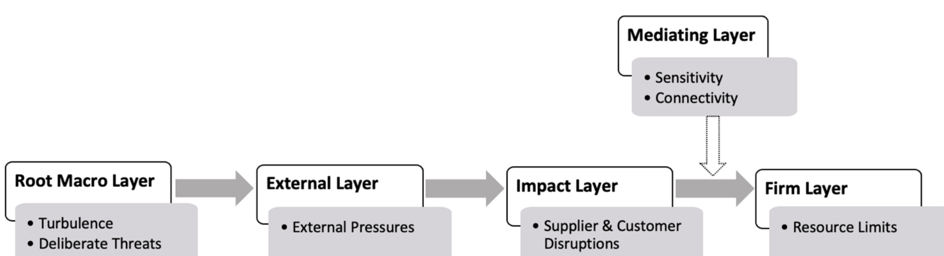
4 Vulnerability interrelationship

Before discussing our framework and mapping out vulnerability factors in an inter-relationship structure, we would like to first revisit the famous Cisco case (Akkermans and Wassenbove, 2018) to set the tone of our discussions. This case thoroughly presented the intricacies of a LPHIR event and the subtle yet relentless process through which a LPHIR event unfolded. IBS Centre for Management Research (ICMR, 2002) stated that '... in early 2001, the global IT business slowdown and the dotcom bust altered the situation. Reportedly, Cisco failed to foresee the changing trends in the industry and by mid-2001 had to cope with the problems of excess inventory. As a result, the company had to write off inventory worth $2.2 billion in May 2001…'. Actual pain felt squarely by supply chain practitioners could be traced back to deeper reasons. Weinberger (2016) commented on the market environment before IT bust around year 2000 as 'venture capitalists and investment banks, sensing a chance to make a lot of money from this boom and taking advantage of low interest rates, started investing millions in companies like grocery-delivery startup Webvan…'. The abundance of investment capital was not created out of thin air. Prevailing low interest rates propelled money into the economy and enabled inventory carrying at lower costs. Akkermans and Wassenbove (2018) pointed directly to Cisco's supply chain structure and outsourcing model as the root cause. Cisco had the bulk of its inventory made by contract manufacturing. The rationale was that Cisco's internet-powered organisation was supposed to bind together its vendors, contract manufacturers and Cisco into a smooth process. Unfortunately, such network-heavy structure did not alleviate much of the pain when the bubble burst (Bryne and Elign, 2002). ICMR (2002) documented that Cisco shipped equipment directly from manufacturers to buyers. The handful of contract manufacturers relied upon large sub-tier vendors for components, such as chips and other elements. The sub-tier vendors further depended on commodity suppliers around the globe. In order to counter the scarcity of commodities and components, Cisco had to lock in supplies via long term contracts. Inventory piled up through this process and artificially inflated demand up the supply chain.

At the beginning, we could clearly see low interest rates drove easy capital. That fed into an unpredictable demand and distorted currencies and prices. They led to price pressures on supplies which further caused Cisco to over-purchase and secure supplies' capacity. Cisco's unique product, by design, rendered itself sensitive to a complex network of supply chain entities. First, its products required a slew of components and scarce commodities. Capacity was concentrated within a handful of contract manufacturers (ICMR, 2002). Manufacturing and components were highly outsourced through a complex network of supply chain entities. Cisco's own visibility couldn't go deep enough into upper streams of supply chains. Suppliers struggled to meet Cisco's order before the economy went into a recession driven by the IT bubble. Both supplier side and demand side were disrupted. Cisco's own resources then felt the pain by writing off a huge amount of inventory that was expedited through its own supply, production and distribution networks. Vulnerability factors cascaded from macro-factors to supply chain and then firm specific aspects.

The Cisco case was not alone. Supply chain risk events often unfolded in a similar manner. Risk events tended to be sequential. Sweeping all of them under one carpet missed the interactive/correlative nature of risks. We therefore proposed a theoretical interrelationship structure of SCM risk vulnerabilities as illustrated in Figure 2.

Figure 2 Vulnerability interrelationships and structure



The structure had five layers. We were not suggesting that every event strictly followed the entirety of our structure or all elements were at work strictly as we proposed. Instead, our structure served as a general depiction of how risk events could take place.

Turbulence and deliberate threats were the root layers. These macroeconomic factors often looked irrelevant and distant at the beginning. Managers immersed in daily operations usually didn't care to look out for these macroeconomic causes and failed to detect early signals. Managers connected the dots of these vulnerabilities to supply chain problems only in hindsight.

External pressures could be traced back to macro reasons in many cases. For instance, issues in California part-time labour policies led to the passing of a regulation broadly banning almost all gig workers (Associated Press, 2021). This could render all part time delivery services illegal, which heavily impacted the last mile of supply chains. Microeconomic level manifestations of macroeconomic impacts belonged to the layer of external pressures. They were narrower in scale. Vigilant managers could often smell them when these factors lurked in the darkness.

A direct hit to a supply chain could be either right on an individual entity or first on the entity's supply/demand partners. Vendors' tight supply or buyers' cancellation of orders could be caused by price pressure, cultural changes, better competitive innovations and so on. This was where a supply chain manager, even the most insensitive ones, started to feel the pain of risk events. How much this may hurt could be either alleviated or exacerbated by the mediating layer. Sensitivity of a firm's process and product requirement might offer a manager more or less leeway in countering the impact of a risk event. Similarly, a tightly weaved network without much room of decoupling simply felt more pain from a risk event. The mediating layer really defined the pain levels.

Finally, after all previous vulnerabilities had their turns, a firm would have nowhere to hide. Pandora's box of risks would be wide open. Distribution, production, material supply and labour sometimes all ran into complete turmoils. A manager would be left to scramble through the full mess if no preventative measures were timely taken. The process of a low probability yet high impact risk, like the Cisco case above, could impact all layers above. This was a reason why we believed our structure of vulnerabilities bore more relevance especially to low probability and high impact risks. For a detailed discussion of vulnerabilities, please refer to Appendix A.

5 Capacity and vulnerability typology

In this section, we turn our attention to how capacity factors could be better sorted within the structure of vulnerability factors (The complete list and a thorough review of capacity factors are included in Appendix B). Resilience literature laid the foundation of vulnerability and capacity factors. But how relevant or helpful each capacity factor could be in dealing with a vulnerability factor has not been discussed much. One reason for that has been the lack of a structure of vulnerability factors. For instance, Pettit et al. (2013) established some links between vulnerability and capacity factors in absence of a vulnerability structure but the discussion was more about potential relevance than practically strategic guidance. All capacity factors seemed to be relevant to every vulnerability factor. What capacity factors best protected a firm from a certain vulnerability scenario was unclear. Lack of clarity in how vulnerability and capacity factors interacted would make it harder to achieve the goal of '... create and maintain a state of balanced resilience that mitigates risks without overly investing in excessive capacities…' (Pettit et al., 2013). We tried to cluster and organise capacity factors where they looked most relevant. Our discussion did not exclude the possibility that these capacity factors could be relevant to every vulnerability factor in some indirect, remote and/or even extreme cases. We were simply arguing that some capacities were positioned to be more directly relevant than others in dealing with a vulnerability factor. It was important to understand that capacity factors varied by their strategic or operational scales. The strength of their relevance to each vulnerability context, based on our anecdotal evidence, guided us in fitting them within our vulnerability factor structure. Our perspective was more about what a firm could swiftly pick out of the list of capacity factors when it came to a specific vulnerability factor.

