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Measuring supply chain resilience

Optimization potential in Vorarlberg's industry

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Abstract

Measuring supply chain resilience: Optimization potential in Vorarlberg's industry

Supply shortages faced in products and resources from semiconductors to natural gas in recent years have had impact massive on global economy, but such challenges are not new for supply chain professionals. Many major events in the past have disrupted supply chains: 9/11 attack in New York, Tsunami in Japan to name a few, but COVID19 have had the biggest and widespread impact in the modern times.

Even though supply chain resilience being a term coined in early 2000's, its usage and importance has increased since then. With the curiosity of assessing the current state of supply chain resilience literature and finding a resilience measurement method which is a one-fit for all supply chains in the manufacturing industry of Vorarlberg, the following research project was undertaken. Research is carried out with mixed methods, using a systematic literature review followed by expert interviews.

In the conclusion of the research the author argues that there is a significant difference in the understanding of the term resilience within industry, there is a lack on the need for a measure for resilience. The ways in which the structure of an organization impacts the level of resilience, foreseen benefits of digitalization and technologies for resilience are also discussed. A comparative analysis on the SCR measurement methods discovered in literature, resulted in recommending Resilience index for on-time delivery proposed by Carvalho et al [1] for the mentioned industry.

Keywords:

Supply chain, Resilience, Procurement, Business interruption risks, resilience measurement,

[1] Carvalho et al., "The Resilience of On-Time Delivery to Capacity and Material Shortages."

Kurzreferat

Resilienz in der Lieferkette messen: Optimierungspotenziale in Vorarlbergs Industrie

Versorgungsengpässe bei Produkten und Ressourcen, von Halbleitern bis hin zu Erdgas, hatten in den letzten Jahren massive Auswirkungen auf die Weltwirtschaft, aber solche Herausforderungen sind für Fachleute der Lieferkette nicht neu. In der Vergangenheit haben viele Großereignisse die Lieferketten gestört: Der Anschlag von 9/11 in New York, der Tsunami in Japan, um nur einige zu nennen, aber COVID19 hatte die größten und weitreichendsten Auswirkungen in der heutigen Zeit.

Obwohl der Begriff der Widerstandsfähigkeit der Versorgungskette erst Anfang der 2000er Jahre geprägt wurde, hat seine Verwendung und Bedeutung seither zugenommen. Mit dem Ziel, den aktuellen Stand der Literatur zur Resilienz von Lieferketten zu bewerten und eine Methode zur Messung der Resilienz zu finden, die für alle Lieferketten in der verarbeitenden Industrie Vorarlbergs geeignet ist, wurde das folgende Forschungsprojekt durchgeführt. Die Forschung wird mit gemischten Methoden durchgeführt, wobei eine systematische Literaturrecherche, gefolgt von Experteninterviews, verwendet wird.

In der Schlussfolgerung der Forschung argumentiert der Autor, dass es einen signifikanten Unterschied im Verständnis des Begriffs Resilienz innerhalb der Industrie gibt, es fehlt ein Maß für die Resilienz. Die Art und Weise, wie sich die Struktur eines Unternehmens auf den Grad der Resilienz auswirkt, die voraussichtlichen Vorteile der Digitalisierung und die Technologien für die Resilienz werden ebenfalls erörtert. Eine vergleichende Analyse der in der Literatur gefundenen SCR-Messmethoden führte zu einer Empfehlung für den von Carvalho et al. [2] vorgeschlagenen Resilienz index für die termingerechte Lieferung in der genannten Branche.

Schlüsselwörter:

Lieferkette, Resilienz, Beschaffung, Betriebsunterbrechungsrisiken, Resilienz messung,

[2] Carvalho et al., “The Resilience of On-Time Delivery to Capacity and Material Shortages.”

Table of Contents

List of Figures 6

List of Tables 7

List of Abbreviations and Symbols 8

1 Introduction 9

1.1 Research Purpose 11

1.2 Research questions 12

1.3 Research Scope 12

2 Research Methodology 13

2.1.1 Research philosophy 13

2.1.2 Research approach 13

2.1.3 Research strategy 14

2.1.4 Research method 14

2.1.5 Research Time horizon 14

2.1.6 Data collection and analysis 14

2.1.6.1Sampling 16

2.1.6.2Collection 17

2.1.6.3Analysis 18

3 Literature review 22

3.1 Defining Supply Chain Resilience 22

3.2 Resilience versus Risk management 24

3.3 Supply Chain Resilience dimensions 25

3.3.1 Absorptive capacity 26

3.3.2 Adaptive/Response capability 26

3.3.3 Recovery capability 27

3.4 Theoretical perspectives towards Supply Chain Resilience 27

3.4.1 Resource-based view 27

3.4.2 Dynamic capability 27

3.4.3 Contingent resource-based view 28

3.4.4 Graph theory 29

3.4.5 Network theory 29

3.5 Enablers of Supply chain resilience 30

3.6 Supply chain resilience measurement methods 34
3.6.1 Resilience index from LARG Index 34
3.6.2 Component Resilience Index 37
3.6.3 Resilience index based on Graph theory. 40
3.6.4 Resilience index for on-time delivery 42
3.7 Technological impact on supply chain resilience 43
3.7.1 Digitalization 43
3.7.2 Blockchain 44
3.7.3 Industry 4.0 44
3.7.4 Big data analytics 46
3.7.5 Artificial Intelligence 47
4 Results and findings 48
4.1 Findings on RQ 1.1 50
4.2 Findings on RQ 1.2 52
4.3 Findings on RQ 1.3 57
4.4 Lessons learned 60
5 Discussion 62
5.1 Limitations 66
6 Conclusion 68
7 Summary 70
References 76
Appendix 81
Statement of Affirmation 82

List of Figures

Figure 1: Excerpt of Concept matrix maintained in Microsoft Excel 15

Figure 2: Interviewees 17

Figure 3: Thematic analysis process 19

Figure 4: Excerpt from MAXQDA 20

Figure 5: Resilience capacity of supply chains 26

Figure 6: Resilient supply chain metrics 29

Figure 7: Material shortages and resilience practises (Adapted to fit) 31

Figure 8: Capacity shortages and resilience practises (Adapted to fit) 31

Figure 9: Creating the resilient supply chain 32

Figure 10: Resilience-enhancing features 33

Figure 11: Resilience-enhancing features 33

Figure 12: Hierarchical relationships evolved in the LARG company behavior assessment 35

Figure 13: Hierarchical relationships involved in the supply chain LARG index 36

Figure 14: Resilient behaviour result from the case study 36

Figure 15: Supply network example 37

Figure 16: Nomenclature 38

Figure 17: Resilience for the Node Rin 39

Figure 18: Resilience for the arc $Rija$ 39

Figure 19: Results of resilience of each node from example supply chain network 39

Figure 20: Results of resilience of each arc from example supply chain network 39

Figure 21: Resilience enablers 40

Figure 22: Sample Diagraph 41

Figure 23: adjacency matrix 41

Figure 24: Result of resilience index on the case study automotive industry 42

Figure 25: Resilience triangle 42

Figure 26: SCRES framework 46

Figure 27: AI-enabled SCR capabilities 47

List of Tables

Table 1: Literature search process 15

Table 2: Resilience practises and weightage 34

Table 3: Theme: SCR definition 49

Table 4: Theme: Regional dependence 51

Table 5: Theme: Multisourcing 52

Table 6: Theme: supplier relationship management 54

Table 7: Theme: Transparency 55

Table 8: Theme: Local for local 56

Table 9: Theme: Corporate structure and size 57

Table 10: Theme: No measure for SCR 57

Table 11: Theme: Need for SCR measure 58

Table 12: Theme: Risk management process 59

Table 13: Theme: Logistic KPI's 60

Table 14: Theme: Lessons learned 61

Table 15: SCR measurement methods comparison 66

List of Abbreviations and Symbols

SCM – Supply Chain Management

SC – Supply chain

SCR – Supply Chain Resilience

SCRM – Supply chain risk management

BI risk – Business Interruption risk

TTM - Time to Money

OTD – On time delivery

VMI – Vendor managed inventory.

BCT - business continuation time

ERP - enterprise resource planning

OEM - original equipment manufacturer

TTR - time-to-recover.

TTS - time-to-survive.

CRI – Component resilience index

LARG – Lean, Agile, Resilient and Green

1 Introduction

Supply chains have existed for as long as humans have engaged in trade and commerce[3]. The Silk Road, in the 14th century CE, was the first major trade route that facilitated the exchange of goods, ideas, and culture across vast distances[4]. It also presented several challenges to traders which includes security risks, logistical hurdles, harsh terrain and weather, political instability, navigation through different customs regulations, languages, and currencies [5]. Despite these challenges, Silk Road traders were remarkably resilient[6], and this resilience can be attributed to several factors, including the adaptability of the traders, the network's decentralization, and the development of diverse trade routes[7].

The industrial revolution in the 18th and 19th centuries; multinational companies searching for low labor cost countries and China's entry into WTO in late 20th century gave an exponential growth to trade in manufactured goods[8]. With highly interconnected global economy, with SCs spanning worldwide linking producers to consumers, which led to a high degree of interdependence among nations and businesses. This makes the global supply chain a critical component of the world economy because of which it is now difficult to imagine a product that is not the result of a complex global supply chain. The global supply networks across the world deliver the products with high efficiency with the focus on lean but these networks have high chance of containing vulnerabilities. COVID-19 has by far the biggest impact on the supply network in modern period, but it was not the first one. The terrorist attacks on September 11, 2001, had a significant impact on global supply chains as it led to increased security measures, including stricter customs inspections, which slowed down the movement of goods and increased costs for companies[9]. Japan is a major player in the global supply chain, with many companies relying on Japanese suppliers for critical components. The tsunami in 2011 caused widespread damage to factories and infrastructure, disrupting the production of components, and finished goods around the world. The automotive industry was particularly affected, with many plants in Japan and other countries forced to shut down

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[3] Susan Whitfield, *Life along the Silk Road / Susan Whitfield*, Second edition (Oakland, California: University of California Press, 2015).
[4] Valerie Hansen, *The Silk Road: A New History with Documents* (New York: Oxford University Press, 2017).
[5] Xinru Liu, *The Silk Road in World History*, New Oxford World History (Oxford ; New York: Oxford University Press, 2010).
[6] John E. Hill, *Through the Jade Gate to Rome: A Study of the Silk Routes during the Later Han Dynasty 1st to 2nd Centuries CE*, Nachdr. (Charleston, SC: BookSurge, 2011).
[7] Whitfield, *Life along the Silk Road / Susan Whitfield*.
[8] Susan Lund, et al., "Risk, Resilience, and Rebalancing in Global Value Chains," Special Report (McKinsey Global Institute, June 8, 2020), https://www.mckinsey.com/capabilities/operations/our-insights/risk-resilience-and-rebalancing-in-global-value-chains.
[9] Andreas Norrman and Ulf Jansson, "Ericsson's Proactive Supply Chain Risk Management Approach after a Serious Sub-supplier Accident," *International Journal of Physical Distribution & Logistics Management* 34, no. 5 (June 1, 2004): 434–56, https://doi.org/10.1108/09600030410545463.

due to the disruption of critical component supplies. [10] These historical developments have contributed to the current state of supply chain resilience, which requires businesses to be able to quickly adapt to unforeseen events, such as natural disasters or pandemics, to ensure the continuity of their operations.[11] At the time of writing this thesis, the ongoing Ukraine with Russia has had its ripple effect on the world economy. Followed sanctions on Russian economy are already having big impact on Russian economy, with long lasting consequences.

To discuss about one company specific hazard: In year 2000, a small fire incident at a chip provider company in Albuquerque disrupted a huge supply chain network for major customers such as Ericsson and Nokia. Nokia was quick and effective in responding by reaching out to other suppliers and thus, later were successful to achieve its sales target. On the other hand, Ericsson did not look search for alternative suppliers, this resulted in massive $400 million loss of revenue.[12] Companies constantly face a big range of risks; according to a recent report from McKinsey[13] "Disruptions lasting a month or longer now occur **every 3.7 years** on average, and the financial toll associated with the most extreme events has been climbing. Adjusted for the probability and frequency of disruptions, companies can expect to lose more than **40 percent of a year's profits every decade** on average. But a single severe event that disrupts production for 100 days—something that happens every five to seven years on average—could erase almost a year's earnings in some industries." [14]

Due to these disruptions impacting not just organizations but entire industries, and economies; it is imperative to design resilient business models to tackle such disruptions. To design or build resilient business models, it is critical to measure the current level and target level of resilience. In the research, expert consensus on a common SCR measurement method is still lacking. To address SCR and effectively study it, researchers need to integrate perspectives and insights from different disciplines, as SCR is a multidisciplinary field. This thesis is aimed at reviewing the current SCR literature, and assessing the SCR measurement methods that are available. This will be followed by an analysis on expert interviews which will provide the current level of SCR understanding in the industry and the methods that are being used.

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[10] Yosef Sheffi, *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage*, 1. MIT paperback ed (Cambridge, Mass. London: MIT Press, 2007).
[11] Benjamin Tukamuhabwa, Mark Stevenson, and Jerry Busby, "Supply Chain Resilience in a Developing Country Context," *Supply Chain Management: An International Journal* 22, no. 6 (November 13, 2017): 486–505, https://doi.org/10.1108/SCM-02-2017-0059.
[12] Yossi Sheffi and James B Rice Jr, "An Organization's Ability to Recover from Disruption Quickly Can Be Improved by Building Redundancy and Flexibility into Its Supply Chain. While Investing in Redundancy Represents a Pure Cost Increase, Investing in Flexibility Yields Many Additional Benefits for Day-to- Day Operations.," 2005.
[13] Susan Lund, et al., "Risk, Resilience, and Rebalancing in Global Value Chains."
[14] Susan Lund, et al.

1.1 Research Purpose

When it comes to taking a decision on future action, managers take the help of performance measurement tools, but according to Brusset et al. [15] "they do not pay much attention to routine measurement of the effectiveness of resilient actions". Although resilience is widely discussed in the supply chain literature, Behzadi et al.[16] conclude that appropriate metrics to measure resilience are rarely suggested. Despite the increase in the supply chain risk management studies, Chowdhury et al[17] find that "theoretically supported and empirically validated study on justifying the antecedents and measurement dimensions of supply chain resilience (SCRE) is rare". SCR is considered as multidimensional, and challenging to measure as it is spread over multiple tiers in supply chain[18]. Rajesh R. [19] found that "the lack of effective measurement systems and measurement metrics has kept the firms from attaining significant improvement in firms' resilient actions". Further, Soni et al.[20] identified the lack of an in-depth understanding of resilience practices and the development of relevant measures to assess those practices, as a major hindrance to firms' capacity to manage SC disruptions.

With this premise, it is critical to assess the status of understanding and usage of SCR in the industry of Vorarlberg, to understand how the company's asses the status, target level and benchmark SCR level within the industry. Along with this need, it is also required to assess what actions are the companies taking towards building SCR in the wake of the COVID19 pandemic. The SCR measurement methods used in the industry must be compared with one proposed in the current literature to assess and recommend SCR measurement method.

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[15] Xavier Brusset and Christoph Teller, "Supply Chain Capabilities, Risks, and Resilience," *International Journal of Production Economics* 184 (February 2017): 59–68, https://doi.org/10.1016/j.ijpe.2016.09.008.

[16] Golnar Behzadi, Michael Justin O'Sullivan, and Tava Lennon Olsen, "On Metrics for Supply Chain Resilience," *European Journal of Operational Research* 287, no. 1 (November 2020): 145–58, https://doi.org/10.1016/j.ejor.2020.04.040.

[17] Md Maruf Hossan Chowdhury and Mohammed Quaddus, "Supply Chain Readiness, Response and Recovery for Resilience," *Supply Chain Management: An International Journal* 21, no. 6 (September 12, 2016): 709–31, https://doi.org/10.1108/SCM-12-2015-0463.

[18] Albert Munoz and Michelle Dunbar, "On the Quantification of Operational Supply Chain Resilience," *International Journal of Production Research* 53, no. 22 (November 17, 2015): 6736–51, https://doi.org/10.1080/00207543.2015.1057296.

[19] R. Rajesh, "Forecasting Supply Chain Resilience Performance Using Grey Prediction," *Electronic Commerce Research and Applications* 20 (November 2016): 42–58, https://doi.org/10.1016/j.elerap.2016.09.006.

[20] Umang Soni, Vipul Jain, and Sameer Kumar, "Measuring Supply Chain Resilience Using a Deterministic Modeling Approach," *Computers & Industrial Engineering* 74 (August 2014): 11–25, https://doi.org/10.1016/j.cie.2014.04.019.

1.2 Research questions

Following the research purpose, which was mentioned before, the research questions are as follows. The main sub question is split into 3 sub question to provide an holistic understanding of the SCR and its measurement status.

Which available method of measuring resilience of a supply chain fits best for manufacturing industry in Vorarlberg?

RQ1.1: What are the wants and needs in terms of resilience level in manufacturing companies in Vorarlberg?

RQ1.2. How manufacturing companies in Vorarlberg are building resilience within their supply chain?

RQ1.3: Is there a method existing to measure the resilience which fits the best for the industry?

1.3 Research Scope

The scope of the research is limited within the resilience of supply chains of manufacturing industry within procurement / sourcing function, and the organizational resilience at the corporate level is not considered in the focus. The research is also carried out within the boundaries of the state of Vorarlberg which limits the scope of the study. Although traditional risk management and risk exposure measurement methods exist in the literature and used heavily in the literature, this research focuses on reviewing measurement methods SCR in literature and in practice in the SC of Vorarlberg's manufacturing industry.

2 Research Methodology

This chapter discusses the research methodology, including the research design and the mechanisms it used to facilitate reaching conclusions and answering the questions. To ensure consistency, the rationale for each methodological choice is presented. This is to allow the reader to understand how these decisions are linked and follow one another. Using the research onion proposed by Saunders et al. [21] which is a tool used for designing the business research this research was also designed.

2.1.1 Research philosophy

In research there are multiple philosophies that are used, but to research a multidisciplinary field like SCR, it is needed to acknowledge multiple interpretations and realities that coexist parallelly. Charmaz[22] explains that researchers employing an interpretive approach seek to uncover and understand the diversity of perspectives and meanings attached to a given phenomenon. According to Denzin and Lincoln[23] interpretivism allows researchers to explore and understand the subjective meanings and experiences of individuals, acknowledging that individuals construct their reality based on their interpretations. This approach helps capture the complexity and richness of human experiences in social contexts[24] Interpretivism acknowledges that multiple interpretations and realities can coexist within a social setting. Researchers employing an interpretive approach seek to uncover and understand the diversity of perspectives and meanings attached to a given phenomenon[25]. Hence it can be said that the interpretivism fits as the philosophy for this research.

2.1.2 Research approach

The aim of this research is to explore SCR measurement methods proposed in the literature and the actual SCR measurement methods used in practice in the mentioned industry. When starting with the literature review, deductive approach is planned be followed as with deductive approach different theories, concepts, related to SCR can be identified. Subsequently with the expert interviews both deductive and inductive approaches is planned to be used. The reasoning to apply deductive approach is that discovering theories and concepts in the literature review at the start will provide a basis for structuring the upcoming interview. The

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[21] M. N. K. Saunders, Philip Lewis, and Adrian Thornhill, *Research Methods for Business Students*, Eighth Edition (New York: Pearson, 2019).
[22] Kathy Charmaz, *Constructing Grounded Theory*, 2nd edition, Introducing Qualitative Methods (London ; Thousand Oaks, Calif: Sage, 2014).
[23] Norman K. Denzin and Yvonna S. Lincoln, eds., *The SAGE Handbook of Qualitative Research*, Fifth edition (Los Angeles London New Delhi Singapore Washington DC Melbourne: SAGE, 2018).
[24] John W. Creswell and Cheryl N. Poth, *Qualitative Inquiry & Research Design: Choosing among Five Approaches*, Fourth edition (Los Angeles: SAGE, 2018).
[25] Charmaz, *Constructing Grounded Theory*.

reasoning to apply inductive method as well is to keep the research open for discovering possible new concepts and measurement methods during the interview.

2.1.3 Research strategy

SCR being a multidisciplinary term, as it takes in information from different fields, such as operations management, procurement management, supply chain design, strategy management etc. Due to such a diverse nature of the term SCR, it is essential that an explorative approach is required to research this field, and which will provide a holistic view to gather inputs from all the mentioned fields. In-depth **literature review** provides the status of research, existing theories, frameworks, and methods. Exploratory research is flexible in nature, allowing researchers to adapt their methods and strategies based on emerging insights[26] which is crucial as it is foreseen that the **expert interviewees** will provide different insights in their ways of SCR and measurement. Hence, to apply exploratory strategy to current research, Grounded theory is the best strategy to be used.