5.1 Root macro layer

- Turbulence: Visibility, anticipation, and dispersion.
- Deliberate threats: Visibility, anticipation, and security

At the most root cause layer, some capacities deserved more attention from a supply chain manager. These capacities shall help a firm dealing with macro layer vulnerability factors. Turbulence's beyond-your-control nature required a manager to first envision the possibility that turbulence could take place and hurt. Recognition and foresight were paramount in order to respond to these seemingly remote yet devastating risk causes. For instance, political forces that turn economic systems into offensive tactics have not been rare in our current world (Farrell and Newman, 2020). At this layer, visibility and dispersion were top priorities to stay alert to turbulence. Sheffi (2015a) advocated early detection systems, which included monitoring not only weather and news for political and economic changes, but even social media for a timely update of major markets and vendor locations. The key was to build up visibility beyond traditional supply chain operations and expand into macro-level monitoring. These data would enable predictive analysis for anticipation. Having better visibility through an early warning system also enabled anticipation. With predictive insights, a firm might even engage in active lobbying to delay or prevent drastic adverse changes. Dispersion in supply chain structure helped a company hedge against risks of over-concentrating within a certain area or market. Dispersion reminded a manager of the idea of diversification by spreading resources in multiple locations so that turbulence in one area wouldn't disable the entire system. O'Neil (2016) showed a good example of how dispersion could help alleviate supply chain risks. It was the year 2000 when Philips Electronics facility in Albuquerque, New Mexico, caught fire due to lightning. The facility was responsible for manufacturing cellphone chips that supplied many cellphone makers, including Ericsson and Nokia. Impacts on these cellphone makers were sharply different. Nokia maintained relationships with other suppliers. These suppliers managed to open up capacity for replacement parts. Nokia was a lot less impacted. Ericsson, on the other hand, lived a different life. Their dependence on Philips cell phone chips devastated Ericsson's operations.

Deliberate threats shared two common capacities of visibility, anticipation with turbulence because of similar logics. A different capacity for deliberate threat was security in order to prepare for thefts, espionage and even sometimes terrorism/sabotage. McDowell (2020) presented some major issues in supply chain security that were deliberately designed to undermine data and information integrity along a supply chain: '...With up to 80% of cyber-attacks now beginning in the supply chain, breaches at even the smallest vendors can have big consequences for enterprise level operations. The problem of supply chain cybersecurity has become so pressing that the USA Department of Defense is rolling out the cybersecurity maturity model certification (CMMC) as a means to help secure the defense industry. Prime contractors and subcontractors will have to achieve CMMC compliance to do business as part of a DoD contract...' He identified four steps to build up security capacities, starting with each member of a supply chain. In a digital era, the importance of information and data security couldn't be overstated.

Our anecdotes suggested that the most relevant capacities had to be doing a better job to alarm (anticipation and security) and prepare (visibility and dispersion) supply chains for turbulence and deliberate threat risks of a supply chain.

5.2 External layer

- External pressures: visibility, anticipation, security, dispersion, financial strength, and market position

External pressures were more microeconomic in nature. Sub-factors included competitive innovation, social/cultural change, political/regulatory change and so on. A supply chain manager shall actively monitor these vulnerabilities through visibility, anticipation, dispersion and security capacities as described previously. Financial strength was a direct preparation for price pressures and environmental changes. Financial reserves shall be on a firm's top agenda when external pressures were considered probable risk causes. Market position encouraged strengthening branding and product differentiation, building customer loyalty and sometimes bettering customer communications. These capacities involved more than just supply chain departments. Senior management had to champion such initiatives as support and cooperation from other functions would be needed.

When the iPhone unveiled the smartphone era, markets for existing models by Nokia, Blackberry and Motorola were severely squeezed. When people became more aware of food health information, traditional fast foods had to adjust to the newer cultural changes. But none of these trends would be on the task list of a supply chain manager's daily routines. Competitive innovation and social cultural changes were often off the radar of a company's supply chain functions. As we discussed previously, Sheffi (2015b) research advocated a system that broadly monitors many social-economic aspects. This early alarm system shall also cover scanning for competitive innovation and social/cultural changes through building on visibility and anticipation. The ten supply chain risks identified by Kamal and Larsson (2019) presented several such factors for a supply chain manager to consider, such as tougher environmental regulations, drones and aviation safety. All of these shall be better understood through visibility and anticipation capacities. Similarly, corporate responsibility and environmental changes were most often policy and socially/culturally driven. Changes on these aspects could take a long time to become noticeable, from the beginning of discussions to actual policy mandates and/or social/cultural movements. Visibility and anticipation capacities covering these aspects would be greatly beneficial for SCM. A large firm or an industry association might even have the power to influence such changes.

An industry that has been experiencing fluid conditions was the pharmaceutical industry. Key active pharmaceutical ingredients (API) have been more often sourced from developing countries. Price (2017) warned about the impact of stricter inspection enabled by the generic drug user fee amendments (GDUFA). Failure to pass inspections by FDA could easily cancel out all the savings from cheaper prices overseas. Meanwhile, regulatory changes imposed great risks on product approval overseas. New regulatory requirements in China were determined to be challenging standards for pharmaceutical companies. A supply chain manager in this industry would have to better understand regulatory policies in preparation for more stringent requirements.

A noticeable sub-factor of the external pressure layer was price pressure. This was just one sub-factor but it carried significant operational importance. SCM was not an isolated function within a firm. It was impacted by many external factors of a business. Mishler (2017) documented a very interesting case related to price and procurement costs: '…Unilever blamed its price increase on the British pound's devaluation against both the euro and the dollar since the UK's Brexit vote in June 2016…Under the scenario where Unilever's ice cream sold in the UK. denominated in pounds had a product cost in dollars, Unilever's profit (and cash flow) decline would be 21%. (The profit decline is greater than the currency decline because the sales in British pounds are greater than the costs in dollars.) In a less profitable business, such an adverse currency rate movement could potentially wipe out any profits from sales or, even worse, render a company insolvent.'

The root cause was currency change under Turbulence, but it further materialised into price pressure as procurement costs and sales price both were inflated. There were other reasons for how the price of a product could be under pressure. For instance, when Uber first came to the market, their rates were severely reduced simply to drive competitions out of the market (Krisher and Liedtke, 2019). Price pressure could come from supply side cost increase, competitors' pricing and other sources. Several capacities could be established to deal with price pressure for a supply chain. Mishler (2017) specifically discussed dispersion where a large firm sourcing from multiple countries could hedge against currency fluctuations and price pressures by contracting in local currencies. Companies with good financial strengths would better weather the storm of price pressure. Financial strength was not just about having more reserves. Actively managing and hedging financial risks were good indicators of financial strength as well. A good example was reported by Industry week in 2013 (Blanchard, 2013). Toyota Industrial Equipment Manufacturing ran a budget system under close collaboration between the finance and supply chain department. The budget was about making sure all key activities were funded. The same article also documented the establishment of a commodity risk management system at PepsiCo for more effective SCM. As advocated by consulting firms like Accenture, an integrated team that combined both finance and SCM expertise, shall focus on not only real product flow, but also corporate level risk and financial performance.

Market position served as an alternative to supplement financial strength capacity. Price sensitivity of a market greatly exacerbated or alleviated the impact of price pressure from sourcing. A less sensitive market would be much calmer under price pressures. Market position could well desensitise price sensitivity, such as differentiation, loyalty, brand power and customer relationships. Though these sounded way out of control from SCM, senior executives shall at least try to understand the impact of price disruptions within the context of price and customer sensitivity of relevant markets.

5.3 Impact layer

- Supplier disruptions: Flexibility in sourcing and collaboration.
- Customer disruptions: Flexibility in order fulfillment, collaboration, and market position.

Flexibility in sourcing or order fulfillment could be confused with dispersion. Dispersion was more a concept of organisation structure and internal decision process. Flexibility on the other hand meant multiple sources and fulfillment which necessitated design modularity, contract flexibility, channel variety, inventory responsiveness and transportation, etc. Collaboration encouraged a firm to define and authorise information sharing. That sharing was not limited to only demand or quality information, but also things related to risk management. Market position was brought up here again as customer loyalty surely helped in the case of disruptions.

Let us focus on supplier disruptions first. Lynch (2012) presented a case that wreaked havoc along the healthcare supply chain: In May 2009, Atomic Energy of Canada Ltd. scheduled an NRU reactor shut down for maintenance for five days. 'The medical diagnostic isotopes produced at this facility represent approximately 50% of global production and are a critical element in the North American healthcare supply chain. It is the only source of base isotope for technetium-99. They are used for diagnosing and treating heart conditions and certain types of cancer, and are injected into patients in the USA 20 million times a year'. But this routine shutdown resulted in an unforeseen 60-day delay, leaving procurement managers at hospitals, imaging services, and healthcare organisations throughout North America unprepared. A repeating and routine five-day maintenance shaped the comfort zone of these managers and they prepared their inventory accordingly. This prolonged delay warned nobody ahead of time.