2.1.4 Research method

As mentioned above, literature review followed by expert interviews are designed to be carried out in this research, which is why the research method which fits this is the mixed method.

2.1.5 Research Time horizon

Cross sectional time horizon is applied to the research as the research objective is to find out the SCR measurement methods in the research and in practice at the time of the research.

2.1.6 Data collection and analysis

As per Webster et al. [27] "An Effective literature review creates a firm foundation for advancing knowledge and facilitates theory development, closes areas where a plethora of research exists, and uncovers areas where research is needed". With this as a guiding principle, literature review on the topic of measuring SCR was carried out. FHV provided free of cost access to one of the most reliable platform ProQuest, containing scholarly multidisciplinary literature and FHV's digital library Olav. The process of search query and content

[26] Yanyi K. Djamba and W. Lawrence Neuman, "Social Research Methods: Qualitative and Quantitative Approaches," *Teaching Sociology* 30, no. 3 (July 2002): 380, https://doi.org/10.2307/3211488.
[27] Jane Webster and Richard Watson, "ANALYZING THE PAST TO PREPARE FOR THE FUTURE: WRITING A LITERATURE REVIEW," *Management Information Systems Research Center, University of Minnesota*, accessed June 29, 2018, http://www.jstor.org/stable/4132319.

filtration steps on the site ProQuest is mentioned in Table 1: Literature search process, same process was also carried out for Olav.

Action	Filter specification and result on ProQuest
Filter 1:	Abstract of the document contains the terms (supply chain resilience measurement) OR (quantifying supply chain resilience) OR (measure for supply chain resilience) OR (Measuring supply chain resilience) OR (index for supply chain resilience)
Result:	250 documents
Filter 2:	Access to Full text documents only
Result:	179 documents
Filter 3:	Peer Reviewed documents only
Result:	114 documents
Filter 4:	Language: English
Result:	112 documents
Filter:	Manual filtrations for Relevancy
Result:	42 documents

Table 1: Literature search process

After removing the duplicates between ProQuest and Olav, total **52** documents were found to be relevant. The process was then repeated multiple times, with further insights and connections being uncovered through the review of literary sources. All of documents were analyzed using the following concept matrix, the process which was suggested by Webster et.al.[28] This process helped in making sure to provide a structure to the literature search, no relevant sources are left out to be considered and record of each aspect of the document is maintained. This process also helps in bringing repeatability to the research. As shown in the following Figure 1 the concept that was carried out.

A	B	C	D	E	F	G	H	I
Source	Research Paper	Year	Approach	Literature review	SCR definition	Existing SCR measure method	New SCR measure method	SCR enablers/inhibitors/capability factors
Proquest	Pettit, Timothy J., Joseph Fiksel, and Keely L. Croxton. "ENSURING SUPPLY CHAIN RESILIENCE: DEVELOPMENT OF A CONCEPTUAL FRAMEWORK." Journal of Business Logistics 31, no. 1 (March 2010): 1–21. https://doi.org/10.1002/j.2158-1592.2010.tb00125.x.	2010			x			
Proquest	Azevedo, Susana Garrido, Helena Carvalho, and V. Cruz-Machado. "LARG Index: A Benchmarking Tool for Improving the Leanness, Agility, Resilience and Greenness of the Automotive Supply Chain." Edited by Niranjan Pati. Benchmarking: An International Journal 23, no. 6 (August 1, 2016): 1472–99. https://doi.org/10.1108/BIJ-07-2014-0072.	2016	Case study		x		x	x
Proquest	Chowdhury, Md Maruf Hossan, and Mohammed Quaddus. "Supply Chain Readiness, Response and Recovery for Resilience." Supply Chain Management: An International Journal 21, no. 6 (September 12, 2016): 709–31. https://doi.org/10.1108/SCM-12-2015-0463.	2016	Qualitative field study	x			x	x
FH Olav	Hosseini, Seyedmohsen, Abdullah Al Khaled, and Md Sarder. "A General Framework for Assessing System Resilience Using Bayesian Networks: A Case Study of Sulfuric Acid Manufacturer." Journal of Manufacturing Systems 41 (October 2016): 211–27. https://doi.org/10.1016/j.jmsy.2016.09.006.	2016	Bayesian network	x			X	
Proquest	Kumar, Siva, and Ramesh Anbanandam. "An Integrated Delphi – Fuzzy Logic Approach for Measuring Supply Chain Resilience: An Illustrative Case from Manufacturing Industry." Measuring Business Excellence 23, no. 3 (October 22, 2019): 350–75. https://doi.org/10.1108/MBE-01-2019-0001.	2019	Delphi – fuzzy logic	x			x	x
FH Olav	Ahmadian, Navid, Gino J. Lim, Jaeyoung Cho, and Selim Bora. "A Quantitative Approach for Assessment and Improvement of Network Resilience." Reliability Engineering & System Safety 200 (August 2020): 106977. https://doi.org/10.1016/j.ress.2020.106977.	2020	Quantitative		x		x	

Figure 1: Excerpt of Concept matrix maintained in Microsoft Excel

[28] Webster and Watson.

2.1.6.1 Sampling

When it comes to qualitative expert's interviews, there are multiple sampling methods which are purposeful or purposive sampling, snowball sampling, Expert panel sampling, theoretical sampling. It's crucial that the choice of sampling method in qualitative expert interviews must align with the research objectives, the nature of the research topic, and the available resources. Purposeful or purposive sampling uses the method of selecting participants which is based on their expertise, knowledge, or relevance to the topic of research. Patton[29] identify that individuals who possess the desired characteristics or have valuable insights related to the research focus. This sampling method is commonly used in qualitative expert interviews to ensure that participants have the necessary expertise and experience to provide valuable insights. Hence purposive sampling is chosen as the sampling method.

As mentioned, the scope of the research is limited within the procurement/supply function of manufacturing industry of the state of Vorarlberg, which is why the sampling is to be carried out within the limited number of companies in the region. Due to this the sample size reduces to companies with procurement function. The head of procurement/supply are the persons responsible for deciding the supply base for the companies which is why it makes them the experts for the research as they are the most knowledgeable in the field of this research. As this research is not focused on any specific manufacturing ex. Only electronics but open for different manufacturing companies, which increases its scope to be sufficient for the research.

The list of top 100 employers in the Vorarlberg[30] was used to find the companies in the region who have manufacturing function. Using the professional network and social networking site "Linked-in" the perspective experts were contacted with a request for an interview on the research theme. The mentioned list consists of all types of industries, which is why the filter at the manufacturing had to be set up before selecting the companies with the request for interview. The 9 experts from 6 companies agreed for the interview. As per the self-submitted date from the companies these 6 companies employ approximately 25% of the workforce from the list. (11602 employees out of 45203 total employees). Interviews were carried out with everyone who showed willingness, which is also the reason of the limited number of interviews. This list of top 100 employers consists of all types of companies which is why this percentage does not show an exact share of how many employees are exactly from manufacturing sector. To maintain the confidentiality the interviewees, we use the reference codes i.e. Company 1 expert 1 is C1.1 while the second employees of the same company would be C1.2. We have 6 companies which is why the list goes up to C6.1. The size of the companies

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[29] Michael Quinn Patton, *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*, Fourth edition (Thousand Oaks, California: SAGE Publications, Inc, 2015).

[30] "Vorarlbergs Größte Unternehmen" (Vorarlberger nachrichten, n.d.), https://www.vn.at/2022/04/Top-100-2022.pdf.

is categorized as per the number of employees: S is <=500 employees; M is >500 employees; L is >=1500 employees; sorted according to the interview scheduled.

Ref.	Size	Industry	Position
C1.1	M	Construction technology	Head of Procurement - Business Unit
C1.2	M	Construction technology	Team lead procurement - Business Unit
C1.3	M	Construction technology	Head of Logistics - production plant
C2.1	L	Lighting appliance manufacturing	Head of Purchasing
C3.1	L	Metal fittings manufacturing	Head of Logistics - production plant
C3.2	L	Metal fittings manufacturing	Head of Purchasing
C4.1	L	Automotive parts manufacturing	Head of Procurement - Production plant
C5.1	M	Vibrations isolation manufacturing	Head of Procurement - Production plant
C6.1	S	Electronic locking system manufacturing	Chief Operations officer

Figure 2: Interviewees

2.1.6.2 Collection

In the context of qualitative business research using interviews as the data collection method, there are many types of data collection ways that are used: Bryman et al[31] explain that difference between different interview types: differences between interviews are reduced when interviews are carried out in **structured way** and with u**nstructured interviews** "usually there may be just a single question that the interviewer asks, and the interviewee is then allowed to respond freely, with the interviewer simply responding to points that seem worthy of being followed up". A **semi-structured interview** is where the researcher only has a list of questions on the topics, and the interviewee has freedom in the way he or she chooses to answer. Questions usually do not follow a defined pattern or schedule. Questions are modified as the topics are picked up during the conversation.

As the field of SCR being comparatively new and being still evolving, and its multidisciplinary aspect requires the data collection to be done using semi structured way. Historically Interviews have always been done face to face, Knox & Burkard[32] find that "face-to-face interactions can help build rapport and establish trust between the interviewer and the interviewee". The physical presence and personal connection may create a more comfortable environment, leading to more open and candid responses.[33] In face-to-face interviews, interviewers can adapt their questioning or approach based on the interviewee's reactions or cues. They can tailor the interview process in real-time, ensuring that the questions and

[31] Alan Bryman and Emma Bell, *Business Research Methods*, Fourth edition (Cambridge, United Kingdom ; New York, NY, United States of America: Oxford University Press, 2015).
[32] Sarah Knox and Alan W. Burkard, "Qualitative Research Interviews," *Psychotherapy Research* 19, no. 4–5 (July 2009): 566–75, https://doi.org/10.1080/10503300802702105.
[33] Herbert Rubin and Irene Rubin, *Qualitative Interviewing (2nd Ed.): The Art of Hearing Data* (2455 Teller Road, Thousand Oaks California 91320 United States: SAGE Publications, Inc., 2005), https://doi.org/10.4135/9781452226651.

prompts are relevant and appropriate. [34] With development in technology, it has become easy and less time consuming to conduct interviews virtually, where the benefits of face-to-face interviews might be missed. This is the reason which is why it was preferred to conduct the interviews face to face with physical presence, which was not feasible for all the interviewees. Therefore, the mix of physical face to face and virtual interviews were carried out. Digital tools such as Microsoft teams was used for the virtual meeting, which was decided based on the availibilty of the software both on the interviewee and interviewer's digital setup. Video camera was used throughout on both sides to detect the emotions and provide the instant feedback of confirmation or understanding of answer. All the interviews were audio recorded with the prior consent and with the assurance of confidentiality of the personal data. Microsoft teams also offers live transcription function which was used to ease the process of post interview transcription tasks. During the face-to-face interviews, Google recorder was used to record audio and its transcription function. Both Microsoft teams and Google recorder do not provide 100% correct audio to transcription solution, which needs a manual correction at multiple instances.

2.1.6.3 Analysis

As per Nowell et al. [35] "researchers need to be clear about what they are doing, why they are doing it, and include a clear description of analysis methods". To bring this clarity in the current research the analysis method and the reasoning behind the choice will be discussed in this section. For analyzing semi-structured interviews, many methods exist in literature, such as narrative analysis, grounded theory, thematic analysis, content analysis. Braun and Clarke [36] argue "through its theoretical freedom, thematic analysis provides a highly flexible approach that can be modified for the needs of many studies, providing a rich and detailed, yet complex account of data". For the current research, thematic analysis method fits the best as thematic analysis allows for the identification and exploration of themes and patterns within interviews, which is useful for capturing the challenges, experiences, and insights shared by the interviewees[37]. They propose the following step-by-step guide to carry out thematic analysis.

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[34] Denzin and Lincoln, *The SAGE Handbook of Qualitative Research*.
[35] Lorelli S. Nowell et al., "Thematic Analysis: Striving to Meet the Trustworthiness Criteria," *International Journal of Qualitative Methods* 16, no. 1 (December 2017): 160940691773384, https://doi.org/10.1177/1609406917733847.
[36] Virginia Braun and Victoria Clarke, "Using Thematic Analysis in Psychology," *Qualitative Research in Psychology* 3, no. 2 (January 2006): 77–101, https://doi.org/10.1191/1478088706qp063oa.
[37] Braun and Clarke.

Figure 3: Thematic analysis process[38]

1. **Familiarizing yourself with your data:**

As mentioned before, Microsoft teams and Google recorder were used to transcribe the interviews, which do not show 100% accuracy because of technical limitations. Due to this, all the interview transcriptions had to be thoroughly checked and manually corrected using Microsoft word by comparing them with the audio files. In case some terms discussed during the interview were missed to be clarified, these terms were clarified with the interviewee on email communication. After a thorough review, another in-depth review of all the transcriptions were carried out which gave initial ideas about the possible codes, which were noted down separately.

1. **Generating initial codes:**

After getting familiarizing with all interviews, all the transcriptions were taken into the software MAXQDA. MAXQDA is the software recommended by FHV for qualitative data analysis. Using the initial ideas around the interviews, the initial codes were formed in the MAXQDA. Codes are "the most basic segment, or element, of the raw data or information that can be assessed in a meaningful way regarding the phenomenon"[39]. As suggested by Braun and Clarke[40] the entire data set was entirely worked through, full attention was given to each and every point mentioned, and interesting aspects were identified that may form the themes. The initial codes can be seen in the following except from MAXQDA.

[38] Braun and Clarke.
[39] Richard E. Boyatzis, *Transforming Qualitative Information: Thematic Analysis and Code Development* (Thousand Oaks, CA: Sage Publications, 1998).
[40] Braun and Clarke, "Using Thematic Analysis in Psychology."

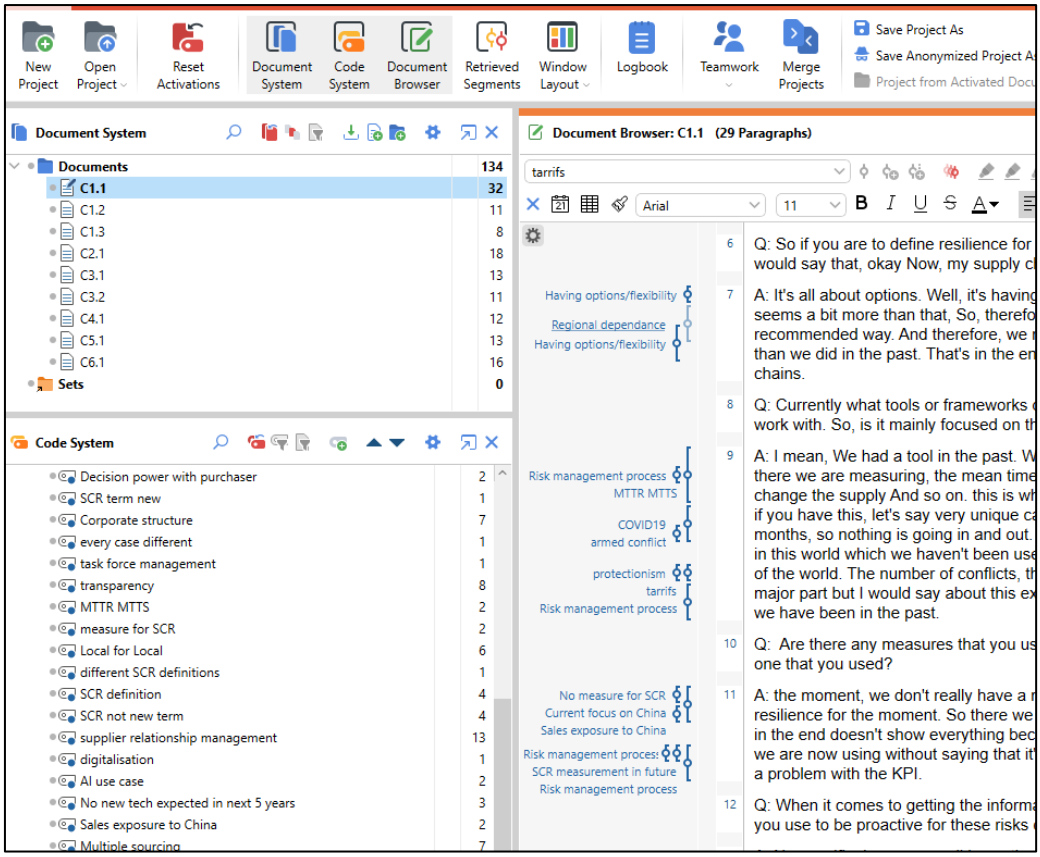

Figure 4: Excerpt from MAXQDA

2. Searching for themes:

After enlisting all the initial codes, these codes were extracted to be analyzed and sorted. These codes were sorted into potential themes, and started the process of analyzing them and considering how they can be formed into overarching themes. The heatmap of the codes in MAXQDA showed the frequency and presence of the code in multiple interviews.

3. Reviewing themes:

This step refines the initially thought themes, as with the multiple reviews the themes might either get deleted as not enough data to support them, or they get collapsed into each other as similar themes may form one theme, or one theme might get broken into multiple.[41] At the end of this stage, clarity about the multiples themes is achieved which will be basis for the further analysis.

4. Defining and naming themes:

After the reviews of the themes, it is important that each of the theme is names in a such a way which is concise self-explanatory of what it is about and its scope. Braun and Clarke[42] suggest that it is needed that each theme is considered with itself and in relations with others.

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[41] Braun and Clarke.
[42] Braun and Clarke.

They also add that with time sub-themes can also be identified within the themes which "*are essentially themes within theme and can be useful for giving structure to a particularly large and complex theme, and for demonstrating the hierarchy of meaning within the data*."

5. Producing report:

After completing the review and finalization of the themes, this step involves carrying out a final analysis and writing up of the report. As per Braun and Clarke[43] the report must "*provide a concise, coherent, logical, nonrepetitive, and interesting account of the story the data tell*". Following this, the findings of this research is explained in the next section.

[43] Braun and Clarke.

3 Literature review

Academic research in supply chain resilience has received significant attention in two decades. The first phase, which was prompted by the September 11 attacks, promoted the importance of recognizing vulnerabilities and sources of disruption risks in a supply chain (Kamalahmadi and Parast, 2016). While interest in supply chain resilience has kept its momentum, a second phase, COVID-19, also increased research in supply chain resilience (Remko, 2020; Modgil et al., 2022). This section 3 is dedicated to share the findings in the literature review. First in section 3.1 definitions proposed for the term SCR by researchers will be explored. This will be followed in section 3.2 with understanding what is the difference between risk and resilience in the context of SC. Afterwards in section 3. the proposed dimensions of SCR will be explored, followed in section 3.4 where we focus on the theoretical perspectives researchers has taken to explore the field of SCR and specifically the measurement of it. Section 3.5 will be focused on the strategies and enablers that are proposed in the literature which contribute to improve the SCR and also to measure it. Section 3.6 will include the methods that are found in the literature for measuring SCR. The last section 3.7 in the literature will explore the ways in which the new technologies are expected to make an impact on SCR.

3.1 Defining Supply Chain Resilience

As per Oxford English Dictionary, the word "resilience" originates in its current sense in the mid-17th century. The noun form, meaning "the action or an act of rebounding or springing back," was first used in 1626, while the adjective form, "marked by the ability to recover readily, especially from illness or adversity," was used in 1665. While the word "resilience" being Latin word for derived from the verb "resilire," which means "to leap back" or "to rebound", it took several centuries and widespread usage in different fields like ecology, psychology, social sciences, engineering, public health etc. to its conceptual development. More than a decade ago, other fields started to challenge the equilibrium-focused meaning of resilience. Wieland and Durach[44] found that a big change which happened in previous decade where fields other than SC, challenged the “equilibrium-focused meaning of resilience and suggested that resilience does not just relate to the ability of a system to “bounce back” after an impeding event, but also to the capacity to adapt and transform.”

In the context of supply chain, motivated by the disruption in the start of twenty-first century the term “supply chain resilience” received an attention and many definitions were proposed.

[44] Andreas Wieland and Christian F. Durach, “Two Perspectives on Supply Chain Resilience,” *Journal of Business Logistics* 42, no. 3 (July 2021): 315–22, https://doi.org/10.1111/jbl.12271.

Rice and Caniato[45] in 2003 were one of the first ones who proposed the definition for SCR as "*The ability of SC to react to unexpected disruption and restore normal supply network operations*." Followed by Christopher and Peck[46] in 2004 with "*The capability of SCs to operate in the face of disturbances and disruptions with or without a limited decrease in their performance*". In the same direction in 2007 Gaonkar and Viswanadham[47] proposed "*The ability of a SC to maintain, resume and recover operations aftermath of a severe disruptive event*" All these 3 prefer to call SCR being an ability or capability to maintain the operations in the aftermath of disruption. But Falasca and Zobel[48] in 2008 took it one step forward and added the ability of the SC to reduce the likelihood of disruption and the consequences with the definition "*The capability of SC to reduce the likelihood of disruption, to reduce the consequences of those disruptions when they occur and to reduce the time to recover normal performance*." Ponomarov and Holcomb [49] added the missing element from the previous definition which is the preparation of SC for disruption in "*Ability of SC to prepare for unexpected events, respond to disruptions, and restore from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function*." Which also resonates in the definition of Ponis and Koronis[50] from 2012 with the added element of designing the SC network for SCR "*The ability of SC to proactively plan and design the SC network for anticipating unexpected disruptive events, respond adaptively to disruptions while maintaining control over structure and function and transcending to a robust state of operations*."

Kamalahmadi and Mellat-Parast[51] in 2016 shared a comprehensive definition which include all the elements with "*The adaptive capability of a SC to reduce the probability of facing sudden disturbances, resist the spread of disturbances thereby maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the SC to a robust state of operations*." Evidently

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[45] Rice and Caniato, "Building a Secure and Resilient Supply Network," *Supply Chain Management Review*, 2003.
[46] Martin Christopher and Helen Peck, "Building the Resilient Supply Chain," *The International Journal of Logistics Management* 15, no. 2 (July 1, 2004): 1–14, https://doi.org/10.1108/09574090410700275.
[47] Roshan S. Gaonkar and N. Viswanadham, "Analytical Framework for the Management of Risk in Supply Chains," *IEEE Transactions on Automation Science and Engineering* 4, no. 2 (April 2007): 265–73, https://doi.org/10.1109/TASE.2006.880540.
[48] Falasca, Mauro and Christopher W. Zobel, "A Decision Support Framework to Assess Supply Chain Resilience," 2008.
[49] Serhiy Y. Ponomarov and Mary C. Holcomb, "Understanding the Concept of Supply Chain Resilience," *The International Journal of Logistics Management* 20, no. 1 (May 22, 2009): 124–43, https://doi.org/10.1108/09574090910954873.
[50] Stavros T. Ponis and Epaminondas Koronis, "Supply Chain Resilience: Definition Of Concept And Its Formative Elements," *Journal of Applied Business Research (JABR)* 28, no. 5 (August 21, 2012): 921, https://doi.org/10.19030/jabr.v28i5.7234.
[51] Masoud Kamalahmadi and Mahour Mellat Parast, "A Review of the Literature on the Principles of Enterprise and Supply Chain Resilience: Major Findings and Directions for Future Research," *International Journal of Production Economics* 171 (January 2016): 116–33, https://doi.org/10.1016/j.ijpe.2015.10.023.

many more definitions are proposed with the different perspectives and relations until the most recent definition by Ivanov[52] "*ability to maintain, execute and recover (adapt) planned execution along with achievement of the planned (or adapted, but yet still acceptable) performance*."

In summary with the literature review it is found that there is no one correct definition for SCR but each one takes different perspectives and includes similar elements. Ivanov[53] very well used an analogy of human immune system to explain the SCR: "*Immune system is an inherent property of any human being to absorb negative events and helps to recover. In supply chain terms, risks are negative events and resilience is an inherent property*."

3.2 Resilience versus Risk management

With a review on supply chain risk management (SCRM) literature, researchers[54] concluded that the SCRM literature is based on the traditional organizational risk management methodologies with the steps of identify, assess, treatment and monitor. On this view Wieland and Durach[55] argue that just using organizational risk management methodologies for supply chain risks is not sufficient, as the supply chains are way more complex than organizations as they are not confined by legal or geographical boundaries. They conclude with *"In sum, traditional risk-management approaches that work more or less well for an organization are not fully scalable to a system that is as complex as a supply chain."* In the same direction, Zavala et al. [56] add that applying traditional risk management strategies to each part of a global supply chains and for each possible risk is difficult as its approach is based on the probabilities and the impact. On the other hand, SCR provides the framework that is holistic and considers the unknown disruptions as well. Therefore, companies need to develop supply chain contingency plans to identify, monitor and mitigate unforeseen supply chain risks. Resilience is being used in many other fields as solution on the disruption situations, before it was used in SC context. While risk management only focuses on certain list on risks,

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[52] Dmitry Ivanov, *Structural Dynamics and Resilience in Supply Chain Risk Management*, vol. 265, International Series in Operations Research & Management Science (Cham: Springer International Publishing, 2018), https://doi.org/10.1007/978-3-319-69305-7.
[53] Dmitry Ivanov, *Introduction to Supply Chain Resilience: Management, Modelling, Technology*, Classroom Companion Business (Cham, Switzerland: Springer, 2021), https://doi.org/10.1007/978-3-030-70490-2.
[54] Yiyi Fan and Mark Stevenson, "A Review of Supply Chain Risk Management: Definition, Theory, and Research Agenda," *International Journal of Physical Distribution & Logistics Management* 48, no. 3 (March 22, 2018): 205–30, https://doi.org/10.1108/IJPDLM-01-2017-0043.
[55] Wieland and Durach, "Two Perspectives on Supply Chain Resilience."
[56] Araceli Zavala, David Nowicki, and Jose Emmanuel Ramirez-Marquez, "Quantitative Metrics to Analyze Supply Chain Resilience and Associated Costs," *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability* 233, no. 2 (April 2019): 186–99, https://doi.org/10.1177/1748006X18766738.

resilience deals with building the capacities of absorbing, responsive and recovery capacities which helps in the risks which are not even identified in the risk management.

3.3 Supply Chain Resilience dimensions

One important direction is to identify the dimensions of resilience when applied in the context of supply chain. While most of the researching organizational and supply chain resilience treats resilience as a unidimensional construct, there is emerging literature that treats resilience as a multidimensional construct. This includes constructing resilience in 2 dimensions which are either proactive or reactive proposed by scholas such as Sahitya Elluru et al.[57] Some authors such as Ortas et al. [58] have added a third dimension of resilience called adaptive resilience. Ivanov [59] has proposed the following Figure 5 of the 3 dimensions which are arranged where absorptive capacity being the "first line of defense"' to the disruptive event which is followed by adaptive and restorative capacity. The reason to identify them as dimensions is because they use the time attribute as proposed by researchers[60] and the notion of resilience capacity comes from Vugrin et al. [61] The absorptive capacity which is utilized before disruption, response capability during the disruption and recovery capacity after the disruption; all these 3 are independent and Parast[62] concludes "companies need to integrate different resources to form the corresponding capabilities to respond to different types of disruptions".

[57] Sahitya Elluru et al., "Proactive and Reactive Models for Disaster Resilient Supply Chain," *Annals of Operations Research* 283, no. 1–2 (December 2019): 199–224, https://doi.org/10.1007/s10479-017-2681-2.
[58] Eduardo Ortas et al., "Does Sustainability Investment Provide Adaptive Resilience to Ethical Investors? Evidence from Spain," *Journal of Business Ethics* 124, no. 2 (October 2014): 297–309, https://doi.org/10.1007/s10551-013-1873-1.
[59] Ivanov, *Introduction to Supply Chain Resilience*.
[60] Seyedmohsen Hosseini, Dmitry Ivanov, and Alexandre Dolgui, "Review of Quantitative Methods for Supply Chain Resilience Analysis," *Transportation Research Part E: Logistics and Transportation Review* 125 (May 2019): 285–307, https://doi.org/10.1016/j.tre.2019.03.001.
[61] Eric D. Vugrin, Drake E. Warren, and Mark A. Ehlen, "A Resilience Assessment Framework for Infrastructure and Economic Systems: Quantitative and Qualitative Resilience Analysis of Petrochemical Supply Chains to a Hurricane," *Process Safety Progress* 30, no. 3 (September 2011): 280–90, https://doi.org/10.1002/prs.10437.
[62] Parast, "Toward a Contingency Perspective of Organizational and Supply Chain Resilience."

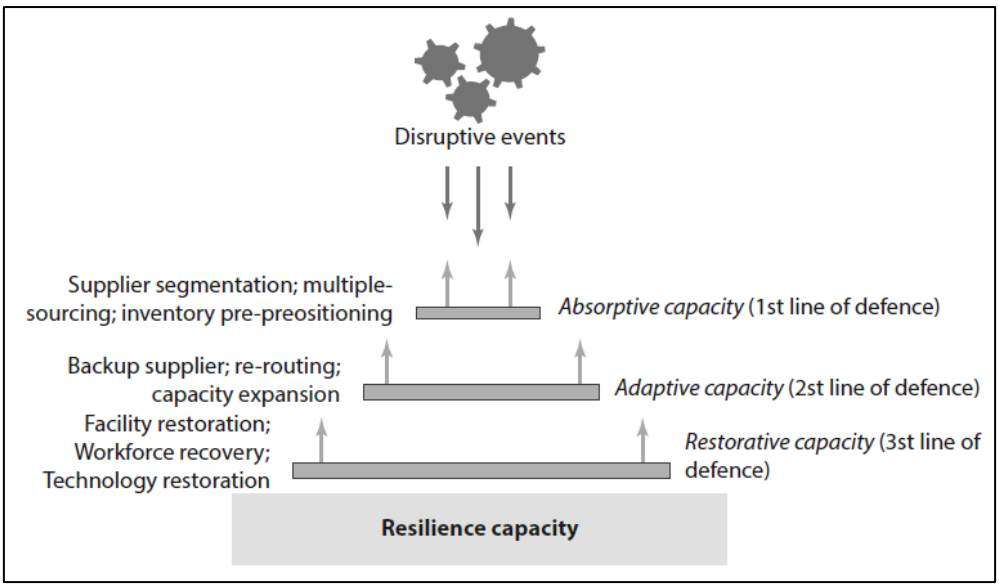

Figure 5: Resilience capacity of supply chains[63]

3.3.1 Absorptive capacity

As per Ivanov[64] absorptive capability is the ability of a SC to absorb and withstand disruptions by using its redundant resources and risk prevention activities. As shown in the Figure 5 above, absorptive capacity is the first step when faced with disruption[65]. For a company to have absorptive capacity, it must be aware of its current state and be proactively prepared. As per Ivanov[66] for a company to be proactively prepared: it must have supply chain situational awareness, have enough redundancy, and have visibility over the entire supply chain.

3.3.2 Adaptive/Response capability

Ivanov[67] defines Response capability as *"a supply chain's ability to respond correctly to risk on time by adjusting the flow of activities and resource allocation in the face of a disruption event*." Sheffi et al. [68] conclude that for companies to solidify their position in the market,

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[63] Ivanov, *Introduction to Supply Chain Resilience*.
[64] Hosseini, Ivanov, and Dolgui, "Review of Quantitative Methods for Supply Chain Resilience Analysis."
[65] Hosseini, Ivanov, and Dolgui.
[66] Dmitry Ivanov, "Lean Resilience: AURA (Active Usage of Resilience Assets) Framework for Post-COVID-19 Supply Chain Management," *The International Journal of Logistics Management* 33, no. 4 (October 17, 2022): 1196–1217, https://doi.org/10.1108/IJLM-11-2020-0448.
[67] Hosseini, Ivanov, and Dolgui, "Review of Quantitative Methods for Supply Chain Resilience Analysis."
[68] Sheffi, Yossi and Rice, Jr, James, "A Supply Chain View of the Resilient Enterprise. MIT Sloan Management Review. 47.," 2015.

they must respond fast to the disruption and capture the opportunity. Christopher and Peck[69] considers that a company has response capability when it can review the status of operations when disruption or risk of disruption occurs, and quickly make and implement response strategies to reduce the impact.

3.3.3 Recovery capability

Recovery capability can be referred as the capability to “Bounce back” and returning to the before the disruption status in terms of its demand fulfillment level. As seen in the Figure 5 recovery capability is the last step of defense for SC against the disruption risk. Christopher and Peck[70] conclude that when absorptive and response capability fail to keep the initial operational level of the SC, recovery capability is needed to be quickly improved.

3.4 Theoretical perspectives towards Supply Chain Resilience

During the literature review, it has been found that the topic of SCR has been dealt with by many researchers using different theories. Following are the theories (non-exhaustive list) with which the topic of SCR has been researched:

3.4.1 Resource-based view

The Resource-Based View theory[71], in the context of SCR, highlights the importance of internal resources and capabilities in enhancing SCR. According to this theory companies that possess unique and valuable resources are better equipped than others to respond to disruptions and recover quickly. Kochan et al.[72] [73] found this theory being used most as this provides a” basis to explore relationships among specific resources, capabilities, and performance”.

3.4.2 Dynamic capability

Dynamic capability theory is a management framework that emphasizes an organization's ability to adapt, innovate, and learn in response to changing environments and competitive

[69] Christopher and Peck, “Building the Resilient Supply Chain.”
[70] Hosseini, Ivanov, and Dolgui, “Review of Quantitative Methods for Supply Chain Resilience Analysis.”
[71] Birger Wernerfelt, “A Resource-Based View of the Firm,” *Strategic Management Journal* 5, no. 2 (1984): 171–80, http://www.jstor.org/stable/2486175.
[72] Cigdem Gonul Kochan and David R. Nowicki, “Supply Chain Resilience: A Systematic Literature Review and Typological Framework,” *International Journal of Physical Distribution & Logistics Management* 48, no. 8 (September 12, 2018): 842–65, https://doi.org/10.1108/IJPDLM-02-2017-0099.
[73] Kochan and Nowicki.

pressures[74]. It builds upon the resource-based view of the firm, extending the perspective to highlight the importance of continuously reconfiguring and developing the organization's resource base[75]. According to dynamic capability theory, organizations need to develop three core types of capabilities i.e. **Sensing capabilities**: to sense opportunities in the market; **Seizing capabilities**: Ability to respond to identified opportunity; **Transforming capability**: to transform existing resources. Zhao et al. [76] and many other researchers[77] [78] [79] [80] see SCR as a "*dynamic capability that emphasizes timely risk anticipation, adequate resource mobilization, and reconfiguration of supply chain resources in crises to maintain competitive advantage and sustainable performance levels in a volatile environment*". This is why many scholars have started to consider dynamic capability as base for studying SCR.

3.4.3 Contingent resource-based view

After finding the dominance of dynamic capability perspective in the SCR literature, Parast[81] proposed a contingency perspective which complements the dynamic capability perspective. The contingent resource-based view (CRBV) incorporates contingency theory in the resource-based view of the firm, which asserts that the effectiveness of organizational resources and/or capabilities in enhancing a firm 's competitive advantage and capabilities is "contingent" upon the organizational context and the environment.[82] While differentiating the contingencies in 2 strategic and operational; Parast [83] raised a good point which is improving organizational resilience should be viewed from the perspective of both strategic and

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[74] David J. Teece, "Explicating Dynamic Capabilities: The Nature and Microfoundations of (Sustainable) Enterprise Performance," *Strategic Management Journal* 28, no. 13 (December 2007): 1319–50, https://doi.org/10.1002/smj.640.
[75] David J. Teece, Gary Pisano, and Amy Shuen, "Dynamic Capabilities and Strategic Management," *Strategic Management Journal* 18, no. 7 (August 1997): 509–33, https://doi.org/10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z.
[76] Nanyang Zhao, Jiangtao Hong, and Kwok Hung Lau, "Impact of Supply Chain Digitalization on Supply Chain Resilience and Performance: A Multi-Mediation Model," *International Journal of Production Economics* 259 (May 2023): 108817, https://doi.org/10.1016/j.ijpe.2023.108817.
[77] Zhao, Hong, and Lau.
[78] Juneho Um and Neungho Han, "Understanding the Relationships between Global Supply Chain Risk and Supply Chain Resilience: The Role of Mitigating Strategies," *Supply Chain Management: An International Journal* 26, no. 2 (February 10, 2021): 240–55, https://doi.org/10.1108/SCM-06-2020-0248.
[79] Chiung-Lin Liu and Ming-Yu Lee, "Integration, Supply Chain Resilience, and Service Performance in Third-Party Logistics Providers," *The International Journal of Logistics Management* 29, no. 1 (February 12, 2018): 5–21, https://doi.org/10.1108/IJLM-11-2016-0283.
[80] Salomée Ruel and Jamal El Baz, "Disaster Readiness' Influence on the Impact of Supply Chain Resilience and Robustness on Firms' Financial Performance: A COVID-19 Empirical Investigation," *International Journal of Production Research* 61, no. 8 (April 18, 2023): 2594–2612, https://doi.org/10.1080/00207543.2021.1962559.
[81] Parast, "Toward a Contingency Perspective of Organizational and Supply Chain Resilience."
[82] Emma Brandon-Jones et al., "A Contingent Resource-Based Perspective of Supply Chain Resilience and Robustness," *Journal of Supply Chain Management* 50, no. 3 (July 2014): 55–73, https://doi.org/10.1111/jscm.12050.
[83] Parast, "Toward a Contingency Perspective of Organizational and Supply Chain Resilience."

operational contingencies. Unless the investment in organizational capabilities is well aligned with both the strategic and operational contingencies discussed here, organizations may not achieve the desired outcomes from their investment in such efforts.

3.4.4 Graph theory

As the name suggests, Graph theory mathematical framework that uses node (vertices) which are connected by edges (links) which in relation to SCR shows the interconnected ness of various nodes which are suppliers, manufacturers, distributions centers, customers etc. Using this theory researchers[84] took all the dimensions of 16 SCR enablers identified in the literature and modelled them through a graph, with a goal of finding a resilience index.

3.4.5 Network theory

Mari et al.[85] have proposed new SCR matrix using complex network theory, for which the reasoning provided being the overall importance of complex network theory. Based on the argument of Hearnshaw and Wilson [86] that "*the properties of complex network models are applicable to real-world supply chains*", the following resilience metrics with measuring methods are developed.

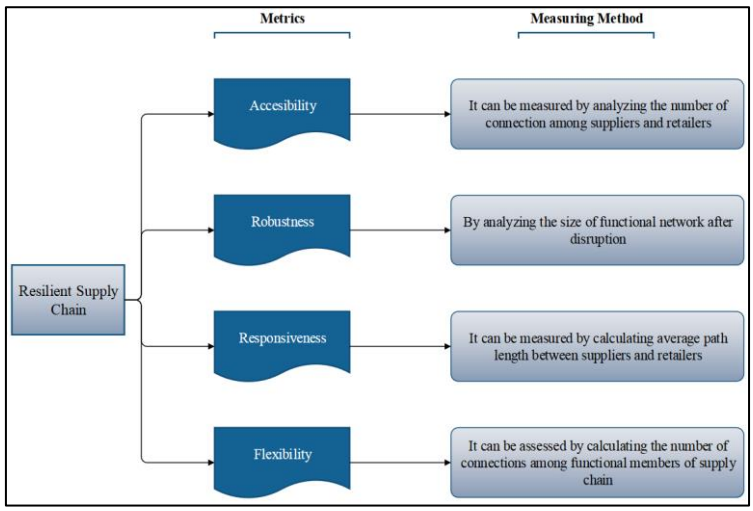

Figure 6: Resilient supply chain metrics[87]

[84] Nishtha Agarwal, Nitin Seth, and Ashish Agarwal, "Evaluation of Supply Chain Resilience Index: A Graph Theory Based Approach," *Benchmarking: An International Journal* 29, no. 3 (March 8, 2022): 735–66, https://doi.org/10.1108/BIJ-09-2020-0507.
[85] Sonia Irshad Mari, Young Hae Lee, and Muhammad Saad Memon, "Complex Network Theory-Based Approach for Designing Resilient Supply Chain Networks," *International Journal of Logistics Systems and Management* 21, no. 3 (2015): 365, https://doi.org/10.1504/IJLSM.2015.069733.
[86] Edward J.S. Hearnshaw and Mark M.J. Wilson, "A Complex Network Approach to Supply Chain Network Theory," *International Journal of Operations & Production Management* 33, no. 4 (March 15, 2013): 442–69, https://doi.org/10.1108/01443571311307343.
[87] Mari, Lee, and Memon, "Complex Network Theory-Based Approach for Designing Resilient Supply Chain Networks."

3.5 Enablers of Supply chain resilience

As discussed earlier the 3 capacities mentioned are independent to each other, which is why there are different strategies and enablers to build each of these capacities. There are several literatures which categorize the enablers at this mentioned method and Agarwal et al.[88] categorized the enablers at the managerial levels: Strategic level, Operative level, tactical level.