Chopra and Sodhi (2014) alerted supply chain professionals to segment and be flexible in sourcing. Flexibility in sourcing, such as multiple sources, gained popularity. London-based Diageo, the world's largest distiller, regionalised its supply chain by sourcing from multiple regions. Zara has sourced from Turkey and Asia, instead of simply concentrating in expensive European countries. Multiple sourcing often required a supply chain to standardise common parts and modularise design. Supply chain facilities shall possess the capacity of multiple uses. For example, Zara has set up its production system in a way that multiple facilities could produce both high and low volume products.

As discussed before, Nokia was a lot less impacted from the fire at the Philips Electronics facility than its competitors because it maintained relationships with other suppliers that set aside capacity for Nokia to produce replacement parts (O'Neil, 2016). It was very likely that there were some flexible contracting arrangements between Nokia and its suppliers as business relationship with suppliers was a foundation for Nokia. More importantly, their contracting couldn't be so rigid or fixed which left no room for flexibility. O'Neil (2016) specifically commented on contract flexibility as a capacity for dealing with supplier disruptions: 'Some companies may enter into contracts with suppliers that allow for last-minute orders in the event of a disruption without necessarily buying regularly. While it may still be necessary to keep some additional inventory, a focus on flexibility lessens the need for costly and often unused duplication at every stage of the supply chain.' Both cases pointed to contract flexibility as key apparatuses to mitigate supply risks.

Expanding a supply chain demands a higher level of collaboration. When traditional IT investment focused heavily on monitoring material flows and information flows, these systems could be better deployed to counter disruptions (Chopra and Sodhi, 2014). Information sharing along a supply chain and automated systems assisted a manager in identifying incidents and quickly reformatting plans to come up with solutions. For example, Hong Kong based Li & Fung Ltd used their IT for a variety of contingent plans (Chopra and Sodhi, 2014). IT lifted the level of collaborations along their supply chain.

Flexibilities in order fulfillment means multiple alternatives and leeways for a company to reach its clients. When Japan was hit by the Tsunami in 2011, it was not only sourcing that was stopped. The shipping routes to clients were unusable either (Tokuyama, 2012). When some routes were blogged, having alternative routes or vendors from other areas could greatly help a company keep its performance. Apple Stores has been the company's major brick-and-mortar channel of order fulfillment. The COVID-19 made in person businesses entirely impossible. Having online distribution through its own website and other online retailers, such as BestBuy, made business performance more sustainable. Postponement strategies like the Benetton strategy (Dapiran, 1992) could come in handy in dealing with demand uncertainties. Classification of inventory and deploying risk pooling strategies would be smart choices. Illinois based Grainger company kept fast moving items at stores and distribution centres. The slow-moving items were only in distribution centres in Chicago. This arrangement greatly prepared the company's supply chain against potential disruptions (Chopra and Sodhi, 2014).

Warnica (2014) mentioned Lululemon's new CEO Laurent Potdevin, who was the former CEO of snowboarding company Burton. Potdevin's tenure at Burton was highlighted by his expansion of Burton's product lines 'The hardcore snowboard market was loyal and growing, but like the yoga niche, it was limited. And the company's sales at the time were dangerously weighted toward hard goods–snowboards, bindings and other technical gear. That left Burton vulnerable to bad snow years, when sales would drop, or to new rivals who could swoop in and steal a chunk of the market.' The market position Burton held in the snowboarding market and among snow enthusiasts was strong and unique. This enabled Burton to successfully add product lines for bad snow years. 'Most action sports brands... made more than a quarter of their sales from basic clothes–T-shirts, hats, hoodies. But at Burton, that business was almost non-existent. Potdevin changed this, quickly.' Under his direction, a new line of simple branded clothes, Burton Basics, was set up. 'It was such low-hanging fruit... in the first year it went from US$1 million to US$8 million.' By the third year, sales had reached US$27 million.' This was a clear example where a market position helped a firm hedge against customer disruption risks.

5.4 Mediating layer

- Sensitivity: Flexibility in sourcing, flexibility in order fulfillment, adaptability, and product stewardship.
- Connectivity: Flexibility in sourcing, flexibility in order fulfillment, dispersion/capacity, security, collaboration, and product stewardship.

Sensitivity defined how stringent operations requirements would be for a supply chain to function normally. When sourcing and/or fulfillments were discussed at the level of product modularity and postponement, they became relevant to sensitivity. A modular product or modularly designed product could adjust better and easier when an unforeseeable event struck or when the tide changed in demand, supply and/or operations conditions. Wiggle rooms thanks to modularity in product design and operations process (postponement) rendered a situation less sensitive and more manageable. Adaptability has been at the core of sensitivity. Modifying operations with pre-developed plans and simulated results made a firm better prepared and less sensitive. Product stewardship's sustainability aspect could reduce sensitivity if sensitivity was a factor considered in product design. Restricted materials apparently would not be so sustainable. Production processes could be designed to ease the stringency or purity requirements. Complexity of operations could be simplified by segmenting production processes using work cell groups (Russell and Taylor, 2019).

Connectivity touched on how connected a supply chain system would be. A tightly connected supply chain tended to be more interdependent. Again, flexibilities came into play as capacities for a supply chain manager to consider. Parts of the very definition of flexibility in sourcing and fulfillment meant network design and intermingling relationships. Right level of flexibility decided how connected a supply chain could be. Having alternatives in supplies enabled a supply chain to quickly reshape and reshuffle for alternative sources, which made a supply chain less tightly connected. Decoupling some functions from the same chain of flows limited the rippling effect along the supply chain by keeping adverse impacts contained within a smaller set of elements of a supply chain. Modular design helped a supply chain to diverge in supplies when tasks were modularised for alternative sources. These sourcing preparations would alleviate the pain of a tightly connected network of vendors. On the demand side, inventory management got to be better organised as modularity reduced inventory level and enabled risk pooling. Contained and isolated functions of modules could make sourcing from multiple vendors easier, which in turn benefited flexibility in order fulfillment. Similar to sensitivity, connectivity could also use some help from product stewardship. Specialty sources and import/outsource channels could both exacerbate a risk situation where a firm's system/process design at the product stage could take such matters into its consideration. Solutions from product stewardship could overlap with some other discussions, such as diversifying channels and sources, but a discussion here shall serve as a necessary reminder at a different operations stage for actively approaching these vulnerabilities.

Dispersion/capacity would be a good method to build redundancy for the reduction of connectivity. Additional nodes along a supply chain could be intentionally built just to be mobilised in the case of emergencies. Dispersion strategy in general could be a double-edged sword. On one hand, an overly centralised decision process could be more vulnerable to external impacts. On the other hand, decentralisation could undermine decision and operations efficiency. Dispersion shall be carefully gauged to a balanced level. Collaboration combined with dispersion could determine the scale to which a supply chain entity depended on others. Redundancy established by dispersion could mean lower probability of collaboration as the supply chain grew too big and too complex. On the other hand, more collaborative entities within a supply chain would be more dependent but also sharing information better, which facilitated early risk detection and joint risk treatment efforts. When more members of a supply chain communicated, everyone got to be better prepared. Lastly, security was always a concern for any connected networks. Security for information privilege and protection reduced the rippling effects rising from connectivity issues.

It was a challenge to find anecdotes that fully described every aspect of capacities pertinent to sensitivity and connectivity factors. Ro et al. (2007) discussed modularity for the automobile industry. When parts and components were modularised and then outsourced, three things could happen: efficiency in production, specialisation in expertise and simplified management due to specialisation. Efficiency meant specialised vendors constructed modules '...in a one-piece flow cell and moved and turned about to add components…' This was in sharp contrast to the traditional assembly line where a worker had to manoeuvre in a small space inside of the vehicle and lay down to reach in for wiring and assemblies. The specialised vendor model created much neater production conditions that reduced sensitivity of production environments of a supply chain. Diversified vendor groups took away tasks that used to be centralised at one facility. Such diversification made a supply chain more agile and more adaptable to changes in one or more components or parts. The specialised vendors of impacted parts or components would respond to the changes rather than the entire system being forced to adjust accordingly.

Adaptability was indirectly touched by Ro et al. (2007). Volkswagen pioneered the idea of bringing suppliers into assembly plants to build modules for a better fit. Ford and GM followed suit. Close collaboration offered vendors more down-stream information on site than being informed through a sequential supply chain structure. They could much better learn, prepare and plan for changes at an earlier time. This made the supply chain more adaptable than when members of a supply chain were more separated and isolated.

A good example of how connected an industry could be and how the entire industry got impacted was the 2011 Thailand flood. After the flood, the list of impacted company names went so long that it almost covered the entire harddisk industry and some peripheral user application industries. For instance, Western digital expected its December quarter revenue would drop by 60% as most of its capacities were concentrated in flooded areas. Seyyon Semiconductor, the maker of spinning motors of harddrives, was also severely affected. Seagate, although mostly spared, had to struggle to source its components. Even Apple's CEO Tim Cook described the supply situation as 'fluid', stressing how connected things were for the global harddrive industry. One of the companies mentioned above, Seyyon Semiconductor, was among the early movers to shift their productions to China and Philippines (Dignan, 2011) to build dispersion capacity. O'Neil (2016) presented the Nokia case where flexibility in order fulfillment made a world of differences when compared to Ericsson. The author also discussed the strategy of duplication, which referred to inventory management and sourcing alternatives. Other solutions include modular design, delayed commitment, multiple sources, inventory management as capacities to deal with supply chain risks, and last minute order contracts with suppliers, which was essentially supplier contract flexibility (O'Neil, 2016).

A new trend of reverse logistics and product sustainable design best attested to the importance of product stewardship in supply chain connectivity and sensitivity. Sensing (2020) documented an example where Ryder co-located distribution and reverse logistics in one location for their clients. This was due to the fact that retailers no longer saw reverse logistics as only cost centres, but found ways to turn return handling into competitive advantage. Such mindset change was enabled by including return as an element of product life cycle considerations at the design stage. A sustainably designed product would facilitate recovering, refurbishing, inspecting, testing, and dispositioning when it came to returns. Co-locating facilities made more sense as reverse logistics was no longer an irrelevant step from distribution. This example showed that Ryder's co-locating facility led by product stewardship thinking better positioned recovered and/or refurbished inventory/components, which ultimately reduced sensitivity due to restricted materials and operations complexity. On the connectivity side, added inventory and capacity surely buffered against channel or network uncertainties.

5.5 Firm layer

- Resource limits: capacity, efficiency, financial strength, organisation, and product stewardship.

Firm layer would be the most local level of attention. Capacities at this level had the most direct effects on a firm and often they were better under a firm's own control. Capacity and financial strength were both related to extra resources. When all other capacities were depleted or utilised, buffers in resources would help sustain a system a lot longer. Organisation was a great capacity in human behaviour that encouraged accountability, creativity, leadership and caring. A plan was only as good as the people who implemented it. This is the layer where sustainability is at its very imminent work. Shortage of raw materials, utilities and/or natural resources, even human resources, should not be something unimaginable. At the product stage, all parties involved in product design shall actively anticipate such probabilities and duly plan for them. This may mean an efficient design and a backup plan on the material side. Human resources can be a very interesting resource to plan for, which means preparing buffers and versatile skills that render a system more resilient.

Sheffi (2015b) presented how Intel handled its supply chain after the 2011 earthquake and tsunami in Japan. Intel procured many different kinds of materials, such as Silicon wafer and some specialty chemicals from Japanese suppliers. Intel's response was a good combination of almost every capacity factor we identified for the resource limit vulnerability. Intel's mature organisation structure was able to respond immediately to this disaster. Intel established its own Corporate emergency operations centre (CEOC) for emergent situations. CEOC was quickly activated to come up with plans and solutions for responding to the earthquake and tsunami. Human resource concerns were at the top of CEOC's to-do list. Intel's Tsukuba office was flooded due to broken sprinkler pipes. They were able to quickly locate a temporary site for the three hundred workers at the office. They leveraged their global construction arm to expedite the repairing of the facility. These helped Intel keep their human resource and capacity impacts to as minimum a level as possible. Intel's organisational strength took another critical role in clarifying the scale of impacts. Four days after the disaster, they were able to conclude that tier one suppliers were mostly unimpacted. That was a critical capacity assurance, which defined impacts on tier one suppliers to 'a few days of downtime' but no major threat to the overall production scheduling. Tracing further down its supply chains returned more worry-some information to Intel, tier three and tier four suppliers were in much more deeper troubles. About sixty suppliers had major issues, most of which were single-source specialty chemical vendors.

Organisational strength maintained good transparency and information clarity for Intel, which led to highly effective capacity management. Shin-Etsu Handotai (SEH) plants in Shirakawa (Japan), producing 20% of the world's 300 millimeter silicon wafers, found its production equipment damaged by earthquakes. Intel mobilised its extra capacity in Japan, shifted SEH productions to other facilities, and fast tracked new vendor qualification, and searched for alternative vendors. Intel's engineering processes of alternative materials were expedited and risky materials were purchased at larger quantities.

Efficiency was also a key solution for Intel to deal with the disaster. Intel diluted a key chemical and qualified it for use for eight weeks. A team found a way to clean off and resume test wafers that would have been moved to scrap piles. They even worked with their suppliers to minimise the consumption of tight supplies from specialty tier-4 vendors.

Apparently, none of the above would be achievable if Intel didn't manage their financial strength well. That would be a time when supplies were tight for the entire industry. Abilities to cough up the extra dollars made sure their supply chain operated at as normal a condition as possible. We believe Intel's handling of this natural disaster set great examples for every business about how firm layer impacts could be managed and hopefully minimised. ELGi, a global air compressor manufacturer, documented their measures for countering the impacts of COVID-19. One key measure was financial related: they extended payment terms for distributors and smaller suppliers to reduce their financial stress (Varadaraj, 2020). This is a great example where financial strength went beyond firm boundaries to assist other members of a supply chain.

We would like to quote a human resource example for product stewardship as this is often less discussed along a supply chain. Polhamus (2020) quoted a case that was caused by unexpected customer demand in the software industry. The customer accounted for 15% of their revenue and the customer threatened to cancel the order if a function could not be developed within a week. They had to tell a team of engineers to put everything else on hold and fully dedicate themselves to the function. His takeaway was about designing such unanticipated events into your system by better preparing and managing design teams. Supply chain is normally about physical goods, but agility on the human resource side greatly enhanced sustainability under product stewardship in this case. We believe this is true for both service and product supply chains.

6 Conclusions and future research

Although supply chain risk research has been flourishing recently, most studies have focused on risks either from a single perspective (much more from a buyer's perspective than a supplier's perspective), or in a single stage in the supply chain risk management process (significantly less coverage in risk treatment and risk monitoring than in risk identification and risk treatment). A systematic and structural study of the risks and their inter-relationships is in need for both the researchers and the practitioners. In the effort to answer that need, building upon existing supply chain resilience literature, this research first established a five-layer supply chain risks framework, which categorised risk vulnerability factors and mapped out the inter-relationship structure among risk vulnerabilities. The five inter-connected layers, root macro layer, external layer, impact layer, mediating layer, and firm layer, shed light on identifying the root cause or the most critical risk(s). It also helps forecast the rippling effect of risks down the supply chain. Aside from improving risk assessment, this framework facilitates a more accurate risk treatment. The dependence between risk vulnerability factors signals the efficacy of a risk treatment: whether treating one risk could help uproot other risks or instead create new ones.

Building upon the framework of risk vulnerability factors inter-relationships, we then established a capacity and vulnerability typology which matches capacity factors within each vulnerability category. From anecdotal evidence, we mapped out capacity factors according to their potentials to treat or alleviate the consequences of each risk factor. This derived capacity-vulnerability typology illustrated the links between vulnerability and capacity factors, and constructed a structural model for risk prioritisation in LPHIR supply chain risk management. The organised list of capacity factors helps managers in risk treatment to evaluate a capacity factor's relevance and capability in face of a specific vulnerability factor. With both risk vulnerabilities and capacity-vulnerability relationships mapped out, managers could take the systematic view, identify the root cause, examine the rippling effects of the risk factor with ease, and more effectively, target the issue with the critical capacity strategies. Furthermore, this framework could also guide managers' selection of capacity investment in order to enhance supply chain resilience. It points out viable directions toward building the balanced resilience for supply chains, where risk vulnerabilities are sufficiently prepared for and/or controlled with reasonable investment in capacities.