- **Enablers at strategic level:**
  - Collaborative decision-making
  - Real time information flow
  - Collaborative forecasting
  - Backup local supplier
  - Business intelligence system
  - Information tracking
  - Information sharing with partners.
  - Reserve capacity for machinery/parts
- **Enablers at operative level**
  - Distribution logistics flexibility
  - Contract flexibility
  - Production flexibility
  - Sourcing flexibility
- **Enablers at tactical Level**
  - Proactive identification disruptions
  - Quick actions on disruptions
  - Collaborative operations with partners
  - Multi-skilled workforce

Agarwal et al.[89] noted that different enablers become effective for SCR as industry and country context change, which means that not all the enablers mentioned will be applicable to all of the supply chains. SCR measure proposed by Carvalho et al.[90] focuses on

[88] Agarwal, Seth, and Agarwal, "Evaluation of Supply Chain Resilience Index."
[89] Agarwal, Seth, and Agarwal.
[90] Helena Carvalho et al., "The Resilience of On-Time Delivery to Capacity and Material Shortages: An Empirical Investigation in the Automotive Supply Chain," *Computers & Industrial Engineering* 171 (September 2022): 108375, https://doi.org/10.1016/j.cie.2022.108375.

reducing 2 shortages: Material shortage and capacity shortages. For both, the SCR practices are categorized for each shortage in reducing the severity and reducing the recovery time:

Material Shortages	Resilience practice	Supply chain state variable	Metrics
Reducing Severity	Use materials buffers	Raw materials level	Availability of raw material strategic buffers (RAW)
		WIP level	Availability of Work in Progress (WIP) strategic buffers
		FGI level	Availability of Finished Goods Inventory (FGI) strategic buffers
	Deliver a temporary substitute product	Product alternative	Availability of product alternatives/dummies
		Materials/components alternative	Ease (time and cost) of using new/substitute components
	Use alternative delivery paths	Available alternatives for delivery	Number of available alternatives for delivery routes
		Transport mode	Number of available alternatives for transporting goods and material
		Distribution channels	Ease (cost and time) of switching between distribution channels
	Use alternative suppliers/strategic sourcing	Available alternatives for sources of supply	Number of available alternatives for sources of supply
			Number of different suppliers contracted per component
			Ease (cost and time) of switching between suppliers
		Relationship with suppliers	Close relationship with suppliers
			The level of expertise in developing supply sources
Reducing Recovery time	Reduce delivery lead time	Delivery lead time	Ease (cost) of reducing delivery lead time [c][d]
	Change delivery schedules	Delivery schedule adaptability	Ease (cost and time) of changing delivery schedules
	Reduce supply lead time	Supply lead time	Ease (cost) of changing the supplier lead time
	Find new suppliers	Time to contract	Ease (cost and time) of contracting new suppliers

Figure 7: Material shortages and resilience practises (Adapted to fit) [91]

Capacity Shortages	Resilience practice	Supply chain state variable	Metrics
Reducing Severity	Use alternative production	Available alternatives for production processes	Possibility to outsource production processes
			Operations versatility (number of operations a workstation can perform)
			Redundancy in production processes
		Available alternatives for production sites	Number of available alternatives for production sites
	Use maximum capacity	Production capacity slack	Ease (time and cost) of adjusting the production capacity
Reducing Recovery time	Reduce response time	Production lead time	Ease (cost) of reducing production lead time
		Setup time	Ease (cost) of reducing setup or changeover times
	Reallocate resources	Resources relocatability	Ease (cost and time) of relocating equipment from one cell, site, or business partner to another
			Ease (cost and time) of reallocating workers
			Ease (cost and time) of disabling equipment and re-commissioning if necessary
	Increase capacity	Supplier capacity	Possibility to influence the short-term capacity of suppliers
		Production capacity scalability	Ease (time and cost) of increasing production capacity
	Change the production schedule	Production schedule adaptability	Ease (cost and time) of changing the production schedules

Figure 8: Capacity shortages and resilience practises (Adapted to fit) [92]

Christoph and peck [93] in 2002 summarized the principles that underpin SCR in 4 stages: First principle is that the resilience should be engineered in the supply chain itself, which can be done by mapping the critical paths/routes, maintaining the risk register, and overall getting a clear understanding of the supply chain itself. The second principle is with the collaboration, which needs to be on high level for a company to be resilient as the companies in general extend to more than one organization. Third principle is focused on agility of the supply chain which is the ability to react quickly on the adverse events, which gives the advantage to the organization in uncertainty. The fourth principle is that the SCR is

[91] Carvalho et al.
[92] Carvalho et al.
[93] Christopher and Peck, “Building the Resilient Supply Chain.”

enhanced with the risk management culture in the organization, which includes creating SC continuity teams, considering risk as a factor in decision making, and having board level responsibility and leadership.

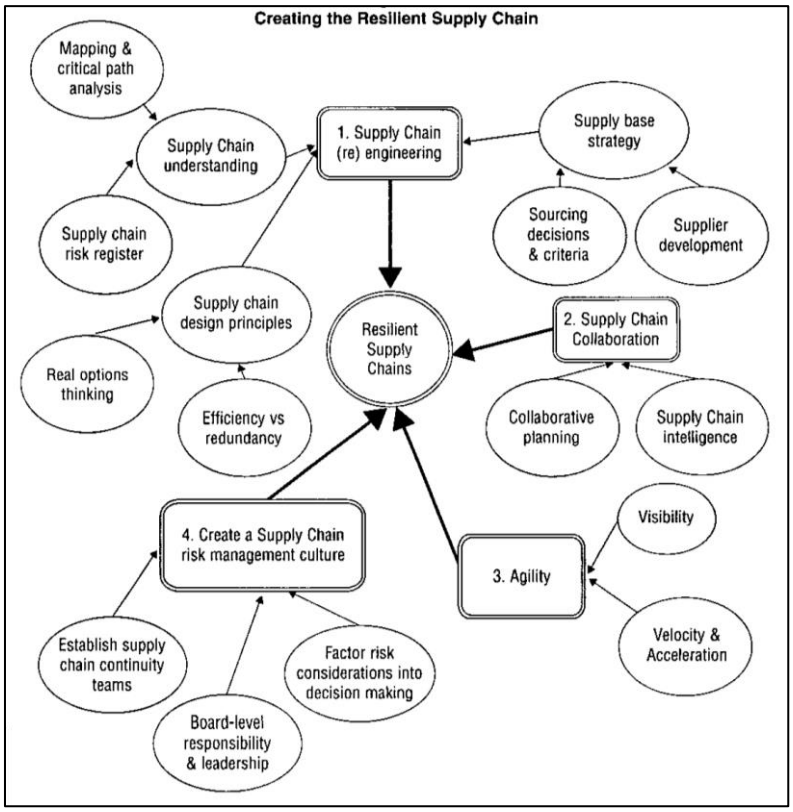

Figure 9: Creating the resilient supply chain[94]

Hsu et al. [95] proposed a new strategy for the fashion industry, for improving resilience and sustainability of the supply chains. After a literature they collected 26 resilience enhancing features, which are shown in Figure 10 and Figure 11:

[94] Christopher and Peck.
[95] Chih-Hung Hsu et al., "Deploying Resilience Enablers to Mitigate Risks in Sustainable Fashion Supply Chains," *Sustainability* 13, no. 5 (March 8, 2021): 2943, https://doi.org/10.3390/su13052943.

Dimension	Resilience-Enhancing Feature
Management	Reconfiguring company resources
	Strengthen staff training and leadership
	Construct risk emergency mechanism
	Establishing a feasible incentive system
	Employ multiple supplier sources
Enterprise culture	Encourage non-hierarchical communication
	Enliven culture of trust and accountability
	Foster awareness of environmental protection and social responsibility
	Strictly abide by the rules and develop self-discipline
Relationship	On-site risk monitoring and responsibility sharing
	Recruit experts for improvement
	Strengthen the linkage between production site and support
	Improve and summarize customer feedback
	Maintain communication and cooperation with customers and suppliers
System	Upgrade information systems that integrate resources
	Upgrade system functionality and transaction automation
	Establish and train cross-functional organisations
	Develop standard operating procedures
	Improve product design and development

Figure 10: Resilience-enhancing features [96]

Dimension	Resilience-Enhancing Feature
System	Upgrade information systems that integrate resources
	Upgrade system functionality and transaction automation
	Establish and train cross-functional organisations
	Develop standard operating procedures
	Improve product design and development
	Sharing real-time job information
	Implement concurrent engineering strategy
Logistics	Maintain and update equipment
	Improve facility layout
	Arrange and reorganize storage space
	Maintain adequate buffer stock
	Optimize transportation modes and routes

Figure 11: Resilience-enhancing features [97]

[96] Hsu et al.
[97] Hsu et al.

3.6 Supply chain resilience measurement methods

In this section we discuss the SCR measurement methods proposed in the research. These are sorted as per the date of the research paper.

3.6.1 Resilience index from LARG Index

Azevedo et al.[98] in 2013 proposed a single benchmarking tool for automotive SC's to measure 4 SC paradigms: Leanness, Agility, Resiliency and Greenness combined, the first letters of each make the word LARG. The rational provided behind this model is that any SC is consisting on *n* different companies and all these companies have different level of LARG. By aggregating the level of LARG of each company will provide us the LARG of the SC. This index uses Delphi technique to measure weights for every paradigm with the help of linear aggregation. Although the current research only focuses on resilience and not on leanness, agility, or greenness but still it can be used to solely measure the resilience of a SC. This is the reason why we will only discuss here the resilience part of the LARG index and exclude the other 3 paradigms. To compute the individual company behavior according to resilience paradigm, the resilience indicator will be obtained by combining the information from the sub indicators. These sub indicators can vary with the type of the industry, size, and relevance. After a literature review Azevedo et al.[99] concluded the following sub indicators for the resilience of the automobile industry. Each of these sub indicators have a weightage on the overall resilience index, and this weightage is calculated by using a Delphi technique questionnaire, with 9 academics and 9 automotive industry professionals.

Resilience practices	**Weightage**
P_{R1} = sourcing strategies to allow switching of suppliers	0.15
P_{R2} = flexible supply base/flexible sourcing	0.16
P_{R3} = strategic stock	0.14
P_{R4} = lead time reduction	0.14
P_{R5} = creating total supply chain visibility	0.15
P_{R6} = flexible transportation	0.14
P_{R7} = developing visibility to downstream inventories and demand conditions	0.12

Table 2: Resilience practises and weightage[100]

[98] Susana Garrido Azevedo, Helena Carvalho, and V. Cruz-Machado, "LARG Index: A Benchmarking Tool for Improving the Leanness, Agility, Resilience and Greenness of the Automotive Supply Chain," ed. Niranjan Pati, *Benchmarking: An International Journal* 23, no. 6 (August 1, 2016): 1472–99, https://doi.org/10.1108/BIJ-07-2014-0072.
[99] Azevedo, Carvalho, and Cruz-Machado.
[100] Susana Garrido Azevedo, Helena Carvalho, and V. Cruz-Machado, "LARG Index: A Benchmarking Tool for Improving the Leanness, Agility, Resilience and Greenness of the Automotive Supply Chain," ed. Niranjan Pati, *Benchmarking: An International Journal* 23, no. 6 (August 1, 2016): 1472–99, https://doi.org/10.1108/BIJ-07-2014-0072.

For each company j, formula shown below is proposed to measure the indicator B_R. According to the paradigm R, for resilient. Following equation shows that the company behavior according to resilience paradigm is function of each resilience practice's implementation level (P_{Ri}) and corresponding weight (W_{xi}):

$$(B_R)_j = f\left[W_{x1} \times (P_{R1})_j \ldots W_{x2} \times (P_{x2})_j, W_{x7} \times (P_{R7})\right]$$

Being $W_x \geq 0$ and $\sum W_x = 1$

The implementation level of each resilience practice which is or is assessed on a five-point Likert scale where 1 means "practice not implemented" and 5 "practice totally implemented. W_{xi} is the weight of practice i of paradigm x.

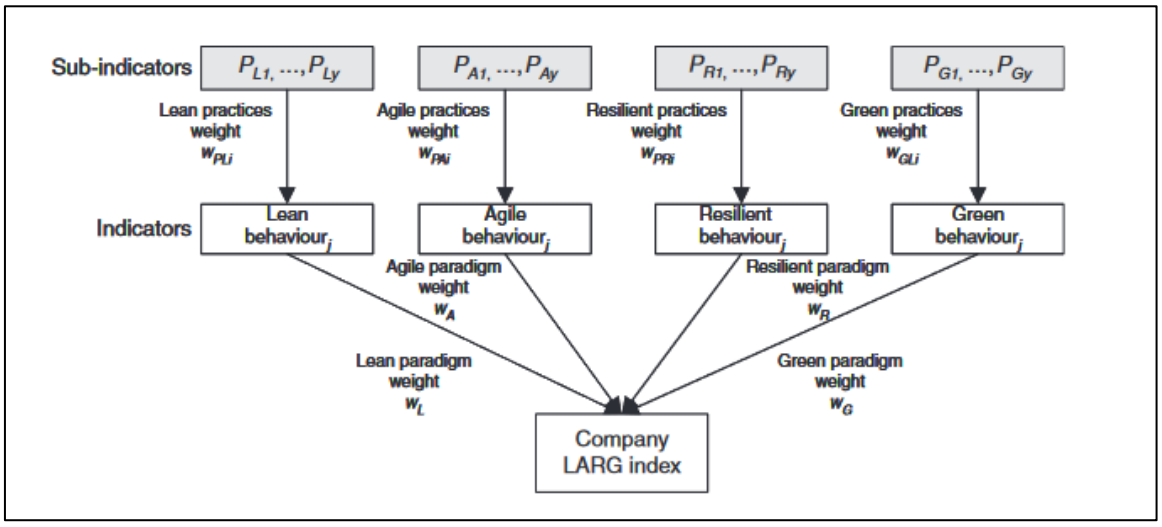

Figure 12: Hierarchical relationships evolved in the LARG company behavior assessment[101]

Using the above-mentioned formula for $(B_R)_j$, the resilience index can be measured for each company and aggregating the resilience index for each company which is in the SC, the resilience index of the entire SC will be computed.

[101] Susana Garrido Azevedo, Helena Carvalho, and V. Cruz-Machado, "LARG Index: A Benchmarking Tool for Improving the Leanness, Agility, Resilience and Greenness of the Automotive Supply Chain," ed. Niranjan Pati, *Benchmarking: An International Journal* 23, no. 6 (August 1, 2016): 1472–99, https://doi.org/10.1108/BIJ-07-2014-0072.

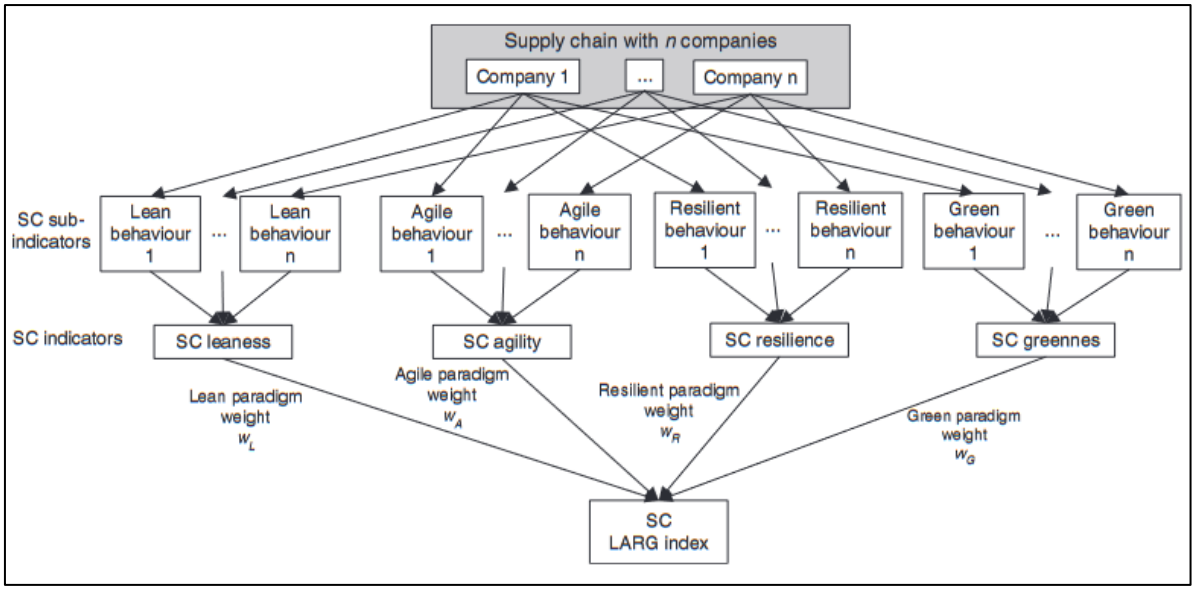

Figure 13: Hierarchical relationships involved in the supply chain LARG index[102]

Below Figure 14 adapted from Azevedo et al.[103] shows the result of the resilience index of the SC consisting of 6 companies under case study, where the aggregated resilience result out of the LARG index is 3.78

LARG practices	w_{xi}	Practices implementation level Companies ($n=6$) 1	2	3	4	5	6	Behaviour for SC $SCI_x = \sum(B_x)_j/n$
P_{R1}	0.15	4	5	3	4	3	1	Resilient behaviour for SC = 3.78
P_{R1} = sourcing strategies to allow switching of suppliers	0.16	4	5	4	4	3	1	
P_{R2} = flexible supply base/flexible sourcing	0.14	5	5	5	5	4	4	
P_{R3} = strategic stock	0.14	4	4	4	4	3	4	
P_{R4} = lead time reduction	0.15	5	4	5	4	4	1	
P_{R5} = creating total supply chain visibility	0.14	4	4	3	4	3	3	
P_{R6} = flexible transportation	0.12	5	4	5	4	4	1	

Figure 14: Resilient behaviour result from the case study[104]

[102] Susana Garrido Azevedo, Helena Carvalho, and V. Cruz-Machado, "LARG Index: A Benchmarking Tool for Improving the Leanness, Agility, Resilience and Greenness of the Automotive Supply Chain," ed. Niranjan Pati, *Benchmarking: An International Journal* 23, no. 6 (August 1, 2016): 1472–99, https://doi.org/10.1108/BIJ-07-2014-0072.
[103] Azevedo, Carvalho, and Cruz-Machado.
[104] Susana Garrido Azevedo, Helena Carvalho, and V. Cruz-Machado, "LARG Index: A Benchmarking Tool for Improving the Leanness, Agility, Resilience and Greenness of the Automotive Supply Chain," ed. Niranjan Pati, *Benchmarking: An International Journal* 23, no. 6 (August 1, 2016): 1472–99, https://doi.org/10.1108/BIJ-07-2014-0072.

3.6.2 Component Resilience Index

Ahmadian et at.[105] proposed a quantitative method to measure the resilience of the network components and the resilience of the whole network itself, with the rational that the entire network is as resilient as much as its weakest/least resilient component/link. For this, resilience index of each of component is quantified on the function of criticality, frequency of disruption, disruption impact and capability of its recovery and the resilience of the component with lowest score is considered as the resilience index for the entire network.

The resilience of the component is defined using the factors which are: the probability of disruption, consequences of the disruptions, recovery to the normal state and the criticality of the component which is the ability of network to perform in the absence of the component. If there is no substitution for the component in the case of disruption, it is considered more critical.

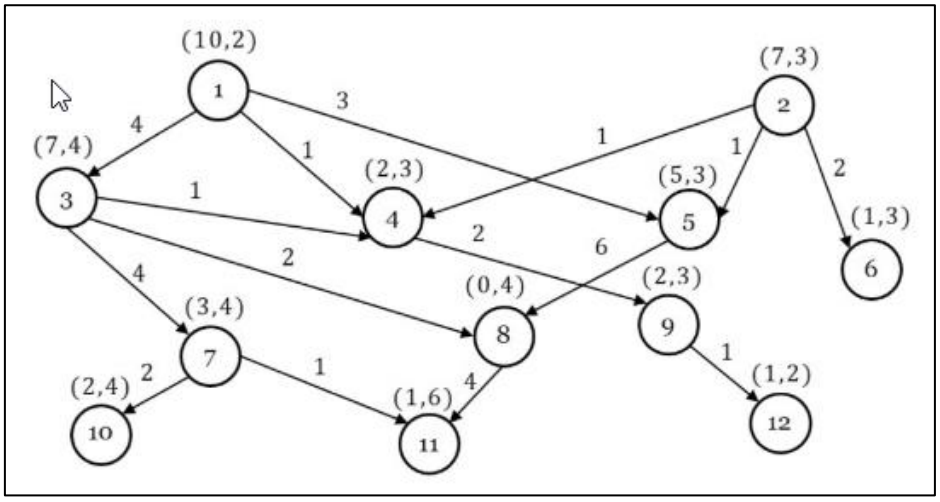

Figure 15: Supply network example[106]

The image above shows the example of the supply network with nodes (the circles) and arcs joining them. There are 12 nodes which are connected by at least 1 arc, the value in the middle of the nodes show the flow amount and the 2 values in the brackets above show the supply and demand of that arc respectively. It can be said that this method of measuring network resilience can also be applied to the supply network where nodes are the suppliers, and the arcs are the shipping routes to measure the SCR.

[105] Navid Ahmadian et al., "A Quantitative Approach for Assessment and Improvement of Network Resilience," *Reliability Engineering & System Safety* 200 (August 2020): 106977, https://doi.org/10.1016/j.ress.2020.106977.

[106] Navid Ahmadian et al., "A Quantitative Approach for Assessment and Improvement of Network Resilience," *Reliability Engineering & System Safety* 200 (August 2020): 106977, https://doi.org/10.1016/j.ress.2020.106977.

Below is the Figure 16 which shows all the nomenclatures and followed by the explanation of the parameters which are used for the proposed CRI measurement method:

Nomenclature

$G = (\mathcal{N}, \mathcal{A})$	Network with a set of nodes $\mathcal{N}$ and a set of arcs $\mathcal{A}$	r_i^n	disruption on node $n \in \mathcal{N}$ Repair rate function of node $i \in \mathcal{N}$
f_{ij}	Flow of arc $(i, j) \in \mathcal{A}$	r_{ij}^a	Repair rate function of arc $(i, j) \in \mathcal{A}$
T	Standard time interval	Q_i^n	Cumulative repair rate of node $i \in \mathcal{N}$
d_i	Demand of node $i \in \mathcal{N}$	Q_{ij}^a	Cumulative repair rate of arc $(i, j) \in \mathcal{A}$
s_i	Supply of node $i \in \mathcal{N}$	I_i^n	Impact of node $i \in \mathcal{N}$ disruption on the network
γ_{ij}	Capacity of arc $(i, j) \in \mathcal{A}$	I_{ij}^a	Impact of arc $(i, j) \in \mathcal{A}$ disruption on the network
l_i	Demand loss of node $i \in \mathcal{N}$	C_i^n	Criticality of node $i \in \mathcal{N}$
	Estimated damage level on node $i \in \mathcal{N}$ caused by a disruption on the same node	C_{ij}^a	Criticality of arc $(i, j) \in \mathcal{A}$
		$\mathcal{L}_i^n$	Likelihood of having disruption on node $i \in \mathcal{N}$
φ_{ij}^a	Estimated damage level on arc $(i, j) \in \mathcal{A}$ caused by a disruption on the same arc	$\mathcal{L}_{ij}^a$	Likelihood of having disruption on arc $(i, j) \in \mathcal{A}$
		R_i^n	Resilience of node $i \in \mathcal{N}$
$\tilde{\varphi}_{ijn}^a$	Estimated damage level on arc $(i, j) \in \mathcal{A}$ caused by a	R_{ij}^a	Resilience of arc $(i, j) \in \mathcal{A}$

Figure 16: Nomenclature[107]

Impact of a Node Disruption (I_i^n) This is the total loss when the node is disconnected from network which is calculated by the sum of node supply and the incoming flow.

Impact of an Arc Disruption (I_{ij}^{na}) This is the total loss when an arc is disconnected from the network which is calculated by the total flow of the arc.

Node criticality (C_i^n) The criticality of the node is the loss of the network in time, when the component is disrupted, this is calculated with an optimization model to find the best alternative to minimize the network loss.

Arc criticality (C) : Just like the node criticality the arc criticality is also measure in the loss of network in time and is calculated with an objective function to minimize the lose with the constraints on the flow capacity of the disrupted and undisrupted arcs.

L1: Loss in network between the time interval of disruption and implementation of alternative plan **L2**: Loss in network between the time interval of implementation of alternative plan and the using the original plan. **L3**: Loss in network between the time interval between switching to original plan and achieving full recover of the network; so the total loss is calculated bu summing **L1**, **L2** and **L3**

The CRI in this proposed approach[108] is calculated as the ratio of the demand loss during time interval which starts from the disruption:

$$CRI = 1 - \frac{\text{Total demand loss due to the component disruption}}{\text{Total demand in the network system during the time interval}}$$

[107] Navid Ahmadian et al., "A Quantitative Approach for Assessment and Improvement of Network Resilience," *Reliability Engineering & System Safety* 200 (August 2020): 106977, https://doi.org/10.1016/j.ress.2020.106977.
[108] Ahmadian et al.

Using the above formula for *CRI* the following 2 equations are proposed which are for CRI measure for node and arcs respectively:

$$R_i^n(\mathcal{L}_i^n, \varphi_i^n, I_i^n, t_{Ri}{}^n, C_i^n) = 1 - \frac{\int_{t=t_{0i}{}^n}^{t_{Si}{}^n} I_i^n \varphi_i^n \mathcal{L}_i^n (1 - Q_i^n(t))di}{T\sum_{i\in\mathcal{N}} d_i} - \frac{C_i^n \varphi_i^n \mathcal{L}_i^n (t_{Ei}{}^n - t_{Si}{}^n)}{T\sum_{i\in\mathcal{N}} d_i} - \frac{\int_{t=t_{Ei}{}^n}^{t_{Ri}{}^n} I_i^n \varphi_i^n \mathcal{L}_i^n (1 - Q_i^n(t))dt}{T\sum_{i\in\mathcal{N}} d_i}, \forall\, i \in \mathcal{N}$$

Figure 17: Resilience for the Node R_i^n

$$R_{ij}^a\left(\mathcal{L}_{ij}^a, \varphi_{ij}^a, I_{ij}^a, t_{Rij}{}^a, C_{ij}^a\right) = 1 - \frac{\int_{t=t_{0ij}{}^a}^{t_{Sij}{}^a} I_{ij}^a \varphi_{ij}^a \mathcal{L}_{ij}^a (1 - Q_{ij}^a(t))dt}{T\sum_{i\in\mathcal{N}} d_i} - \frac{C_{ij}^a \varphi_{ij}^a \mathcal{L}_{ij}^a (t_{Eij}{}^a - t_{Sij}{}^a)}{T\sum_{i\in\mathcal{N}} d_i} - \frac{\int_{t=t_{Eij}{}^a}^{t_{Rij}{}^a} I_{ij}^a \varphi_{ij}^a \mathcal{L}_{ij}^a (1 - Q_{ij}^a(t))dt}{T\sum_{i\in\mathcal{N}} d_i}, \forall\, (i,j) \in \mathcal{A}$$

Figure 18: Resilience for the arc R_{ij}^a

Using the above formulas on a sample case study on 12 nodes and arcs between them by Ahmadian et at.[109], the following Figure 19 and Figure 20 show the resilience of all the nodes and arcs in percentages and the yellow highlighted lines show the ones with the least resilience. This resilience is used as an index for the entire network.

Node #	I_i^n	$\mathcal{L}_i^n$	C_i^n	$t_{Si}{}^n$	$t_{Ei}{}^n$	$t_{Ri}{}^n$	L_1	L_2	L_3	L	R_i^n
1	10	0.2	10	0.2	0	4	0.39	0	3.61	4.00	97.56%
2	7	0.3	7	0.1	0	1	0.20	0	0.85	1.05	99.36%
3	11	0.1	8	0.4	0.55	2	0.40	0.12	0.58	1.09	99.33%
4	5	0.05	5	0.2	0	4	0.05	0	0.45	0.50	99.70%
5	9	0.2	6	0.4	0.67	2	0.65	0.32	0.80	1.77	98.92%
6	3	0.3	3	0.1	0	3	0.09	0	1.26	1.35	99.18%
7	7	0.15	6	0.2	0.29	2	0.20	0.08	0.77	1.05	99.36%
8	8	0.25	6	0.3	0.75	3	0.57	0.68	1.69	2.93	98.21%
9	4	0.2	4	0.5	0	4	0.38	0	1.23	1.60	99.02%
10	4	0.1	4	0.2	0	2	0.08	0	0.32	0.40	99.76%
11	6	0.5	6	0.1	0	3	0.30	0	4.21	4.50	97.26%
12	2	0.35	2	0.3	0	4	0.20	0	1.20	1.40	99.15%

Figure 19: Results of resilience of each node from example supply chain network[110]

ID	Arc #	I_{ij}^a	$\mathcal{L}_{ij}^a$	C_{ij}^a	t_{Sij}^a	t_{Eij}^a	t_{Rij}^a	L_1	L_2	L_3	L	R_{ij}^a
1–3	1	4	0.4	1	0.2	2.25	3	0.31	0.82	0.15	1.28	99.22%
1–4	2	1	0.25	0	0.1	3	3	0.02	0	0	0.02	99.99%
1–5	3	3	0.3	0	0.4	3	3	0.34	0	0	0.34	99.80%
2–4	4	1	0.2	0	0.2	3	3	0.04	0	0	0.04	99.98%
2–5	5	1	0.15	0	0.4	2	2	0.05	0	0	0.05	99.97%
2–6	6	2	0.45	2	0.1	0	2	0.09	0	0.81	0.90	99.45%
3–4	7	1	0.5	0	0.2	4	4	0.10	0	0	0.10	99.94%
3–7	8	4	0.1	3	0.3	0.5	2	0.11	0.06	0.22	0.40	99.76%
3–8	9	2	0.05	0	0.5	3	3	0.05	0	0	0.05	99.97%
4–9	10	2	0.25	2	0.2	0	4	0.10	0	0.90	1.00	99.39%
5–8	11	6	0.3	3	0.1	1	2	0.18	0.81	0.45	1.44	99.12%
7–10	12	2	0.15	2	0.2	0	2	0.06	0	0.24	0.30	99.82%
7–11	13	1	0.2	0	0.1	3	3	0.02	0	0	0.02	99.99%
8–11	14	4	0.25	2	0.4	2	4	0.38	0.80	0.50	1.68	98.98%
9–12	15	1	0.3	1	0.3	0	4	0.09	0	0.51	0.60	99.63%

Figure 20: Results of resilience of each arc from example supply chain network[111]

[109] Ahmadian et al.

[110] Navid Ahmadian et al., "A Quantitative Approach for Assessment and Improvement of Network Resilience," *Reliability Engineering & System Safety* 200 (August 2020): 106977, https://doi.org/10.1016/j.ress.2020.106977.

[111] Navid Ahmadian et al., "A Quantitative Approach for Assessment and Improvement of Network Resilience," *Reliability Engineering & System Safety* 200 (August 2020): 106977, https://doi.org/10.1016/j.ress.2020.106977.

3.6.3 Resilience index based on Graph theory.

Agarwal et al. [112] applied Graph theory and proposed a SCR index, which is based on measuring the interactions between the enablers of the SC. A literature review was carried out to find the SCR enablers, which were then categorized into 3 organizational level which are strategic level, operative level, and tactical level. These enablers are shown in the Figure 21.

Enablers at strategic level
Collaborative decision-making improves resilience
Real time information flow improves resilience
Collaborative forecasting improves resilience
Backup local supplier improves resilience
Business intelligence system improves resilience
Information tracking improves resilience
Information sharing with partners improves resilience
Reserve capacity for machinery/parts improves SC resilience

Enablers at operative level
Distribution logistics flexibility improves resilience
Contract flexibility improves resilience
Production flexibility improves resilience
Sourcing flexibility improves resilience

Enablers at tactical Level
Proactive identification disruptions
Quick actions on disruptions
Collaborative operations with partners
Multi-skilled workforce improves resilience

Figure 21: Resilience enablers[113]

A survey on these enablers using Likert scale was conducted within Indian automotive sector to illustrate the measurement method. Exploratory factor analysis is used to identify the relationships and patterns between the enablers. The dimensions of these 16 enablers are modelled using a diagraph which also shows the influence of each enabler on the other enabler. This following Figure 22 from the research paper Agarwal et al. [114] shows the example of 3 sample enablers in circles and the arrows showing the relationship between them. 3 diagraphs are created for of the 3 levels mentioned in the Figure 21.

[112] Agarwal, Seth, and Agarwal, “Evaluation of Supply Chain Resilience Index.”
[113] Agarwal, Seth, and Agarwal, “Evaluation of Supply Chain Resilience Index.”
[114] Agarwal, Seth, and Agarwal.

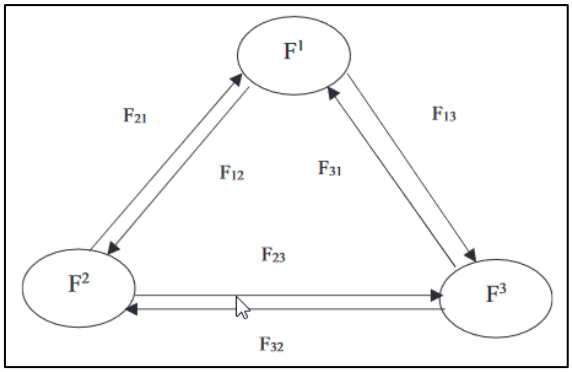

Figure 22: Sample Diagraph[115]

These 3 diagraphs are converted into an adjacency matrix which will be used to mathematically calculate the resilience index.

$$F = \begin{bmatrix} F_1 & f_{12} & f_{13} \\ f_{21} & F_2 & f_{23} \\ f_{31} & f_{32} & F_3 \end{bmatrix}$$

Figure 23: adjacency matrix[116]

In the matric function F above, diagonal elements represent the intensity of each enabler on the SCR, and the rest non diagonal elements represent the interrelationship between enablers. Such adjacency matrix is created for all 3 levels. The permanent function values of these 3 matrixes are the resilience indexes of 3 levels: Strategic, Operative and Tactical. Using these 3 resilience indexes in the diagonal position and the interdependence values of all 3 into the off-diagonal position, the resilience index for the entire SC is calculated.

To compare the result of the SC with the best possible result possible using this method, all the diagonal values in the matrix are changed to the best value possible, (here 5 as it is a likert scale) and for the worst result this one is changed to 1. The non diagonal values have equal relative importance, which is why it is kept as 5 in both cases. Below are the results from the case study carried out[117] which shows the results from the case of the Indian automotive sector under study, with it its best and worst possible result.

[115] Agarwal, Seth, and Agarwal, “Evaluation of Supply Chain Resilience Index.”
[116] Agarwal, Seth, and Agarwal, “Evaluation of Supply Chain Resilience Index.”
[117] Agarwal, Seth, and Agarwal.

Case	Strategic enablers	Tactical enablers	Operative enablers	RI
Indian automotive industry	2575906	13575	8692	3.97×10^{14}
Best case	3375000	15000	8750	4.43×10^{14}
Worst case	1148376	6776	3226	2.51×10^{13}

Figure 24: Result of resilience index on the case study automotive industry[118]

3.6.4 Resilience index for on-time delivery

Carvalho et al.[119] proposed an index modelled on 2 SC failure modes: Capacity shortage and Material shortage, using the "resilience triangle"[120] shown below where the green area is the impact magnitude of disturbance on SC performance which is the product of Severity and the recovery time.

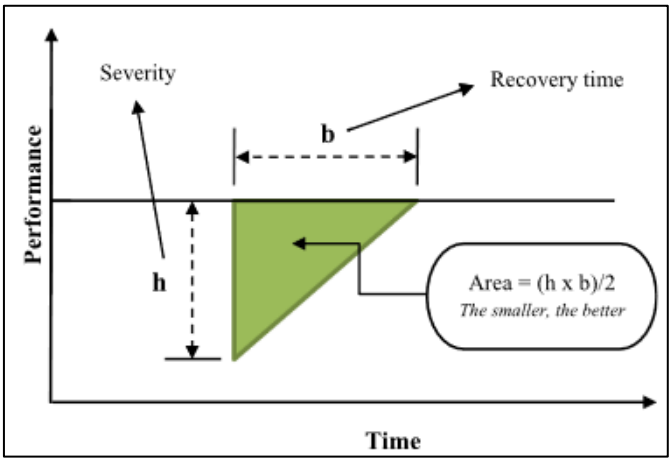

Figure 25: Resilience triangle[121]

The resilience index yields values ranging from 0 to 0,5. Since smaller values represent better outcomes for resilience (i.e., smaller resilience triangle area), 0 signifies "Highly resilient" and 0,5 signifies "Not resilient". The resilience index is 0 when recovery time and/or severity is/are 0. This implies that if severity is non-existent or recovery time is instantaneous, the disturbance will not impact the normal performance of the company. Using Likert scale of 0-5 each SC state variable is aggregated to output the values of severity and Recovery time. These variables are practices ex:

For reducing severity in material shortage: Using material buffers; Delivering a substitute product; Using alternate delivery paths etc.

[118] Agarwal, Seth, and Agarwal, "Evaluation of Supply Chain Resilience Index."
[119] Carvalho et al., "The Resilience of On-Time Delivery to Capacity and Material Shortages."
[120] Benjamin R. Tukamuhabwa et al., "Supply Chain Resilience: Definition, Review and Theoretical Foundations for Further Study," *International Journal of Production Research* 53, no. 18 (September 17, 2015): 5592–5623, https://doi.org/10.1080/00207543.2015.1037934.
[121] Carvalho et al., "The Resilience of On-Time Delivery to Capacity and Material Shortages."

For reducing recovery time on material shortage: Reducing lead time, changing delivery schedules; finding new suppliers etc.

For reducing severity on capacity shortage: Using alternative production paths using maximum capacity, creating SC visibility

For reducing recovery time on capacity shortage: Reducing response time, reallocate resources, increasing capacity etc.

Please note all due to space limitation only few practices are mentioned above, all of the practices and metrics are shared in the appendix.

$$\text{Resilience Index} = \frac{Severity \times Recovery\ time}{2}$$

$$\text{Resilience Index} = \left(1 - \frac{\sum_{s=1}^{N_{ZS}} X_{ZS}}{5N_{ZS}}\right) \times \left(1 - \frac{\sum_{r=1}^{N_{Zr}} Y_1}{5N_{Zr}}\right) \times \frac{1}{2}$$

where:

Z denotes the failure mode ("material shortage" or "capacity shortage"); X_{zs} denotes the SC state variable s, which contributes to minimizing the severity of failure mode Z; N_{zs} denotes the number of SC state variables, which contribute to minimizing the severity of failure mode Z; Y_{zr} denotes the SC state variable r, which contributes to minimizing the recovery time for failure mode Z; N_{zr} denotes the number of SC state variables, which contribute to minimizing the recovery time for failure mode Z.

3.7 Technological impact on supply chain resilience

This section is dedicated to exploring what technologies are used or foreseen to make an impact in supply chain towards resilience and risk management. The most frequently mentioned technologies in the literature are discussed briefly in this section.

3.7.1 Digitalization

Zhao et. al.[122] found that scholars generally agree that more empirical studies will need to be conducted on how digitalization can facilitate supply chain resilience at various stages and enhance supply chain performance in a highly uncertain environment. They developed a mechanism based on dynamic capability theory, which they validated using a survey of 210 Chinese manufacturing companies. Their study identified the paths digitalization and supply chain resilience can take to improve supply chain performance in a turbulent

[122] Zhao, Hong, and Lau, "Impact of Supply Chain Digitalization on Supply Chain Resilience and Performance."

environment. They argue that realization of SCR requires companies to adjust their infrastructure, break down the information barriers between departments and partners, and achieve risk prediction and planning, agile response, and rapid recovery through process optimization and resource reorganization.

3.7.2 Blockchain

Recognized as the creator of Bitcoin, the publicly unknown person Satoshi Nakamoto is also credited with the ideation of the technology Blockchain which is the backbone of Bitcoin[123]. Tapscott and Tapscott[124] explain Blockchain as a distributed ledger technology which enables secure and transparent record-keeping of transactions across multiple participants in a network. Blockchain uses cryptographic techniques which ensures the integrity and immutableness of data, and with that its decentralized nature eliminates the need for a central authority. Thus, it can mitigate risks associated with intermediaries' interventions, including hacking, compromised privacy, vulnerability to political turmoil, costly compliance with government rules and regulation, instability of financial institutions, and contractual disputes[125].

In the context of supply chain, Vadgama and tasca [126] analyzed the blockchain adoption in the supply chain using 271 blockchain projects. They found within supply chain the greatest focus for blockchain adoption is in the product tracking/tracing area. Second is the application area of logistics, involving more complexity and IoT and sensors to track information related to the goods' physical movement. This is followed by the area of financial transactions.

Based on above findings, the integration of blockchain technology in SCM promises enhancing resilience. By leveraging the transparency, decentralization blockchain has to offer, it can be said help build a secure, efficient, and adaptable SC ecosystem that survives disruptions and ensures continuity of operations.

3.7.3 Industry 4.0

Industry 4.0, also known as the fourth industrial revolution, which is about transformation of traditional industries through the integration of automation, digital technologies,

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[123] Satoshi Nakamoto, "Bitcoin: A Peer-to-Peer Electronic Cash System," n.d., https://bitcoin.org/bitcoin.pdf.
[124] Don Tapscott and Alex Tapscott, *Blockchain Revolution: How the Technology behind Bitcoin Is Changing Money, Business, and the World* (New York: Portfolio / Penguin, 2016).
[125] Hokey Min, "Blockchain Technology for Enhancing Supply Chain Resilience," *Business Horizons* 62, no. 1 (January 2019): 35–45, https://doi.org/10.1016/j.bushor.2018.08.012.
[126] Nikhil Vadgama and Paolo Tasca, "An Analysis of Blockchain Adoption in Supply Chains Between 2010 and 2020," *Frontiers in Blockchain* 4 (March 23, 2021): 610476, https://doi.org/10.3389/fbloc.2021.610476.

and data-driven processes. Industry 4.0 consists of technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, big data analytics, cloud computing and advanced manufacturing techniques[127].