There are several important avenues for future research. First, this framework of capacity and vulnerability typology could benefit from empirical study performed on suitable datasets. Our research, for the lack of access to feasible datasets, is based on anecdotes as a practical source of information. It would be ideal to test this framework empirically against comprehensive datasets. For example, some relationship linkage may be more influential in certain industries, while other linkage may not exist in other industries. An extensive empirical study of the model to adapt it in varied supply chains could be an insightful direction. Second, future research can also lie in capacity decisions along the supply chain. The structural topology provides a natural platform for capacity investment study. Analytical models could be derived accordingly to answer the questions, such as what is the best capacity portfolio, what is the optimal capacity level for each capacity category, and how much redundancy is ideal for a risk resilient supply chain.

References

Akkermans, H. and Van Wassenhove, L.N. (2018) 'Supply chain tsunamis: research on low-probability, high-impact disruptions', *Journal of Supply Chain Management*, Vol. 54, No. 1, pp.64–76.

All Answers Ltd. (2018) *Supply Chain Risk in the Hyundai Motor Company* [online] https://ukdiss.com/litreview/supply-chain-risk-and-vulnerability.php?vref=1 (accessed 15 July 2021).

Associated Press (2021) 'Truckers fall under California gig economy law, court says', *US News* [online] https://www.usnews.com/news/best-states/california/articles/2021-04-28/truckers-fall-under-california-gig-economy-law-court-says (accessed 15 July 2021).

Barloon, M.J. (1957) 'The motor carrier industry–its regulation–and piggyback', *Financial Analysts Journal*, Vol. 13, No. 3, pp.119–123.

Beattie, A. (2005) 'Business is exposed to supplier problems', *Financial Times* [online] https://www.ft.com/content/8ce6c4c2-14ce-11da-9df1-00000e2511c8 (accessed 15 July 2021).

Bhatia, G., Lane, C. and Wain, A. (2013) 'Building resilience in supply chains', *In World Economic Forum*, pp.1–44 [online] https://www3.weforum.org/docs/WEF_RRN_MO_BuildingResilienceSupplyChains_Report_2013.pdf.

Blackhurst, J.V., Scheibe, K.P. and Johnson, D.J. (2008) 'Supplier risk assessment and monitoring for the automotive industry', *International Journal of Physical Distribution and Logistics Management*, Vol. 38, No. 2, pp.143–165.

Blanchard, D. (2013) 'Managing the financial supply chain', *Industry Week* [online] https://www.industryweek.com/supply-chain/article/21959994/managing-the-financial-supply-chain (accessed 15 July 2021).

Byrne, J.A. and Elgin, B. (2002) 'Cisco behind the hype', *BusinessWeek* [online] https://www.bloomberg.com/news/articles/2002-01-20/cisco-behind-the-hype (accessed 15 July 2021).

Cao, M. and Zhang, Q. (2011) 'Supply chain collaboration: impact on collaborative advantage and firm performance', *Journal of Operations Management*, Vol. 29, No. 3, pp.163–180.

Chandran, N. (2016) *Hyundai's Largest-Ever Labor Strike to Weigh on South Korean Economy*, CNBC [online] https://www.cnbc.com/2016/09/28/hyundais-largest-ever-labor-strike-to-weigh-on-south-korean-economy.html (accessed 15 July 2021).

Chopra, S. and Sodhi, M. (2014) 'Reducing the risk of supply chain disruptions', *MIT Sloan Management Review*, Vol. 55, No. 3, pp.72–80.

Christopher, M. and Peck, H. (2004) 'The five principles of supply chain resilience', *Logistics Europe*, Vol. 12, No. 1, pp.16–21.

Corbin, J. and Strauss, A. (2014) *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*, Sage Publications, Thousand Oaks, USA.

Cucchiella, F. and Gastaldi, M. (2006) 'Risk management in supply chain: a real option approach', *Journal of Manufacturing Technology Management*, Vol. 17, No. 6, pp.700–720.

Dapiran, P. (1992) 'Benetton–global logistics in action', *International Journal of Physical Distribution and Logistics Management*, Vol. 22, No. 6, pp.7–11.

Dignan, L. (2011) 'Thailand floods to lead to hard drive shortages for months', *ZDNet* [online] https://www.zdnet.com/article/thailand-floods-to-lead-to-hard-drive-shortages-for-months/ (accessed 15 July 2021).

DiPietro, B. (2016) 'Crisis of the week: Welspun India faces 'sheet storm' over Egyptian cotton claims', *Wall Street Journal* [online] https://www.wsj.com/articles/BL-252B-11051(accessed 15 July 2021).

Ehrenhuber, I., Treiblmaier, H., Engelhardt-Nowitzki, C. and Gerschberger, M. (2015) 'Toward a framework for supply chain resilience', *International Journal of Supply Chain and Operations Resilience*, Vol. 1, No. 4, pp.339–350.

Eisenhardt, K.M. (1989) 'Building theories from case study research', *Academy of Management Review*, Vol. 14, No. 4, pp.532–550.

Ellis, S.C., Henry, R.M. and Shockley, J. (2010) 'Buyer perceptions of supply disruption risk: a behavioral view and empirical assessment', *Journal of Operations Management*, Vol. 28, No. 1, pp.34–46.

Fan, Y. and Stevenson, M. (2018) 'A review of supply chain risk management: definition, theory, and research agenda', *International Journal of Physical Distribution and Logistics Management*, Vol. 48, No. 3, pp.205–230.

Farrell, H. and Newman, A.L. (2020) 'Choke points', *Harvard Business Review*, Vol. 98, No. 1, pp.124–131.

Fiksel, J., Polyviou, M., Croxton, K.L. and Pettit, T.J. (2015) 'From risk to resilience: learning to deal with disruption', *MIT Sloan Management Review*, Vol. 56, No. 2, pp.79–86.

Gao, S.Y., Simchi-Levi, D., Teo, C.P. and Yan, Z. (2019) 'Disruption risk mitigation in supply chains: the risk exposure index revisited', *Operations Research*, Vol. 67, No. 3, pp.831–852.

Ghadge, A., Dani, S. and Kalawsky, R. (2012) 'Supply chain risk management: present and future scope', *The International Journal of Logistics Management,* Vol. 23, No. 3, pp.313–339.

Ghadge, A., Dani, S., Chester, M. and Kalawsky, R. (2013) 'A systems approach for modelling supply chain risks', *Supply Chain Management: an International Journal*, Vol. 18, No. 5, pp.523–538.

Hachicha, W. and Elmsalmi, M. (2014) 'An integrated approach based-structural modeling for risk prioritization in supply network management', *Journal of Risk Research*, Vol. 17, No. 10, pp.1301–1324.

Hallikas, J., Karvonen, I., Pulkkinen, U., Virolainen, V.M. and Tuominen, M. (2004) 'Risk management processes in supplier networks', *International Journal of Production Economics*, Vol. 90, No. 1, pp.47–58.

Handfield, R.B. and Melnyk, S.A. (1998) 'The scientific theory-building process: a primer using the case of TQM', *Journal of Operations Management*, Vol. 16, No. 4, pp.321–339.

Heckmann, I., Comes, T. and Nickel, S. (2015) 'A critical review on supply chain risk-definition, measure and modeling', *Omega*, April, Vol. 52, pp.119–132 [online] https://www.sciencedirect.com/science/article/abs/pii/S030504831400125X.

Ho, W., Zheng, T., Yildiz, H. and Talluri, S. (2015) 'Supply chain risk management: a literature review', *International Journal of Production Research*, Vol. 53, No. 16, pp.5031–5069.

Hussain, R., Sweeney, A. and Mort, G.S. (2010) 'Typologies of banner advertisements' attributes: a content analysis', *Journal of Promotion Management*, Vol. 16, Nos. 1–2, pp.96–113.

ICMR (2002) 'Cisco systems – the supply chain story', *IBS Center for Management Research* [online] https://www.icmrindia.org/free%20resources/casestudies/cisco-systems-Story-IT&Systems%20Case%20Studies.htm (accessed 15 July 2021).