Speiske et al[128] in 2021 carried out a literature review on 62 research papers to analyze the link between industry 4.0 and SCR. The framework applied in the Figure 26: At the top, SCRES is the short form used for supply chain resilience[129]; in the below that are the 4 phases of SCRES, where readiness phase is before the disruption, which is followed by response, recovery, and growth based on the study of Hohenstein el al.[130]. From the literature review, the authors summarized 7 antecedents from SCRM culture to collaboration which are based on the study by Christoph and Peck [131]. At the bottom of the pyramid are the industry 4.0 enablers which are connected to all the antecedents showing which have the positive impact on them. Using this framework, the researcher concluded that all listed enablers have potential to support SCR, big data analytics is the most mature one, and is particularly suitable for improving SCR, while other technologies, lack proof of effectiveness. Along with that the top antecedents on which these technologies will have the highest impact are visibility and velocity. Here visibility concerns the ability to access information on the identities, locations, and statuses of entities transmitting between lower-tier suppliers and customers in the Supply chain[132] whereas the velocity is about the organizations ability to quickly react to new environmental conditions, especially when facing disruptions in manufacturing, transportation, sourcing, or labor[133].

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[127] Mohd Aiman Kamarul Bahrin et al., "INDUSTRY 4.0: A REVIEW ON INDUSTRIAL AUTOMATION AND ROBOTIC," *Jurnal Teknologi* 78, no. 6–13 (June 28, 2016), https://doi.org/10.11113/jt.v78.9285.
[128] Alexander Spieske and Hendrik Birkel, "Improving Supply Chain Resilience through Industry 4.0: A Systematic Literature Review under the Impressions of the COVID-19 Pandemic," *Computers & Industrial Engineering* 158 (August 2021): 107452, https://doi.org/10.1016/j.cie.2021.107452.
[129] Christopher and Peck, "Building the Resilient Supply Chain."
[130] Nils-Ole Hohenstein et al., "Research on the Phenomenon of Supply Chain Resilience: A Systematic Review and Paths for Further Investigation," ed. Professor Maria Jesus Saenz and Dr Xenophon Koufteros, *International Journal of Physical Distribution & Logistics Management* 45, no. 1/2 (March 2, 2015): 90–117, https://doi.org/10.1108/IJPDLM-05-2013-0128.
[131] Christopher and Peck, "Building the Resilient Supply Chain."
[132] Rahul C. Basole and Marcus A. Bellamy, "Supply Network Structure, Visibility, and Risk Diffusion: A Computational Approach: Supply Network Structure, Visibility, and Risk Diffusion," *Decision Sciences* 45, no. 4 (August 2014): 753–89, https://doi.org/10.1111/deci.12099.
[133] Christopher and Peck, "Building the Resilient Supply Chain."

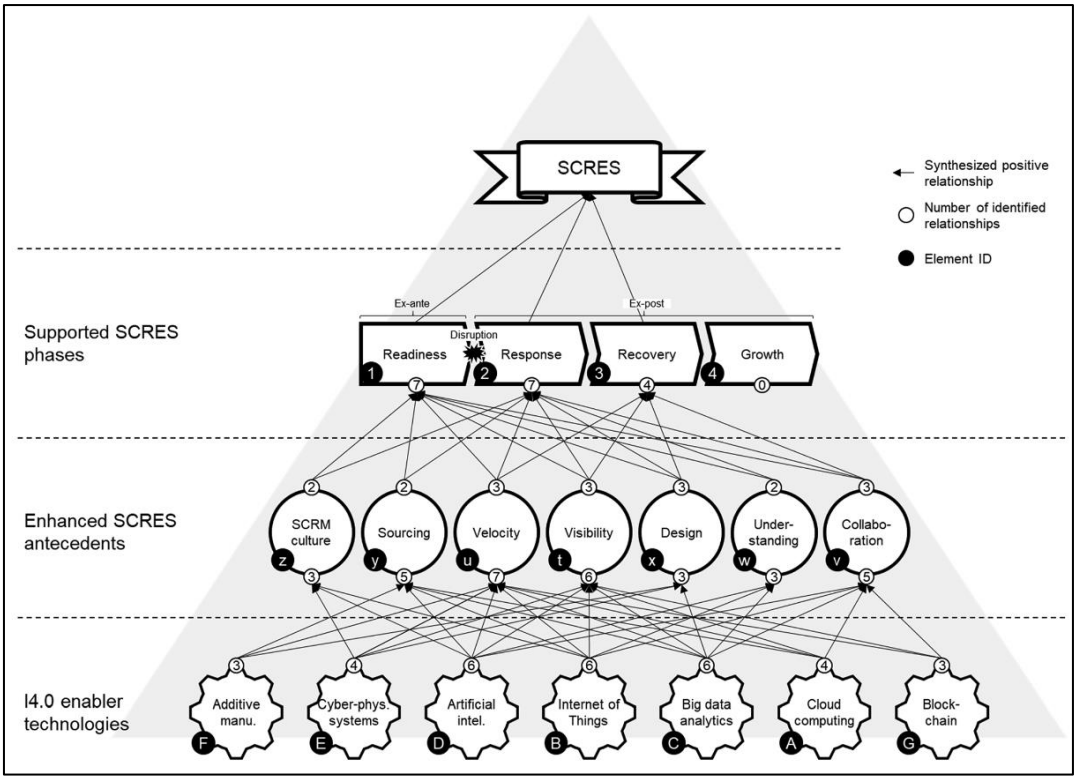

Figure 26: SCRES framework[134]

3.7.4 Big data analytics

Big data analytics is defined by Gunasekaran et al. [135] as a holistic process involving collection, analysis, use, and interpretation of data from various sources for various functional divisions with a view to gaining actionable insights, creating business value, and establishing competitive advantage. Wamba et al. [136] concludes traditional data management tools fail for managing such a huge amount of data which is why it needs advanced analytical techniques to provide valuable inputs. Bahrami et al.[137] carried out a study on the effects of Big data analytics on SCR using survey based approach on 187 respondents and concluded that Big data analytics has biggest positive effect on SCR compared to other technologies.

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[134] Alexander Spieske and Hendrik Birkel, "Improving Supply Chain Resilience through Industry 4.0: A Systematic Literature Review under the Impressions of the COVID-19 Pandemic," *Computers & Industrial Engineering* 158 (August 2021): 107452, https://doi.org/10.1016/j.cie.2021.107452.
[135] Angappa Gunasekaran et al., "Big Data and Predictive Analytics for Supply Chain and Organizational Performance," *Journal of Business Research* 70 (January 2017): 308–17, https://doi.org/10.1016/j.jbusres.2016.08.004.
[136] Samuel Fosso Wamba et al., "How 'Big Data' Can Make Big Impact: Findings from a Systematic Review and a Longitudinal Case Study," *International Journal of Production Economics* 165 (July 2015): 234–46, https://doi.org/10.1016/j.ijpe.2014.12.031.
[137] Mohammad Bahrami, Sajjad Shokouhyar, and Atiyeh Seifian, "Big Data Analytics Capability and Supply Chain Performance: The Mediating Roles of Supply Chain Resilience and Innovation," *Modern Supply Chain Research and Applications* 4, no. 1 (March 30, 2022): 62–84, https://doi.org/10.1108/MSCRA-11-2021-0021.

3.7.5 Artificial Intelligence

The use of artificial intelligence (AI) in purchasing and supply management (PSM) has great potential, but its use cases in PSM is still limited, and mostly in large companies[138]. on the learnings from COVID19, a study by Modgil et. al.[139] examined how firms employ AI and considers the opportunities for AI to enhance supply chain resilience. The results of the study highlights the emergence of five critical areas where AI can contribute to enhanced supply chain resilience: (i) transparency, (ii) ensuring last-mile delivery, (iii) offering personalized solutions to both upstream and downstream supply chain stakeholders, (iv) minimizing the impact of disruption, and (v) facilitating an agile procurement strategy. These are summarized with the details in the Figure 27:

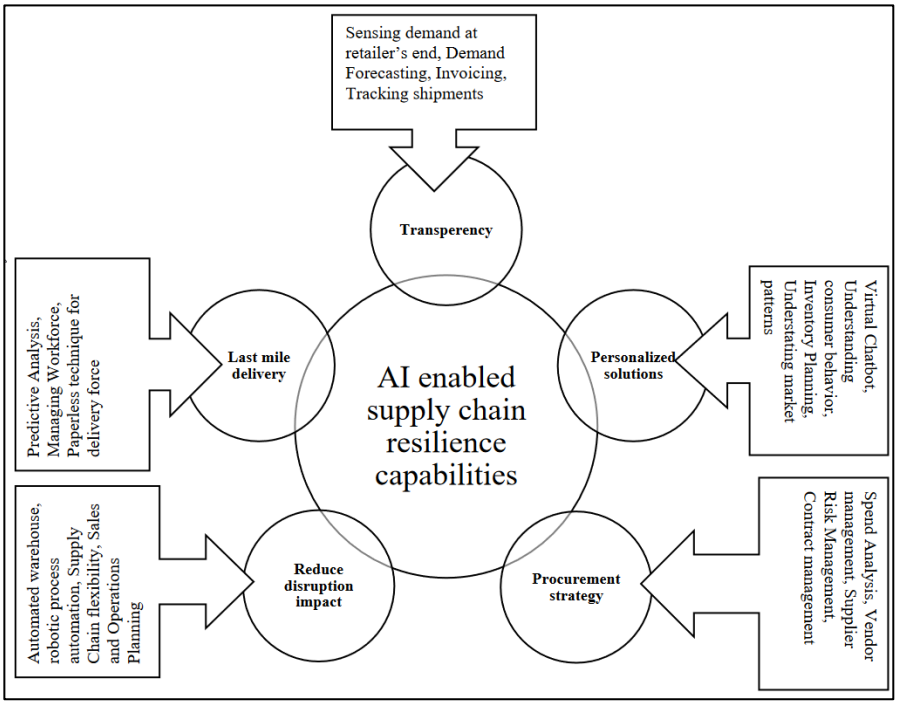

Figure 27: AI-enabled SCR capabilities[140]

[138] Dennis Meyer and Michael Henke, "Developing Design Principles for the Implementation of AI in PSM: An Investigation with Expert Interviews," *Journal of Purchasing and Supply Management* 29, no. 3 (June 2023): 100846, https://doi.org/10.1016/j.pursup.2023.100846.
[139] Sachin Modgil, Rohit Kumar Singh, and Claire Hannibal, "Artificial Intelligence for Supply Chain Resilience: Learning from Covid-19," *The International Journal of Logistics Management* 33, no. 4 (October 17, 2022): 1246–68, https://doi.org/10.1108/IJLM-02-2021-0094.
[140] Sachin Modgil, Rohit Kumar Singh, and Claire Hannibal, "Artificial Intelligence for Supply Chain Resilience: Learning from Covid-19," *The International Journal of Logistics Management* 33, no. 4 (October 17, 2022): 1246–68, https://doi.org/10.1108/IJLM-02-2021-0094.

4 Results and findings

After conducting the literature review, interviews, and its in depth analysis, it is this section where the results and findings of the research will be discussed. Before proceeding with the results, we should remind ourselves with the focused research questions.

The research question with sub questions:

RQ: Which available method of measuring resilience of a supply chain fits best for manufacturing industry in Vorarlberg?

RQ1.1: What are the wants and needs in terms of resilience level in manufacturing companies in Vorarlberg?

RQ1.2. How manufacturing companies in Vorarlberg are building resilience within their supply chain?

RQ1.3: Is there a method existing to measure the resilience which fits the best for the industry?

This following section is categorized in 3 sections wrt. 3 sub question mentioned above, which would further be divided as per the themes that are formed in the analysis phase. Structuring the section this way will help answer the questions systematically. Even though all the companies that are interviewed are from manufacturing sector, still it is important to note the diversity within them in terms of supply chain structure and strategy. This is important to understand before proceeding further, as the supply chain structures which is the way procurement, production processes are linked make a huge difference on how critical SCR is for the company. Next would be assessing the understanding of the way SCR is perceived by each interviewee. After getting these understandings the further in-depth findings will be explored.

- **Supply chain structure/design**

Out of 6 companies, first 5 companies have procurement/supply function and inhouse production facilities in Vorarlberg, while the company number 6 has completely outsourced both procurement and production of their products. "*The complete production process is outside that we have the electronic manufacturing service provider. That means they are doing the purchasing, the manufacturing, the assembling, testing, and packaging. That means our product will come to our office very finalized like in the package, our end customer will receive it."* (C6.1, Pos. 2). All of the 6 companies interviewed confirmed to have suppliers on multiple tiers, in and outside of Europe. The electronic parts in the bill of material, which through the tiers of suppliers is sourced from East Asian countries, mainly China.

- **Understanding of resilience**

Discussing over the definition of SCR within the companies, usage of the term in he past and their own understanding, we see that there are many ways SCR is perceived in different companies, and in some companies not.

Document name	**Theme**	**Code**	**Segment**
C1.1	SCR definition	SCR is Flexibility	*In the end, It's all about flexibility. Being in the position to change supply chains from A to B within a shorter period than we did in the past. That's in the end, what we are looking for.*
C1.2		SCR not defined	*it is not clearly defined yet.*
C2.1		SCR not defined	*I guess we don't have a clear, definition what resilience itself mean. to me, resilience is a kind of, let's say fashion word which became very fashion and trendy in the last two, three, four years.*
C3.2		SCR not defined	*There is not such a known way how we, how we define resilience. Resilience in this being able to produce at any time and almost identical.*
C4.1		SCR is Risk management	*it's a matter of risk assessment and management and you to define critical paths, critical materials. And then let me say define the level of risk you want to take or evaluate risk versus price advantages.*
C5.1		Customer satisfaction	*So resilience, we see it, as we are able to fulfill our customer orders on time in full*
C6.1		Customer satisfaction	*the resilience supply chain exists when you can supply your customer with their order products, even in times of supply chain disruption*

Table 3: Theme: SCR definition

C1.1 shared his/her understanding of SCR as "*It's all about flexibility.*" while the C1.2 from the same company said "*it is not clearly defined yet."* (C1.2, Pos. 5) This difference of SCR understanding within the same company can be attributed to this fact shared by the C1.2 *" I think also that you need to define resilience In the different layers in our organization on its own. So if we talk on corporate level, I think the definition of how do we measure resilience or what is resilience is something different than if you ask head of Manufacturing with regards to technology resilience*" (C1.2, Pos. 5)

Experts from Company 2 and 3 just like company 1, confirmed that they do not have a clear definition of the SCR within their organizations. Expert from company 3 stated SCR is

“the ability to produce at any time”, whereas company 4 expert stated it is the matter of risk assessment and level of risk vs price advantage”. Experts from company 5 and 6 shared a similar customer centric understanding of SCR, where SCR is the ability to fulfill the customer demand.

4.1 Findings on RQ 1.1

RQ1.1: What are the wants and needs in terms of resilience level in manufacturing companies in Vorarlberg?

One of the first and critical need shared was needed to reduce the regional dependency. The theme of regional dependency was mentioned by experts from all 6 companies. C1.1 mentioned multiple times that the current focus of SCR at the organization is to reduce the dependency on procurement from east Asian countries, which originates from the current China-US trade war and fastly changing geopolitics in the east Asia. C1.2 mentioned the monopoly situation which they found when discussing the regional dependence for procuring special materials like Cobalt or lithium, where many African countries have sources.

C2.1 confirmed the dependence of the company on procuring from far east asia, as the electronics being the major part of procured materials, where C6.1 echoed the same dependency. C5.1 mentioned the critical time faced in 2022 with the start of Russia-Ukraine war where the natural gas supply became critical. C4.1 shared a different viewpoint, where it was mentioned with the current changes in the world, any region can become critical with time, so it is not only China or Ukraine/Russia that has to be considered critical.

Document name	**Theme**	**Code**	**Segment**
C1.1	Regional dependence	Regional dependance	*all eggs in one basket in certain regions in this world, that's maybe not the recommended way*
C1.2		Sourcing monopoly countries	*we have all these Cobalt lithium discussions. But here there are only a few countries, which have more less than monopoly situation*
C2.1		Electronics dependent on east-Asia	*We have the electronics division in our plant. There we are dependent on far east Asia, in China especially. Basically, the reason is pretty easy. There is no other let's say graphically region where we can source these parts.*
C5.1		Gas supply dependent on Russia	*we had a big test last year, when war in Ukraine started, because the main source of the main raw material is not for our chemicals is not crude oil, but it's natural gas. it came mainly from Russia*

C6.1		Electronics dependent on east-Asia	*For some parts you are dependent on Asia. At the moment no chance to go away from that.*
C4.1		Any region risky	*You can't judge that and it's not China that is the most critical, the most riskiest market at the moment. It can be any so Ukraine told us that even Europe is not safe.*
C3.2		Electronics dependent on east-Asia	*We've for sure all together try to reduce our dependency on Chinese product but there it's not a high volume for us so there isn't so much we can do and yeah, we try to divide and diversify.*

Table 4: Theme: Regional dependence

Second theme regarding the SCR was discovered to be the need or benefits of multi-sourcing. C1.1 mentioned that having dual sourcing makes life of the supply team easier whereas the logistics team lead from the same organization C1.3 shared that the dual sourcing is not feasible due to low volume of purchased goods and limitations of the ERP system to handle multiple suppliers for same material. C2.1 admitted that due to the supply issues with COVID pandemic accelerated the multi-sourcing approach. In line with the C1.3, C3.1 shared the need for multi sourcing, but the challenge of low purchasing volume makes it difficult. The remaining 3 company executives C4.1, C5.1, C6.1 shared in the same voice that multi sourcing is something that has been used for long time and it has benefited in SCR.

Document name	**Theme**	**Code**	**Segment**
C1.1	Multi-sourcing	Dual sourcing	*big lever was always dual sourcing. And having a second option in place, obviously makes your life simply more easy.*
C1.3		Dual sourcing impossible	*we do not go for dual sourcing because quantities we source are too low and it's not really worth doing it because the most things we source are too special and too, low quantities and besides the system is also not able to really handle it because you need different material numbers*
C2.1		Multiple sourcing after pandemic	*I would say consequence of the pandemic, these allocations, vastly changing demand and all these things changed the overall attitude and probably accelerated the multiple sourcing approach*

C3.1		Dual sourcing impossible	*It's a big wish but it's not fulfillable that you have two or three suppliers for all critical parts. This is impossible. honestly, for the, for the real big volumes, you just have one.*
C4.1		Multiple sourcing	*So our all biggest action towards SCR is basically a dual source strategy Or even multiple source strategy wherever possible and wherever it makes economically sense. wherever possible we do multiple sourcing*
C5.1		Multiple sourcing	*what we try to achieve in the last couple of years is to have not only dual but triple sourcing. We have quite special products, and we have quite narrow tolerances. So that is not easy.*
C6.1		Multiple sourcing	*We have sometimes for the same product, two or three suppliers. This point is here not to have one supplier maybe have a second third, supplier for the same products for all high volumes.*

Table 5: Theme: Multisourcing

4.2 Findings on RQ 1.2

RQ1.2. How manufacturing companies in Vorarlberg are building resilience within their supply chain?

During the interviews, many actions were mentioned which are taken towards building a resilient SC, within which supplier relationship management theme was the most prominent one. 5 out of 6 companies mentioned this multiple times. C1.1 mentions that if your suppliers do not follow the actions which you are taking towards building a resilience, then it is a failure of the entire supply chain, as the same actions must be followed by suppliers. Both C1.2, C3.1 mention that treating the suppliers with respect goes a long way and is one of the key step you can take towards resilience. It will be paid out in the difficult times, with evidence of challenges faced during covid pandemic.

Maintaining long term relationship is something that is found to be highly mentioned strategy when it comes to maintaining a relationship with business partners like suppliers. Rather than having a short term transactional suppliers for partial cost savings, most of the companies choose to maintain a long term relationship with most of the suppliers they do business with. This supplier relationship management method was mentioned multiple times to be supportive for being resilient, with the reasoning given that suppliers in difficult allocation situations like Covid19, would support companies that treated them fairly and maintained a good relationship.

As per C6.1, choosing the right partners which match your organization's values is important, before you invest with your supplier using long term relationship. It is important to know beforehand if the suppliers has the similar "DNA" which makes it easier to not invest in a relationship which might turn out to be a misfit in long run.

Document name	**Theme**	**Code**	**Segment**
C1.1	supplier relationship management	Supplier should follow same practises	*It's the way how you cooperate with your supplies, whatever you are doing is all nice but If your suppliers are not doing the same or the same extend as you're doing it, then in the end you are lost.*
C1.2		Treat suppliers with respect	*Its about treating partners with respect, Don't, what is say milk them. it always pays back in the good or bad times later.*
C2.1		Long term relationship	*It's rather long-term relationship. And I would say all of these helped during the pandemic, because it's rather probably easier to serve a long-term partner than a supplier that just entered in your scope a year*
C2.1		supplier communication	*If I would need to make a list here of the most important things, I would again, rate the supplier relationship management and the constant monitoring of the situation, I would still classify this, the highest.*
C3.1		Treat suppliers with respect	*I would say it's the most important one. Because the way you treat your customers, or the way you treat your suppliers, is the way you get treated. Reliable partnerships, long-term partnerships. This is resilience.*
C3.2		Long term relationship	*We rely on long-term partnerships and to make sure we do not have the wrong partners.*

C5.1		Long term relationship	*We maintain Very long term relationships with our suppliers.*
C6.1		Long term relationship	*We are looking after suppliers which for special points, who's DNA will fit to us. We have very strong relationships to them, we know them, maybe sincesometimes 20 years. So it's a long lasting partnership.*

Table 6: Theme: supplier relationship management

Transparency is seen as a crucial element in SCR, but transparency is mentioned in 2 different ways in the interviews. The first one is the transparency in terms of visibility a company has over its supply chain, over its suppliers, what is procured from where and how. This transparency and its visualization has seen as important for C2.1. On the contrary, to this C1.2 mentions that transparency is half useful if you do not have control over your suppliers. This means even though you have transparency and foresee issues in the supplies, unless you have control and act on these indications, the transparency is only useful.

The second type of transparency is the part of supplier relationship management where the organizations provide transparency to their supplies, about the demand forecast, information on another source etc. which is mentioned by most of the companies. For C3.1, C 5.1 and C6.1 it is honest and open communication with suppliers that is one of the keys to build resilience. More transparently you inform your supplier and customers, it helps in building resilience. Technology like EDI (Electronic Data Interchange is a system that is used for intercompany communication of business documents) was mentioned which has been used by C3.1 and 5.1 for maintaining the transparency over the demand forecast to mitigate probable bull whip effects.

Document name	**Theme**	**Code**	**Segment**
C2.1	Transparency	Transparency and visualization	*For me, the most important thing is to always have the absolute transparency on the parts we buy. Visualize that in a kind of heat map of my personal risk.*
C3.1		Honesty	*You can build up resilience in being through honesty, system wise when you integrate your customers or your supplier in your supply chain or system wise*
C3.1		EDI	*It's EDI data interchange, connect the ERP system from the customer with yours and with the one from the supplier. This gives the most transparency and this will lead to a higher resilient supply chain.*

C5.1		Honest communication	*We quite frankly communicating to our suppliers when we open up another source. So, we do not cheat on them. We say we have now 3rd source, your sales will be smaller, but please continue your service because it helps us all.*
C5.1		EDI	*EDI is state of the art important is to sharing of information. That's one that prevents wrong decisions. So if you have an issue, share your information. Well, you can mitigate or even eliminate bullwhip effect, for example, which helps everyone along the supply chain.*
C6.1		Open communication	*Very important for all these things what we are doing is the culture of the open communication, to have transparent communication to have honest communication. Not only inside, this inside is important but also outside to our suppliers.*
C1.2		Control required	*As long as you don't have control, transparency is only half relevant.*

Table 7: Theme: Transparency

Local for local, meaning sourcing locally as much possible is seen as a one of the key points mentioned for building resiliency. 6 out of 9 experts shared the same opinion that local for local will play a bigger role in future, and shared the view similar to “price is not everything” that a business should look for but risk from procuring foreign overseas countries should be taken into consideration.

Document name	**Theme**	**Code**	**Segment**
C1.1	Local for Local	Local sourcing	*This local for local which anyways, not a bad concept at all, to a certain extent. I think this will play a bigger role*
C3.1		Price is less important	*What we experience this which is not in our company so much but going more, local so price is not everything.*
C3.2		Local sourcing	*make sure you have a good local, local basis of suppliers instead of relying on suppliers that are at the other end of the world*
C4.1		Local sourcing	*it's better to have local for local suppliers instead of just one global supplier with the risk*
C4.1		Local sourcing	*We try to do local for local*
C5.1		Price is less important	*If I have two suppliers, which have, which are technically exactly the same. I have one here nearby, which is easier or is more reliable around the*

			corner. Or I have one which is cheaper, but far away or I expect a higher risk of availability, then we will take the higher cost and not the higher risk

Table 8: Theme: Local for local

Organization structure and culture is something that is seen as critical when it comes to taking critical decisions fast. It also applies to taking decisions on actions towards risks that are seen or faced, and immediate response is needed from an organization. This theme was also seen emerging in the interviews. C1.3 while discussing about the speed of decision-making saw that the matrix organization structure with multiple stakeholders from global logistics, sourcing and materials management makes the decision-making process complex and time consuming. C2.1 mentions and finds it useful that size of the organization is crucial, as it is important that one gets to meet the decision makers regularly and have interconnections. This makes the decision-making process efficient and helps towards SCR. Similar view was shared by C5.1 and C6.1 who said having less steps in hierarchy and easy access to the decision-making persons helps them take the decision quick due to quick communication.

Document name	**Theme**	**Code**	**Segment**
C1.3	Corporate structure and size	Complex structure	*I would say that's a bit of a complex setup of our organization with kind of a matrix structure. That makes a little bit slower.*
C2.1		Size of company	*It tends to become more critical when the size is in a way that you know the people don't have the opportunity to meet the decision makers in the various functions and locations to have that personal interconnection. I guess the way we have it was not wrong to establish the culture of resilience*
C4.1		Different interests within departments	*I would say not all departments have the same interest. Logistic has the target normally I mean to reduce inventory as much as possible for cash flow risks. So to tell them that they have to increase inventory because of resilience and because of critical components is sometimes difficult. The same for development doesn't have any interest to release more than one supplier because for them is just more work, is you have to qualify the same product several times.*
C5.1		Internal controlling	*My boss is just the next floor, and has quite a good understanding, what's Okay And what is really excessive? we also have a good controlling that checks these things. We have a good internal controlling that also we see if something is too big or and then we correct things*
C6.1		Size of company	*It's only three levels we have, for lot of years we are not changing it and it's very important to have this very quick communication inside and very important*

Table 9: Theme: Corporate structure and size

4.3 Findings on RQ 1.3

RQ 1.3: Is there a method existing to measure the resilience which fits the best for the industry?

Before finding out which method fits the manufacturing industry of Vorarlberg, it is important to know what the ways companies in Vorarlberg are measuring the resilience. It was found that none of the companies have a specific resilience measurement method. C2.1 and C5.1 mentioned that there are numerous measurements and KPI's for performance of suppliers and the overall customer satisfaction, which can be used to understand the SCR. C6.1 did not see the need of SCR measurement as it is seen that if the quality and pricing from suppliers are in acceptable level then there is no need for SCR measurement.

Document name	**Theme**	**Code**	**Segment**
C1.1	No measure for SCR	No SCR measure	*At the moment, we don't really have a measure for resilience*
C2.1		No resilience KPI	*So, in the end, you know, there is no as mentioned before I guess there are so many different things we buy or that we don't have one KPI saying, that's the KPI for resilience*
C3.2		SCR not measured	*We are not as such measuring it*
C4.1		No resilience KPI	*We don't have any KPI for resilience*
C5.1		No resilience KPI	*We have several KPI's but the leading KPI is a customer side. So, how are we able to deliver to our customers. This is the basic figure, where it all comes together, you know, it's also not only the performance of our suppliers but also our own performance*
C6.1		SCR not measured	*We have not really doing a measurement or KPI's on it until now, Because if the qualities okay, if pricing is okay, all these main parts It will fit.*

Table 10: Theme: No measure for SCR

Based on the above results of lack of SCR measurement method, it was needed to find out if there is a need for SCR measurement. Here we have a mix picture of answer for the need; where C1.1 accepted that the need for specific metric for SCR is clear whereas C3.2 see no need of SCR measurement with the reasoning of major portion of procurement being done locally in Europe. C2.1 explained that there exist many measures in risk management of

supply chains which are used in combination for each material group differently, and it is not wise to use one common resilience measure for all material groups. One single SCR measure cannot be used for a local supplier and an overseas supplier.

Document name	Theme	Code	Segment
C1.1	Need for SCR measure	Need exists	*I mean the need for the metric, that's clear. Everybody would like to have good KPI which you can use at the moment which we don't have it.*
C2.1		Separate SCR measures	*If I talk about the packaging material which I buy from the supplier who I can see from here and see his production hall and on the other hand side I have probably electronics part which in the end produced in China, but the chip and silicon is flown 4 times around the world before it gets China. So it requires different types of resilience measurements,*
C3.2		Need do not exist	*Because we do most of our sourcing in the in Europe. So, we were not so much affected through the pandemic*
C4.1		Need do not exist	*we don't have any KPI for resilience. What we measure is logistic KPIs in terms of let me say a time to deliver and backlog*

Table 11: Theme: Need for SCR measure

Experts from 4 out of 6 companies admitted that the current SC risk management process in their organization is sufficient for covering most of the supply risks. C1.1 shared that the use of BI risk tool where suppliers mean time to recover from adverse event is maintained, and this tool covers majority of the business needs. As per C2.1, commodity management is used to drill down to material level and analyzing all the possible risk possibilities and the mitigation measures. C3.1 finds supplier audits and follow up on it with the supplier important in risk management process. C4.1 also finds SCR same as risk management, where having plan B / second source for backup is the most important.

Document name	Theme	Code	Segment
C1.1	Risk management process	Business interruption risk	*We called it the BI risk, business interruption risk and there we have a tool in place which we are using and there we are measuring, the mean time to recover for the supplier. this*

			tool in place which I would say, covers majority of our business needs
C2.1		Commodity management	*I would say for us it is just a dedicated commodity dedicated way of analysing the different things and current and material groups, we purchase and in the end, almost going down on the single material, level defining, what can happen with it, what would it costs and what other opportunities to make sure we have it available when we need it or something happens in the supply chain.*
C3.2		Supplier audits	*As I said we do some audits, results from these audits we discuss it with them. We put some measures in place and we'll do some follow up to see if this was, it was achieved. So I would say, this is the main way we promote risk management with suppliers.*
C4.1		Backup sources	*resilience is normally called just risk assessment and risk avoidance. So do you have a backup plan, Do we have a second source qualified? So, in case anything happens that you have a plan B in your pocket.*

Table 12: Theme: Risk management process

Logistic KPI's were often mentioned when discussing about the measure for resilience, 4 out of 9 experts mentioned the usage of them for resilience. C2.1 mentioned the usage of OTD – On time delivery, supplier flexibility and such KPI's which help in getting a status of supply chain performance. C3.1 also mentioned the usage of OTD which is important to give a accurate indication of delivery to the customer. Both C4.1 and C6.1 shared the similarities in the importance of measuring the quality of the material delivered. This is measured by measuring number of good parts delivered in proportion to the total parts delivered, number of returns and complaints.

Document name	**Themes**	**Code**	**Segment**
C2.1	Performance measures	Logistic KPI's	*We measure like OTD, supply of flexibility, how many sources, how many stocks we keep in the different commodities in different plants and I guess all these together sums up and gives a picture.*

C3.1		On time delivery	*We are trying to measure the on-time delivery rates in every step. So how accurate are the confirmations we give to customers, how accurate are the confirmations we get from our suppliers. So it's basically on time delivery rates.*
C4.1		Logistic KPI's	*What we measure is logistic KPIs time to deliver and backlog and how much these disruptions we have and this is basically the key for the delivery performance. It's also about the parts that are delivered in right quality.*
C6.1		Logistic KPI's	*it's delivery reliability, the number of returns, number of complaints. I think these general things are important for us and gives us a good feeling how stable our supply chains are.*

Table 13: Theme: Logistic KPI's

4.4 Lessons learned

Diversity is seen in the lessons learned from working in supply chain function while facing one of the biggest disruptions like COVID19 pandemic. C1.1 emphasized on working closely with suppliers as they manage most of the cost for the business and have the expertise in producing the products for which the company 1 does not have. The second expert from company 1 i.e., C1.2 shared that the biggest learning has been the way task force management attitude has been developed in the company 1. In the interview numerous examples were provided of disruptions which company 1 faced and how they were able to change to task force mode and solve the problems. As per C1.2 this development in task force mode is an evidence that company is prepared to face any future disruptions. Third expert from company being the logistics lead, shared the learning of not following the crowd in raising and decreasing the crowd causing the bullwhip, but instead always maintain a reasonable safety stock.

For C2.1, the biggest learning has been how pandemic had a positive impact on changing the attitude of cross functional teams towards maintaining the second or third source for the same material. As per C2.1, pandemic, and the supply issues along with that provided the backwind which supports the category managers to get resources for qualifying second or third source. C3.1 shared the learning of importance of impact of frequent communication with your business partners, especially in the disruption phase. As per C3.1 "*It's better to reinform somebody about a not changing situation instead of saying nothing"* which keep suppliers informed about the latest update. 2nd expert from Company 3, C3,2 reemphasizes on the need for local sources and reducing the dependence on the suppliers at long distance. For 5.1 the reemergence of the need of warehouses has been a learning, as

maintain buffers nearby has been one of the first activity done by organizations dealing with disruptions. C5.1 reemphasized the honest communication with an example of not faking the communicated demand to suppliers which seems to be done in practice by some to ensure the safety stock.

Document name	Theme	Code	Segment
C1.1	lessons learned	Work closely with suppliers	*80-85% of the cost are generated by suppliers and only few of these parts we're doing for ourselves. So therefore, you should work closer together with your key suppliers, at least for the parts, which are difficult to do inhouse.*
C1.2		task force mode	*In our organization, we have a super good task force management attitude. This is something we learned in the past couple of years.*
C1.3		Maintain the stock without getting influenced by bull whip	*Main lesson is to be prepared as good as possible, Keep the stocks, your orders at a reasonable level and not to drop into this hole, we are at a moment on the other side of the bull whip where every single thing is going down.*
C2.1		Support for multisource	*Consequence of the pandemic accelerated the multiple sourcing approach. Even in the families of the application where people in the past said no we don't want to do it, we can't afford to do it*
C3.1		regular updates	*Clear and fast communication. Even if you Don't know what to come.*
C3.2		localisation	*Make sure you have a good local, local basis of suppliers instead of relying on suppliers that are at the other end of the world*
C5.1		importance of warehouses	*I would say warehouses has become more important. Stocking on the shelf, has become more important than before.*
C5.1		Honest communication	*Communicate really the right numbers, you do not add, do not say hundred, do not say 120 to get the hundred*

Table 14: Theme: Lessons learned

5 Discussion

Before discussing the findings on the 3 research sub questions, it is important to discuss the term SCR itself. In the literature review it is evident that SCR is a term that has received a lot of attention from researchers and practitioners. Numerous scholars have proposed different definitions and it is seen that still there is no consensus on the definition of SCR. This results in fragmented understanding of the concept of SCR which hampers the efforts to develop a standardized measurement method. The field of SCR is still evolving and is expected to receive increasing level of attention with the increasing number of supply disruption, changing global trade, changing environmental impacts and policies around it. As mentioned in the literature review, the numerous definitions of SCR exists and the development of the definition can be clearly noticed. The first definition of SCR emerged as an ability to react to an adverse event and then returning to normal state. After some more research, the ability to reduce the probability of the adverse event was included as a part of SCR.

During the interviews, all the 9 experts admitted that there is no clear definition of SCR in their organizations, and it can be concluded that the understanding of the term SCR is significantly different between the organizations. For some of the organizations, SCR is the same as the risk management in supply chain, and for some it is the ability to satisfy the customer needs irrespective of the disruptions. Not just between different organizations but also within one organization different interpretations of the term SCR are seen. The reason for this was explained by one of the experts C1.2 which can be interpreted as the different function in company which are part of the supply chain, which are manufacturing team, logistic team, sourcing team etc. have different areas of responsibilities. All these teams have their own interpretation of the term resilience; where for Global manufacturing is concerned with having inhouse production in multiple locations around the world, while logistics is concerned with the amount of inventory to hold as safety stock. The sourcing team is concerned with multiple suppliers. At the corporate level, the understanding of resilience is taken one level up by managing long term decisions such as country selection for production plants, regional independence etc.

RQ1.1: Identifying what are the wants and needs in terms of resilience level in manufacturing companies in Vorarlberg?

As the time when this research is carried out is followed by the COVID19 pandemic which has had one of the largest impacts on the global supply chain operations. Due to this fact, it is evident that all the organizations are more alert and aware of risks that such disruptions can have on the supply chains. Covid19 pandemic was not the first disruptions the manufacturing companies in Vorarlberg has seen but it is surely one of the biggest in modern times. During the pandemic, many of the companies with sources which are spread globally

suffered significant losses as the goods were not transported. This has a huge impact on finding the current needs and wants of the companies of Vorarlberg.

The companies which have major share of material being sourced globally have shown the strongest need to be regionally independent, and those who source locally for most of the portion of the volume are seen as not very much concerned. Regional dependence in the interviews ranged from electronics dependence emerging from east Asia, cobalt nickel dependence in certain regions, natural gas supply dependence on Russia. As mentioned by one of the interviewees C4.1, that there is no default risky region, it was seen as China during the trade war with US and COVID pandemic before but with war in Ukraine, Europe can also not be considered as safe anymore.

Multisourcing is also seen as the most frequent need from all the experts, some of them are already maintain multiple sources, while those who cannot maintain the second source have the reasons of purchasing low volume which does not make it feasible for suppliers to provide, and for some it is the highly specialized products which can only be supplied by certain limited suppliers. ERP System limitations to handle multiple suppliers for same material was also mentioned by C1.3 which adds to the reasons to limit the suppliers to only one for one material.

RQ1.2. How manufacturing companies in Vorarlberg are building resilience within their supply chain?

An extensive supplier relationship management is found to be common with all the organizations for acting towards building resilience. Treating the suppliers well, with respect, and maintaining a long-term relationship instead of changing the suppliers purely on slight incentives is said to be beneficial when it comes to working together in the periods of disruption. C1.2 shared that during the pandemic the organization benefited from treating the business partners with respect in past, where the same suppliers were not treated well, especially by the automotive customers who maintain negotiate and change suppliers on the slight price differences. C3.1 also saw the same benefit during the pandemic where the electronics allocation was one of the critical issues of the time, where the good long-term relationship with the supplier gave the benefit in sourcing the critical materials. Selecting the right suppliers from the start, those who match the values of the organization was mentioned as the first step before starting a long-term business relationship with the supplier. If the values of the organization do not match with the supplier, then the efforts taken towards maintaining and nurturing the relationship might be waste if the organization must take a decision in future to discontinue due to misfit. It is also crucial to ensure that the actions carried out by the organizations should be carried out parallelly by their suppliers as well, if not done then the actions carried out are not useful. How it can be interpreted is that if the organization is taking actions towards resilience with the tier 1 supply, these actions could be having transparency over all

suppliers, maintaining safety stock or qualifying 2nd or 3rd source etc., should also be carried by the suppliers with tier 2 suppliers as well.

The frequent communication with the suppliers is seen to play a major role when it comes to maintaining a long-term relationship. Not only how frequent is this communication done but also the honesty, transparency and openness that is maintained with the communication. When it comes to interpreting the transparency, it should be interpreted in both sides, upstream from the suppliers and downstream from the customers. Transparencies on both the sides are equally important for SCR, as it is equally important to understand the multitier suppliers and to understand the source of the customer demand and the forecast. When discussing about the upstream communication with transparency from the suppliers, different ways and strategies are mentioned by the interviewees. Even when the message might not be positive for business relationship with the supplier, maintaining honesty in the communication is a need, which was illustrated by one of the interviewees C5.1 who maintains the honesty even in communicating that the organization would be diverting the purchases to the new supplier. EDI which is the electronic data interchange system used to transfer information withing business was mentioned in 2 interviews, where this system is bringing transparency and increasing the speed in communication. The EDI installed in these organizations provide the information over the customer demand forecasts, customer orders, vendor managed inventory which ensures the transparency in the supply chain.

C1.2 shared "*As long as you don't have control, transparency is only half relevant.*" This statement displays the need for decision and reaction as soon as information is shared by the suppliers. Unless and until proper actions are not initiated after receiving information, the purpose of transparency loses its value. Due to geopolitics, trade wars, protectionism and many more reasons, reliability on global sourcing has seen to be changed. Most of the interviewed companies who have global sourcing model, see the benefit in local sourcing. "Price is not everything" is not just a statement but a sign of realization of the focus on resilience over cost benefits. 4 out of 6 companies mentioned tendency towards localization which is the sign of change of mentality and behavior. Companies who have most of the sourcing done locally are seen to be less affected by the issues mentioned above and are satisfied with the local sourcing strategy.