Ivanov, D., Pavlov, A. and Sokolov, B. (2014) 'Optimal distribution (re) planning in a centralized multi-stage supply network under conditions of the ripple effect and structure dynamics', *European Journal of Operational Research*, Vol. 237, No. 2, pp.758–770.

Jüttner, U., Peck, H. and Christopher, M. (2003) 'Supply chain risk management: outlining an agenda for future research', *International Journal of Logistics: Research and Applications*, Vol. 6, No. 4, pp.197–210.

Kamal, S. and Tobias, L. (2019) 'The top 10 supply chain risks of 2019', *Supply Chain Quarterly* [online] https://www.supplychainquarterly.com/articles/1931-the-top-10-supply-chain-risks-of-2019 (accessed 15 July 2021).

Kern, D., Moser, R., Hartmann, E. and Moder, M. (2012) 'Supply risk management: model development and empirical analysis', *International Journal of Physical Distribution and Logistics Management*, Vol. 42, No. 1, pp.60–2.

Khan, O. and Burnes, B. (2007) 'Risk and supply chain management: creating a research agenda', *The International Journal of Logistics Management*, Vol. 18, No. 2, pp.197–216.

Kinra, A., Ivanov, D., Das, A. and Dolgui, A. (2020) 'Ripple effect quantification by supplier risk exposure assessment', *International Journal of Production Research*, Vol. 58, No. 18, pp.5559–5578.

Kirk, D. (2003) 'Hyundai and Union end 7-week strike', *New York Times* [online] https://www.nytimes.com/2003/08/06/business/worldbusiness/hyundai-and-union-end-7week-strike.html (accessed 15 July 2021).

Kolbe, R.H. and Burnett, M.S. (1991) 'Content-analysis research: an examination of applications with directives for improving research reliability and objectivity', *Journal of Consumer Research*, Vol. 18, No. 2, pp.243–250.

Krisher, T. and Liedtke, M. (2019) 'Uber, Lyft losses keep competitors at bay', *The Washington Post* [online] https://www.washingtonpost.com/business/technology/uber-lyft-losses-keep-competitors-at-bay/2019/05/11/846bac28-73f5-11e9-9331-30bc5836f48e_story.html (accessed 15 July 2021).

Lai, G., Debo, L.G. and Sycara, K. (2009) 'Sharing inventory risk in supply chain: the implication of financial constraint', *Omega*, Vol. 37, No. 4, pp.811–825.

Lynch, G.S. (2012) 'Supply chain risk management', in *Supply Chain Disruptions*, pp.319–336, Springer, London.

McDowell, T. (2020) 'Supply chain cybersecurity: what you need to consider', *Infosecurity* [online] https://www.infosecurity-magazine.com/blogs/supply-chain-cybersecurity/ (Accessed 15 July 2021).

Min, S., Zhou, M., Kim, D. and Kim, J. (2013) 'Assessing the e-service quality of sellers in an industrial e-marketplace', *Journal of Promotion Management*, Vol. 19, No. 5, pp.556–582.

Mishler, M.D. (2017) 'Currency turmoil, price, and profit in global markets', *Journal of Accountancy* [online] https://www.journalofaccountancy.com/issues/2017/mar/currency-turmoil-price-and-profit.html (accessed 10 January 2022).

Neiger, D., Rotaru, K. and Churilov, L. (2009) 'Supply chain risk identification with value-focused process engineering', *Journal of Operations Management*, Vol. 27, No. 2, pp.154–168.

Nesbitt, J. (2016) '4 famous supplier blunders and how to avoid them', *TradeReady* [online] http://www.tradeready.ca/2016/topics/supply-chain-management/4-famous-supplier-blunders-how-avoid/ (accessed 15 July 2021).

Norrman, A. and Lindroth, R. (2004) 'Categorization of supply chain risk and risk management', *Supply Chain Risk*, Vol. 15, No. 2, pp.14–27.

O'Neil, S.K. (2016) 'Managing the unpredictable risks in supply chains', *Council on Foreign Relations*, 15 September [online] https://www.cfr.org/blog/managing-unpredictable-risks-supply-chains.

Pettit, T.J., Croxton, K.L. and Fiksel, J. (2013) 'Ensuring supply chain resilience: development and implementation of an assessment tool', *Journal of Business Logistics*, Vol. 34, No. 1, pp.46–76.

Pettit, T.J., Croxton, K.L. and Fiksel, J. (2019) 'The evolution of resilience in supply chain management: a retrospective on ensuring supply chain resilience', *Journal of Business Logistics*, Vol. 40, No. 1, pp.56–65.

Pettit, T.J., Fiksel, J. and Croxton, K.L. (2010) 'Ensuring supply chain resilience: development of a conceptual framework', *Journal of Business Logistics*, Vol. 31, No. 1, pp.1–21.

Polhamus, A. (2020) 'Proactive versus reactive product development: field notes from an engineering team lead', Medium, 22 April [online] https://aaronpolhamus.medium.com/proactive-versus-reactive-product-development-61f3592e40fb.

Price, E. (2017) 'Outsourcing API manufacturing to Asia: Pros, Cons, & Considerations, four key questions to ask to get the most out of a CMO relationship', *Sequns* [online] https://cdmo.seqens.com/api-manufacturing/outsourcing-api-manufacturing-to-asia-pros-cons-considerations/ (accessed 15 July 2021).

Qazi, A. and Gaudenzi, B. (2016) 'Supply chain risk management: creating an agenda for future research', *International Journal of Supply Chain and Operations Resilience*, Vol. 2, No. 1, pp.12–50.

Rask, M. and Kragh, H. (2004) 'Motives for e-marketplace participation: differences and similarities between buyers and suppliers', *Electronic Markets*, Vol. 14, No. 4, pp.270–283.

Ritchie, B. and Brindley, C. (2007) 'An emergent framework for supply chain risk management and performance measurement', *Journal of the Operational Research Society*, Vol. 58, No. 1, pp.1398–1411.

Ro, Y.K., Liker, J.K. and Fixson, S.K. (2007) 'Modularity as a strategy for supply chain coordination: the case of US auto', *IEEE Transactions on Engineering Management*, Vol. 54, No. 1, pp.172–189.

Russell, R.S. and Taylor, B.W. (2019) *Operations and Supply Chain Management*, John Wiley & Sons, Hoboken, New Jersey.

Sanida, T. and Varlamis, I. (2017) 'Application of affinity analysis techniques on diagnosis and prescription data', *2017 IEEE 30th International Symposium on Computer-Based Medical Systems* (CBMS), pp.403–408.

Sensing, A. (2020) 'How reverse logistics can help optimize value and sustainability for your business', *Supply Chain Minded* [online] https://supplychainminded.com/how-reverse-logistics-can-help-optimize-value-and-sustainability-for-your-business/ (accessed 15 July 2021).

Sheffi, Y. (2007) *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage*, Zone Books, MIT Press, Cambridge, Massachusetts.

Sheffi, Y. (2015) 'Preparing for disruptions through early detection', *MIT Sloan Management Review*, Vol. 57, No. 1, p.31.

Sheffi, Y. (2015) *The Power of Resilience: How the Best Companies Manage the Unexpected*, MIT Press, Cambridge, Massachusetts.

Sheffi, Y. and Rice Jr, J.B. (2005) 'A supply chain view of the resilient enterprise', *MIT Sloan Management Review*, Vol. 47, No. 1, p.41.

Simchi-Levi, D., Schmidt, W. and Wei, Y. (2014) 'From superstorms to factory fires: managing unpredictable supply chain disruptions', *Harvard Business Review*, Vol. 92, Nos. 1–2, pp.96–101.

Simchi-Levi, D., Schmidt, W., Wei, Y., Zhang, P.Y., Combs, K., Ge, Y., Gusikhin, O., Sanders, M. and Zhang, D. (2015) 'Identifying risks and mitigating disruptions in the automotive supply chain', *Interfaces*, Vol. 45, No. 5, pp.375–390.

Sodhi, M.S., Son, B.G. and Tang, C.S. (2012) 'Researchers' perspectives on supply chain risk management', *Production and Operations Management*, Vol. 21, No. 1, pp.1–13.

Svensson, G. (2002) 'Dyadic vulnerability in companies' inbound and outbound logistics flows', *International Journal of Logistics*, Vol. 5, No. 1, pp.1–43.

Tang, C.S. (2006) 'Perspectives in supply chain risk management', *International Journal of Production Economics*, Vol. 103, No. 2, pp.451–488.

Tokuyama, H. (2012) 'Learning from Japan's ordeal', *Public Roads*, Vol. 75, No. 6 [online] https://highways.dot.gov/public-roads/mayjune-2012/learning-japans-ordeal.

Trochim, W.M.K. and Donnelly, J.P. (2008) *The Research Method Knowledge Based*, 3rd ed., Cengage Learning, Mason, OH.

Trudell, C., Kishan, S. and Naughton, K. (2012) 'Auto supplier warns of resin shortage hurting global output', *Bloomberg* [online] http://www.bloomberg.com/news/2012-04-13/auto-supplier-warns-of-resin-shortage-disrupting-output.html (accessed 15 July 2021).

Tummala, R. and Schoenherr, T. (2011) 'Assessing and managing risks using the supply chain risk management process (SCRMP)', *Supply Chain Management: An International Journal*, Vol. 16, No. 6, pp.474–483.

Varadaraj, A.J. (2020) 'Tackling supply chain disruption during COVID-19', *Industry Week* [online] https://www.industryweek.com/supply-chain/article/21132223/tackling-supply-chain-disruption-during-covid19 (accessed 15 July 2021).

Warnica, R. (2014) 'Can Lululemon's new CEO save the company? Laurent Potdevin isn't in for an easy ride', *Canada Business* [online] https://www.canadianbusiness.com/companies-and-industries/can-lululemons-new-ceo-save-the-company/ (accessed 15 July 2021).

Weinberger, M. (2016) 'If you're too young to remember the insanity of the dot-com bubble, check out these pictures', *Business Insider* [online] https://www.businessinsider.com/history-of-the-dot-com-bubble-in-photos-2016-2 (accessed 15 July 2021).

Yadav, A.K. and Samuel, C. (2021) 'An integrated approach for analysis of essential factors of a resilient supply chain', *International Journal of Supply Chain and Operations Resilience*, Vol. 5, No. 1, pp.1–26.

Zhen, X., Li, Y., Cai, G.G. and Shi, D. (2016) 'Transportation disruption risk management: business interruption insurance and backup transportation', *Transportation Research Part E: Logistics and Transportation Review*, June, Vol. 90, pp.51–68 [online] https://www.sciencedirect.com/science/article/abs/pii/S1366554516000053.

Zsidisin, G.A. (2003) 'A grounded definition of supply risk', *Journal of Purchasing and Supply Management*, Vol. 9, Nos. 5–6, pp.217–224.

Appendix A

Vulnerability factors and their description

Vulnerability factor	*Definition*	*Subfactors*
Turbulence	Environment characterised by frequent changes in external factors beyond your control	Natural disasters, geopolitical disruptions, unpredictability of demand, fluctuations in currencies and prices, technology failures, pandemic
Deliberate Treats	Intentional attacks aimed at disrupting operations or causing human or financial harm	Theft, terrorism/sabotage, labor disputes, espionage, special interest groups, product liability
External Pressures	Influences, not specifically targeting the firm, that create business constraints or barriers	Competitive innovation, social/cultural change, political/regulatory change, price pressures, corporate responsibility, environmental change
Resource Limits	Constraints on output based on availability of the factors of production	Supplier, production and distribution capacity, raw material and utilities availability, human resources
Sensitivity	Importance of carefully controlled conditions for product and process integrity	Complexity, product purity, restricted materials, fragility, reliability of equipment, safety hazards, visibility to stakeholders, symbolic profile of brand, concentration of capacity
Connectivity	Degree of interdependence and reliance on outside entities	Scale of network, reliance upon information, degree of outsourcing, import and export channels, reliance upon specialty sources
Supplier/customer disruptions	Susceptibility of suppliers and customers to external forces or disruptions	Supplier reliability, customer disruptions

Source: Pettit et al. (2010, 2013)

The first two factors were mostly political or macroeconomic. *Turbulence* referred to factors that were more force majeure in nature. Subfactors included natural disasters, geopolitical disruptions, unpredictability of demand, fluctuations in currencies and prices, technology failures and pandemic. For example: “Ash from a volcano eruption in Iceland in 2010 grounded air traffic across the European Union and, consequently, decimated fresh food and flower exporters in Africa...” (Sheffi, 2015a). “Unilever’s across-the-board price increases in October 2016 lead to a temporary halt of delivery to Tesco in the UK and Ireland because Tesco refused to accept price change” (Mishler 2017).

In resilience literature’s definition, turbulence vulnerabilities were characterised as ‘beyond your control’, although not all sub-factors were clearly out of anyone’s control. Currency fluctuation and prices could be manipulated by governments and financial institutions, which were more controlled than completely out of control. We believe turbulence refers to economic, social and/or political changes that would be out of a supply chain entity's control or mostly un-influenced by an individual entity along a supply chain. Turbulence factors don't target anyone specifically. Instead, they indifferently, at least in intention, impact everyone in a supply chain.

- Deliberate threats were somewhat in the opposite direction of turbulence. These have been intentional attacks aimed at disrupting operations or causing human or financial harm, such as theft, terrorism/sabotage, labour disputes, espionage, special interest groups, product liability (Farrell and Newman, 2020). They all had one thing in common: a clear target to be impacted. For example, the groundbreaking 7-week labour strike at Hyundai Motor in 2003 halted the manufacturing and distribution operations of the automakers, leading to over US$1.2 billion in lost output (Kirk, 2003). Later, an unusual spree of 21 strikes at Hyundai Motor in the first 9 months of 2016 resulted in a production loss of 117,000 cars, worth over US$2.5 billion (Chandran, 2016). Terrorism, labour disputes and special interest groups would be less under control by any entities in a supply chain, while theft, espionage, and especially product liability looked more preventable within the purview of a firm's own management. Both turbulence and deliberate threats seemed to be broad in impact and more macroeconomic.
- External pressures constrained a firm's operating environment through competitive innovation, social/cultural change, political/regulatory change, price pressures, corporate responsibility and environmental change. For example, the introduction of Apple's iPhone, touchscreen smartphones coupled, and app stores had a devastating impact on the sales of previous mobile phone leaders such as Nokia, Blackberry, and Motorola (Sheffi, 2007). Another example is that European clothes retailers had to have their made-in-China autumn collections stranded in warehouses due to the new European Union new textile quotas in 2005 (Beattie, 2005). External pressure factors have been more microeconomic or industrial organisational, just to borrow terms from economics. Often these factors were responses to macroeconomic and/or political forces mentioned in turbulence or deliberate threats. For instance, the piggy-back collaboration between trucking and railroad industries as an innovation was a result of deregulation in the transportation industry where railroad companies struggled to find a way to adapt to their new economic environment (Barloon, 1957). Note that political/regulatory changes in this category could be more domestic or industry specific.
- Resource limits in our view referred to a facet of business that would be much more tactical and operational. It was directly pertinent to throughput and capacity. It was about constraints that defined outputs given available resources of productions. Subfactors included supplier (in the sense of availability and network), production and distribution capacity, raw materials and utilities availability, human resources. A good example was the 2018 shortage of adiponitrile (ADN), a precursor chemical, which was used to produce engineered plastic components (Kamal and Larsson 2019). In this example, supply limits bottlenecked production and supply chains.
- Sensitivity was more at the product level and network level of a supply chain where product and process integrity were of focus. Product complexity, purity, restricted materials, fragility, reliability of equipment, safety hazard, visibility to stakeholders and brand were more at product level considerations of a supply chain. For example, Target terminated its relationship with textile supplier Welspun India Ltd after the

revelation of using non-Egyptian cotton by this supplier (DiPietro, 2016). The Honest Co., a baby and beauty product seller taking pride in its no sodium lauryl sulfate offerings, was questioned by an independent lab for such product purity claim (Nesbitt, 2016). Different from resource limits, sensitivity was more a design (including network design) and engineering facet to us. A highly sensitive supply chain could amplify or worsen the impacts of a risk as the product by design imposed lower tolerance or variation in standards. It could also be capacity concentration in certain areas or within a limited number of vendors that made the supply chain less versatile and therefore more vulnerable. Overall, engineering of product, supply network and branding exacerbates or attenuates risks within a supply chain through this sensitivity angle.

- Connectivity hinged on two key words, interdependence and reliance. The network nature of a supply chain inevitably necessitated interconnections which by nature meant one firm could not do everything by itself. Given the geographically dispersed nature of a global supply chain, businesses would be exposed to a wider range of turbulence through connectivity. Natural disasters, outbreak of pandemic diseases, fluctuations in currencies, and political upheavals on the other side of the world could bring disruptions to home within a short amount of time. The US housing bubble in 2008 gave rise to 'a foreclosure crisis that threatened to collapse the world financial system like a house of cards. Marked contractions in credit supply and consumer demand triggered a global bullwhip as imports plummeted, causing contraction and bankruptcies throughout global supply chains' (Sheffi, 2015b). To what extent firms within a supply chain depended on and/or relied on each other defined connectivity. Scale of network, reliance upon information, degree of outsourcing, import and export channels, reliance on specialty sources were all sub-factors of connectivity. Risks due to connectivity would be hard to isolate. Companies tended to suffer more from connectivity vulnerabilities when they relied on single-source specialty manufacturers with unique capabilities. In 2012, a blast at a German factory making cyclododecatriene led to potential global disruptions of thousands of different parts used on every vehicle. Cyclododecatriene, also called CDT, is a key element of PA-12 resin used in most fuel and brake-line coatings, flexible hoses and quick connectors supplied to all major automakers, including General Motors Co., Ford Motor Co., Toyota Motor Corp. and Volkswagen AG. Global capacity of CDT is very limited (Trudell et al., 2012).
- Supplier and customer disruptions took an end node perspective of a supply chain. The two ends were powerful nodes fatal to the viability of a supply chain. Sheffi and Rice (2005) provided a good example of supplier disruption: 'In December 2001, UPF-Thompson, the sole supplier of chassis frames for Land Rover's popular Discovery vehicles, suddenly stopped shipping products. UPF was bankrupt. Land Rover learned of this 'one Friday morning [when] no chassis frames were delivered,' according to a Land Rover representative. When Land Rover contacted UPF to determine the cause of the shipping delay, UPF's receiver, KPMG LLP, told Land Rover it was not prepared to deliver any more frames unless Land Rover was willing to make a multimillion-pound 'goodwill' payment. If Land Rover lost the UPF supply of frames, it would have had to suspend its Discovery model production for up to nine months while new tooling was developed. Nearly 1,500 jobs at Land Rover and 10,000 jobs among Land Rover's other suppliers would have been

severely threatened.' Lack of demand and shortage of supply could be root issues for supply chain managers. The unfortunate part has been that they often came together. For instance, one author of this paper knew a local business in California experienced a shortage of supply when China was hit by COVID-19. The moment they thought the supply squeeze was gradually easing, the US went into lock-down. Their demand was put on complete hold.

Appendix B

Capacity factors and their description

Capability factor	*Subfactors*	*Capability factor*	*Subfactors*
Flexibility in sourcing	Part commonality, modular product design, multiple uses, supplier contract flexibility, multiple sources	Recovery	Crisis management, resource mobilisation, communications strategy, consequence mitigation
Flexibility in manufacturing	Ability to quickly and efficiently change the quantity and type of outputs	Dispersion	Distributed decision making, distributed capacity and assets, decentralisation of key resources, location-specific empowerment, dispersion of markets
Flexibility in order fulfillment	Alternate distribution channels, risk pooling/sharing, multisourcing, delayed commitment/production postponement, inventory management, rerouting of requirements	Collaboration	Collaborative forecasting, customer management, communications, postponement of orders, product life cycle management, risk sharing with partners
Capacity	Reserve capacity, redundancy, backup energy sources and communications	Organisation	Accountability, creative problem solving, cross-training, substitute leadership/empowerment, learning/benchmarking, culture of caring
Efficiency	Waste elimination, labor productivity, asset utilisation, product variability reduction, failure prevention	Market position	Product differentiation, customer loyalty/retention, market share, brand equity, customer relationships, customer communications
Visibility	Business intelligence gathering, information technology, product, equipment and people visibility, information exchange	Security	Layered defenses, access restrictions, employee involvement, collaboration with governments, cyber-security, personnel security

Source: Fiksel et al. (2015)

Capacity factors and their description (continued)

Capability factor	*Subfactors*	*Capability factor*	*Subfactors*
Adaptability	Fast rerouting of requirements, lead time reduction, strategic gaming and simulation, seizing advantage from disruptions, alternative technology development, learning from experience	Financial strength	Insurance, portfolio diversification, financial reserves and liquidity, price margin
Anticipation	Monitoring early warning signals, forecasting, deviation and near-miss analysis, risk management, business continuity/preparedness planning, recognition of opportunities	Product stewardship	Proactive product design, resource conservation, auditing and monitoring, supplier management, customer support

Source: Fiksel et al. (2015)

- Flexibility in sourcing referred to adaptability in procurement. Sourcing alternatives to a great extent determined how much a risk event could hurt. Part commonality, modular design, multiple uses, contract flexibility and multiple sources were subfactors of this capacity factor. Product platforms serve as the underlying systems that define core functions and fundamental commonalities of offspring product lines. Platform-regulated part commonality impacted sourcing flexibility and alternatives. A great enabler of commonality was modular design of parts shared by multiple product lines, making parts useful in multiple products; *Flexibility in manufacturing* carried several facets. Modular design enabled a firm to quickly adjust among production and/or sourcing options with well-defined functionalities of each module. Product postponement, changeover speed, reconfiguration, etc. were production system characteristics that enabled flexible manufacturing. This was an added capacity in Pettit et al. (2019). *Flexibility in order fulfillment* was pertinent to the other end of a supply chain in relativity to flexibility in sourcing. Channel flexibility, transportation, risk pooling and inventory, etc. were key concerns in this capacity.
- Capacity pertained to backup and buffer resources in the case of risk events. Any buffer utilities, materials, labour and so on would offer the extra resources to respond quickly or to sustain a little longer. *Efficiency* was precisely the traditional utilisation ratio between input and output. Similar to capacity, improved efficiency earned a firm more resources to counter the impact of risk events. *Visibility* gave managers sight depth along a supply chain. Notice that visibility was not only about information sharing. Visibility enabled a supply chain to understand the inventory and demand side, on top of quality and relevance of information (Cao and Zhang, 2011). *Adaptability*, in our opinion, was not mutually exclusive from many other capacity factors. It was about modifying operations, such as via alternative technologies, simulation and environmental sustainability, so that a system could adapt to uncertainties. Factors like flexibility and several other factors shall also contribute to a firm's adaptability. *Anticipation* referred to foreseeing upcoming risk

events and hopefully taking actions preemptively. Reading signals and not under-estimating the severity of an event often made a huge difference in managing low probability and high impact risks. *Recovery* talked about returning to normality. The key was not only about getting back to normal. Several other research discussed the speed or time it took to recover (Simchi-Levi et al. 2014).

- Dispersion was an organisation structure that was well balanced between centralisation and decentralisation. This included supply chain systems, markets, suppliers and so on. Decentralisation boosted a firm's ability to stand against risk events. Collaboration raised a very good point about not working alone in a risky environment. Those who could team up often weathered a storm better than lone wolves. Information sharing on forecasting, customer, product life cycle and so on greatly enhanced a firm's resilience. *Organisation* referred to culture and policies, which were both created and maintained by human beings. How the culture of a firm might positively approach potential risks and proactively, not passively, dealt with risks ultimately determined survivability out of a risk event. *Market position* was more about the ability for a firm to retain its markets and even obtain customer support when risk events hit. Customer consumption generated real operating income, where a loyal group of customers could stay with a business during the most difficult moments. *Security* built up the defense system against all kinds of risks. A business without building such systems was basically at the mercy of any negative factors. *Financial strength* required a business to well manage its financial with scrupulous planning on financial reserves, investment options and liquidity. Product Stewardship has been relevant to sustainability in product design, reverse logistics, and resource conservation. *Product stewardship* tackled the issue from a design and sustainability perspective while efficiency was more about production and utilisation. Sustainable supply chains in this sense pertained to not only savings, but more supply chain health and resilience under risk events.