Along with these findings, it can be noted the structure of the company has an impact on the velocity with which the decisions are made, also in the context of actions towards SCR. Companies where employees who are responsible for supplier management, when they are in frequent contact with the decision-making management, it was found to be making decisions faster. It was also found that complex matrix structured organizations with multiple stakeholders slow down the decision-making process.

RQ1.3: Is there a method existing to measure the resilience which fits the best for the industry?

Based on the interviews, it can be concluded that SCR is generally understood as a new term for the traditional SC risk management processes. Due to this way of the interpretation of SCR, companies currently do not have any specific measurement method or KPI to quantify the level of SCR. Only one out of the nice interviewee responded positive over the need for such a measure and others did not see a need. Various ways of risk management are seen within the companies. One company uses a special business interruption tool to measure and maintain the time in months required for each critical supplier to recover from a disruption. Another company carries out the risk management through the specific commodity management process which is specific to that commodity. Another company relies on the supplier audits and the follow up on the audit results. The interviewees also shared current performance measurement processes which consists of various supply chain KPI's: On time delivery, supplier flexibility, number of sources per material, delivery reliability.

In the literature review before, 4 SCR measurement methods were mentioned, but out of these 4 methods which method fits the best is be assessed. To do this comparative analysis, 5 parameters which are mentioned in the Table 15 will be used. Table 15 shows the parameters on the left column and the 4 SCR measurement methods in the next 4 columns. All of these 4 methods are graded with the parameters mentioned above with the focus on Vorarlberg's manufacturing industry. Likert scale of 1-5 is used where the larger the number better the methods is for to that parameter.

- **Scalability**: Measurement method should be scalable for all sizes of organizations
    - All of the methods can be scaled up and down as per the size and companies within the SC, which is why all of the methods score similar.
- **Practicability**: measurement method must be ease for implementation, with least time requirement and cost effective to implement.
    - 2nd and 3rd method have a higher data requirement, which consumes more time and cost related to the resources required, which is why they score lower than the other two.
- **Relevance**: Measurement method should be relevant to the manufacturing industry of Vorarlberg.
    - The 1st and 3rd method are proposed with a focus on automotive industry, and the sub-indicators / enablers used for SCR are automotive industry relevant. This is the reason why it is less relevant than other methods. 2nd and 4th method can be easily adopted to any industry, as compared to 1st and 3rd.
- **Applicability**: Measurement method must be applicable using the limited resources.

- The 2nd and 3rd method score slightly lower than the other two because both methods use complex calculation process than others. The reason to score them lower is not just as they are complex but when it comes to applying this method in practice, it takes longer to carry out the calculations and are comparatively difficult to understand and interpret the results by all the members of SC with different level of understanding.

- **Data requirements**: Measurement method should use the data collection and analysis methods which use limited efforts.
  - The 2nd and 3rd method have more data collection requirements than the 1st and the 4th which is why they score lower.

	1. Resilience index from LARG Index[141]	***2. Component Resilience Index[142]***	***3. Resilience index based on Graph theory[143]***	***4. Resilience index for on-time delivery[144]***
Scalability	3	5	5	3
Practicality	5	1	1	5
Relevance	1	5	1	5
Applicability	5	3	3	5
Data requirement	5	3	3	5
Total sum:	**19**	**17**	**13**	**23**

Table 15: SCR measurement methods comparison

Based on the above-mentioned assessment, it can be said that out of the 4 SCR measurement methods; the resilience index method proposed by Carvalho et. al [145] is found to be suitable measurement method for manufacturing industry of supply chain.

5.1 Limitations

In any pursuit of knowledge, the limitation the limitations are inherent. The current research also has limitations of its own. Some of these limitations are noted in this section.

- **Sample size and biases:** The number of industry experts that are interviewed for this research are limited in number, which could affect the generalizability of the findings. A larger sample size can always provide a more comprehensive perspective, which was not possible due to the size of the study. The experts that are interviewed may have certain biases which could influence and limit the diversity of perspectives that are presented in this research.

[141] Azevedo, Carvalho, and Cruz-Machado, "LARG Index."
[142] Ahmadian et al., "A Quantitative Approach for Assessment and Improvement of Network Resilience."
[143] Agarwal, Seth, and Agarwal, "Evaluation of Supply Chain Resilience Index."
[144] Carvalho et al., "The Resilience of On-Time Delivery to Capacity and Material Shortages."
[145] Carvalho et al.

- **English not corporate language in most organizations**: Even though during interviews, all the interviewees spoke the language of research English fluently, still it is not the corporate language at most of the corporation they work for. Due to this fact, interviewees cannot always with full accuracy express their thoughts easily. This is why the opinions shared during the interviews might not reflect accurately what they truly want to express, and which limits the research.
- **Generalizability**: As this research was carried out within Vorarlberg with a focus on manufacturing industry, the findings of this research may be only relevant specific to this context, industry, or geographical region in which the experts operate. In future it may be challenging to extrapolate the results to other supply chain contexts or industries or geographies.
- **Self-reporting bias**: There is a possibility that the interviewees may provide answers they perceive as more socially desirable rather than reflecting their actual practices or opinions. Ex. Interviewees may overstate or exaggerate the extent to which they actively work on SCR, as to present themselves more advanced and competent.
- **Time frame limitation**: As the interviews are carried out post a major event like COVID19 pandemic, the findings may be influenced by such exceptional circumstances of the time. This might limit the applicability of the results to other periods in past or future or in non-crisis situations.
- **Lack of objective measures**: As for the interviewees who do not use specific metrics or measurement methods to evaluate supply chain resilience, it may be challenging to obtain data for analysis. This might affect the reliability and validity of the research findings.

6 Conclusion

With increasing globalization and dependency on global supply chain, the topic of resilience in the context of supply chain disruptions has gained a lot of attention. Although a lot of research has been done on the topic of supply chain resilience, especially after big disruptive events such as 911, COVID19 pandemic, there is still consensus missing from scholars on definitions of SCR. It is evident regarding the definition of SCR, that with time it is maturing, and activities under its scope are increasing. The first time the term SCR was coined for being an ability of the system to “bounce back”; then the ability of resisting the disruption was added, followed by ability of reducing the probability of disruption itself. The interpretation of the term SCR is also found to be done differently not just between different organizations, but also within a same organization. The SCR is interpreted differently by different cross functional teams based on the scope of their actions towards SCR. While for logistics teams, SCR is mainly managing the buffer inventory, whereas for sourcing teams SCR is more towards managing the supply by having multiple sources in different locations. At higher corporate level, SCR is seen from a level where long term strategic decisions towards SCR are taken. From the technologies in the section 3.7 which are discussed in the literature review, it can be concluded that impact of technological development in supply chains have a direct positive impact on SCR. Technologies such as big data analytics are evidently considered mature and have received attention from the researchers.

With the findings on the RQ1.1 it can be concluded that in Vorarlberg’s manufacturing industry, the needs of the companies towards SCR are mainly to get regional independence and procure locally. The impact from supply issues originated in COVID19 pandemic, is seen to have on these results. There are exceptions found on these mentioned needs, with the company which procures most of the purchase volume locally in Europe and one company who has outsourced entire procurement and production to the 3rd party workbench.

With the findings on RQ1.2, it can be concluded that most common and highly mentioned actions taken towards SCR by the companies in the mentioned region are extensive supplier relationship management, maintaining long term relationships. All of the companies interviewed shared the same voice of maintaining good relationship with respect, transparent communication with the long-term suppliers plays a crucial role in long run and especially during the time of disruption. Technologies such as EDI (electronic data interchange) is seen to be used by most of the companies, which is used to exchange data with businesses and is said to help in maintaining transparency with suppliers. Local sourcing is also seen to be one of the frequent actions taken towards resilience, which originates from supply shortages faced due to global supply disruptions in the last few years. As mentioned in the literature, a lot of new technologies such as Big data analytics, AI, blockchain etc are seen by the scholars to support the organizations to bring the transparency, speed and reliability in the supply chains. Such improvements are said to support the organizations towards building SCR. In

practice within the interviews, the implementation of technologies in supply chain shows a different picture, and can be concluded that none of these technologies are directly in use towards SCR. There is an exception for this conclusion, where one of the interviewees confirmed the usage of AI in monitoring supply contract, but not directly for SCR. Based on the findings towards the impact of structure of the organization, it can be argued that a frequent and easy contact between the decision-making management and responsible supply managers increases the speed of decision-making process for actions towards SCR. Complex matrix organizations with multiple stakeholders for delivery of the same product, slows down the decision making process.

On the RQ1.3 and the main research question for finding the best-fit SCR measurement method, it can be concluded that there is no SCR specific measurement method used in the 6 organizations interviewed. All of the organizations use the traditional risk management processes, where each organization has its own tailor-made risk management processes. These processes include measuring the business interruption risk, KPI's suck as supplier flexibility, on time delivery, rate of returns etc. The need for SCR measurement method is not found within the organizations, as only 1 out of 9 interviewees foresee the need for it for the future. With the structured literature review on finding a SCR measurement method, 4 methods were discussed in the literature review. This was followed by an assessment of these 4 methods against the parameters: Practicality; Applicability; Relevance; Data requirement; Scalability. These parameters are taken to make sure that the measurement method is relevant for the industry it is applicable using limited company resources and limited data requirements, which is also scalable for different size of organizations and practical, easy to implement.

Based on the assessment criteria discussed in the section 5, Resilience index proposed by Carvalho et al.[146] for on-time delivery can be recommended for recommending for measuring SCR of the companies in manufacturing industry of Vorarlberg.

[146] Carvalho et al.

7 Summary

With increased frequency of major disruptive events and its impact on supply chains, resilience in the context of supply chain has gained a lot of attention. In the literature, it is evident that post major disruptive events like 911 attack in New York and global COVID 19 pandemic are followed with increase in research towards SCR. Although a lot of SCR is evidently done, not every researcher has focused on proposing a measurement method or a measurement index for SCR. There are some researchers who have proposed SCR measurement methods, each using different theoretical prospective. Focusing on the manufacturing industry of Vorarlberg industry, it is crucial to explore what are the ways SCR is measured in the SCs in the region and if there is a one-fit for all method that is applicable to companies in the Vorarlberg. Hence the objective of the research is assessing the current state of SCR in Vorarlberg's manufacturing industry focused on the measurement methods and analyze which methods from literature review and in practice fits best for the mentioned industry. Based on this objective, the following research question is split in 3 sub questions, which are proposed here:

RQ1: Which available method of measuring resilience of a supply chain fits best for manufacturing industry in Vorarlberg?

RQ1.1: What are the wants and needs in terms of resilience level in manufacturing companies in Vorarlberg?

RQ1.2. How manufacturing companies in Vorarlberg are building resilience within their supply chain?

RQ1.3: Is there a method existing to measure the resilience which fits the best for the industry?

Scope of the study is limited within the Vorarlberg state of Austria, and the procurement/sourcing function of the manufacturing companies in the region. To keep the focus on SCR measurement methods, the traditional risk measurement methods are kept out of scope. Using the research onion proposed by Saunders et al. [147] the research was designed. For researching a multidisciplinary field like SCR, interpretivism research philosophy of is needed. Interpretivism allows researchers to explore and understand the subjective meanings and experiences of individuals, acknowledging that individuals construct their reality based on their interpretations[148]. This research is aimed at finding a SCR measurement method proposed in the theory and the actual SCR measurement methods in practice in the specified industry. With deductive approach different theories, concepts related to SCR can be identified, which is why deductive approach was chosen for literature review. With the expert interviews both deductive and inductive approaches were applied. First deductive

[147] Saunders, Lewis, and Thornhill, *Research Methods for Business Students*.
[148] Denzin and Lincoln, *The SAGE Handbook of Qualitative Research*.

approach is used to provide theories and structure for the interview, followed by an inductive approach for exploring new theories and approaches from interviews. For research grounded theory was used, as the **literature review** provided the status of research, existing theories, frameworks, and methods followed by the **expert interviews** which provided different insights in their ways of SCR and measurement. Using these both makes it a mixed method. As mentioned in detail in the research methodology section, a structured literature search on the online libraries with scholarly content such as ProQuest and Olav from FHV. 52 relevant documents were discovered with relevant filtration process. All of these documents were analyzed using a concept matrix in an MS excel file, which was used to provide structure and collect the presence of the relevant information withing the research papers. Following are the findings using the literature review:

Before discussing about the SCR measurement methods, it is important to understand ways in which the term SCR is defined and constructed by the scholars. Although a lot of research is done on SCR, there is no one definition of SCR which is agreed and followed by most of the researchers. There are many different definitions of SCR proposed and the scope of what must be covered under the term SCR is evolving. The first definition of SCR considered it just as an ability for the system to rebound after disruption. This was then followed by SCR being a capability of first absorbing the impact of a disruption, followed by adapting the system, and at the end recovering from the disruption. With the latest definitions the capability of reducing the probability of the disruption is added also under the term SCR[149]. The organizational risk management practices are used for supply chain risk management practices, but they fail to capture the complexity of the supply chains as they are spread over multiple originations and geographies. Here SCR helps to cover the complexity of supply chains which are not covered under traditional supply chain risk management processes. Based on the capabilities of SCR with respect to the time of disruption; 3 dimensions for SCR are proposed: which are absorptive capacity which absorbs the impact of disruption. The second one is the adaptive capacity which is utilized during the disruption and the third capacity is the recovery capacity used post disruption to recover the system back to normal.

Researchers have used many different theoretical perspectives on SCR: Resource based view theory focuses on the internal resources that an organization has and derives its SCR capability based on the resources the organization has. Dynamic capability theory which is based on the resource-based view focuses on the ability of the organization to adapt, innovate, and learn in response to changing environments and competitive pressures. Contingent resource-based view theory asserts the effectiveness of organizational resources in enhancing its competitive advantage in strategic and operational contingencies. Graph

[149] Falasca, Mauro and Christopher W. Zobel, “A Decision Support Framework to Assess Supply Chain Resilience,” 2008.

theory uses as the name suggest graphs to show the supply chain participants and their interdependencies. These graphs are afterwards converted using adjacency matrix to measure SCR mathematically. Network theory focuses on the complex supply networks and uses matrix to measure the SCR on the networks, which are consisting of nodes and graphs to represent the actual supply chain. 4 SCR measurement methods discovered in the literature review were discussed in detail in the section 3.7 each with a unique methodology.

1. Resilience index from LARG Index – Azevedo et al. [150]
2. Component Resilience Index – Ahmadian at al. [151]
3. Resilience index based on Graph theory – Agarwal at al.[152]
4. Resilience index for on-time delivery – Carvalho at al [153]

A lot of attention has already been raised about usage of new technologies in supply chain. In terms of SCR, there are many technologies which are said by the scholars to make an impact towards building SCR. The technologies with highest attention were discussed in the section 3.7 which include overall digitalization of the SC, Big data analytics, Blockchain, AI, the overarching industry 4.0. As per findings from the researchers Speiske et al[154] and Bahrami et al.[155] , Bid data analytics is found to be the most mature and has received the most attention. Bid data analytics in the context of SCR is said to be supportive mainly in the ways of bringing velocity and visibility in SC.

For the interviews, the expert panel sampling was done using purposive sampling method where 9 participants from 6 organizations in the manufacturing industry of Vorarlberg were selected based on their expertise in the field of research. The interview method was kept as semi structured as the questions were developed using the theories discovered in the literature review and modified based on the relevancy and focus of the discussion. Digital tools such as Microsoft teams, were used to record and transcribe the interviews. A step-by-step guide of thematic analysis[156] was followed to carry out an analysis on the interview. The

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[150] Azevedo, Carvalho, and Cruz-Machado, “LARG Index.”
[151] Ahmadian et al., “A Quantitative Approach for Assessment and Improvement of Network Resilience.”
[152] Agarwal, Seth, and Agarwal, “Evaluation of Supply Chain Resilience Index.”
[153] Carvalho et al., “The Resilience of On-Time Delivery to Capacity and Material Shortages.”
[154] Alexander Spieske and Hendrik Birkel, “Improving Supply Chain Resilience through Industry 4.0: A Systematic Literature Review under the Impressions of the COVID-19 Pandemic,” *Computers & Industrial Engineering* 158 (August 2021): 107452, https://doi.org/10.1016/j.cie.2021.107452.
[155] Mohammad Bahrami, Sajjad Shokouhyar, and Atiyeh Seifian, “Big Data Analytics Capability and Supply Chain Performance: The Mediating Roles of Supply Chain Resilience and Innovation,” *Modern Supply Chain Research and Applications* 4, no. 1 (March 30, 2022): 62–84, https://doi.org/10.1108/MSCRA-11-2021-0021.
[156] Braun and Clarke.

qualitative data analysis tool such as MAXQDA was used for generating the codes and themes. The findings and conclusions were described against every sub question:

RQ1.1: Identifying what are the wants and needs in terms of resilience level in manufacturing companies in Vorarlberg?

Organizations are evidently more alert and aware of the supply risks as the research is followed after COVID19 pandemic which had a significant impact on supply chains. The companies with global sourcing have shown the strongest need to be regionally independent. Regional dependence found to be with electronics sourced from east Asia, cobalt nickel in specific regions of the world, natural gas supply dependence on Russia. Multi sourcing has also seen as the most frequent need from all the experts, some already maintaining multiple sources, while those who cannot maintain the second source have the reasons of purchasing low volume which does not make it feasible for suppliers to provide. ERP System limitations to handle multiple suppliers for same material was also mentioned as a reason to limit the suppliers to only one.

RQ1.2. How manufacturing companies in Vorarlberg are building resilience within their supply chain?

An extensive supplier relationship management is found to be the most frequent action taken by the organizations towards SCR. Supplier relationship management includes treating the suppliers with respect, maintaining a long-term relationship, having transparent and honest communication. Selecting the suppliers who match the values of the organization was found as the first step before starting a long-term business relationship, which helps in focusing the efforts on the right partners. It is found crucial to ensure that the actions carried out by the organizations should be carried out parallelly by their suppliers as well, if not done then the actions carried out by organization are wasteful.

The frequent and open communication with the suppliers is seen to play a major role in supplier relationship and SCR as well. Transparency both on supply and demand side of the supply chain is seen equally important for SCR, as it is equally important to understand the multitier suppliers and to understand the source of the customer demand and the forecast. Not just transparency, but reacting fast after receiving transparency is found crucial, as transparency without reaction is waste of efforts towards SCR.

Due to major disruptions in the recent times, organizations with global sourcing model, see the benefit in local sourcing. "*Price is not everything*" is found to be not just a statement but a sign of realization of the focus on resilience with localization over cost benefits from sourcing from overseas. Companies who have most of the sourcing done locally admit being less affected by the supply issues and are satisfied with their strategy.

In terms of technological use, only a few matured technologies were mentioned that are used by the companies which were interviewed. Such technologies include the usage of EDI and

SAP, both of which are very matured and used worldwide since years. It can be concluded that the advanced technologies to build SCR found in the literature such as big data analytics, blockchain, Industry 4.0 etc. are yet to be used extensively in the region especially towards SCR.

Based on the findings it can also be argued that the structure of the organization has an impact on the velocity of the decisions, especially the decisions on the actions towards SCR. Organizations where supply management is in frequently in contact with the decision-making management, are seen to be making the decisions faster. It can also be concluded that the organizations with complex matric structure with multiple stakeholders for delivering same product are slower in decision making, due to longer time required for getting consensus on the SCR actions.

RQ1.3: Is there a method existing to measure the resilience which fits the best for the industry?

Based on the interviews, it can be concluded that SCR is generally understood as a new term for traditional risk management processes because of which none of the companies currently have a measurement method or KPI to quantify the level of SCR. One of the reasoning for the lack of SCR measure mentioned was that one common SCR measure cannot be applied to all suppliers, as there is a significant difference between the level of risk from supplier to business. It was mentioned that one common SCR measure cannot be used for both a local supplier and an overseas supplier as the risk form both are not comparable. Only one out of the nine interviewees responded positive over the need for such a measure. Various ways of risk management are carried out in the companies. Out of these 4 methods which method fits the best was assessed. To do this comparative analysis, 5 parameters which are mentioned in the Table 15 will be used on the Likert scale of 1-5. These 5 parameters were used to assess:

- **Relevance**: Measurement method should be relevant to the manufacturing industry of Vorarlberg.
- **Applicability**: Measurement method must be applicable using the limited resources.
- **Data requirements**: Measurement method should use the data collection and analysis methods with limited efforts.
- **Scalability**: Measurement method should be scalable for all sizes of organizations
- **Practicability**: measurement method must be ease for implementation, with least time requirement and cost effective to implement.

After assessing the 4 above mentioned methods on these parameters: the Resilience index proposed by Carvalho at al [157] can be recommended as the one method to be used by the industry under study for measuring supply chain resilience.

[157] Carvalho et al.

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Appendix

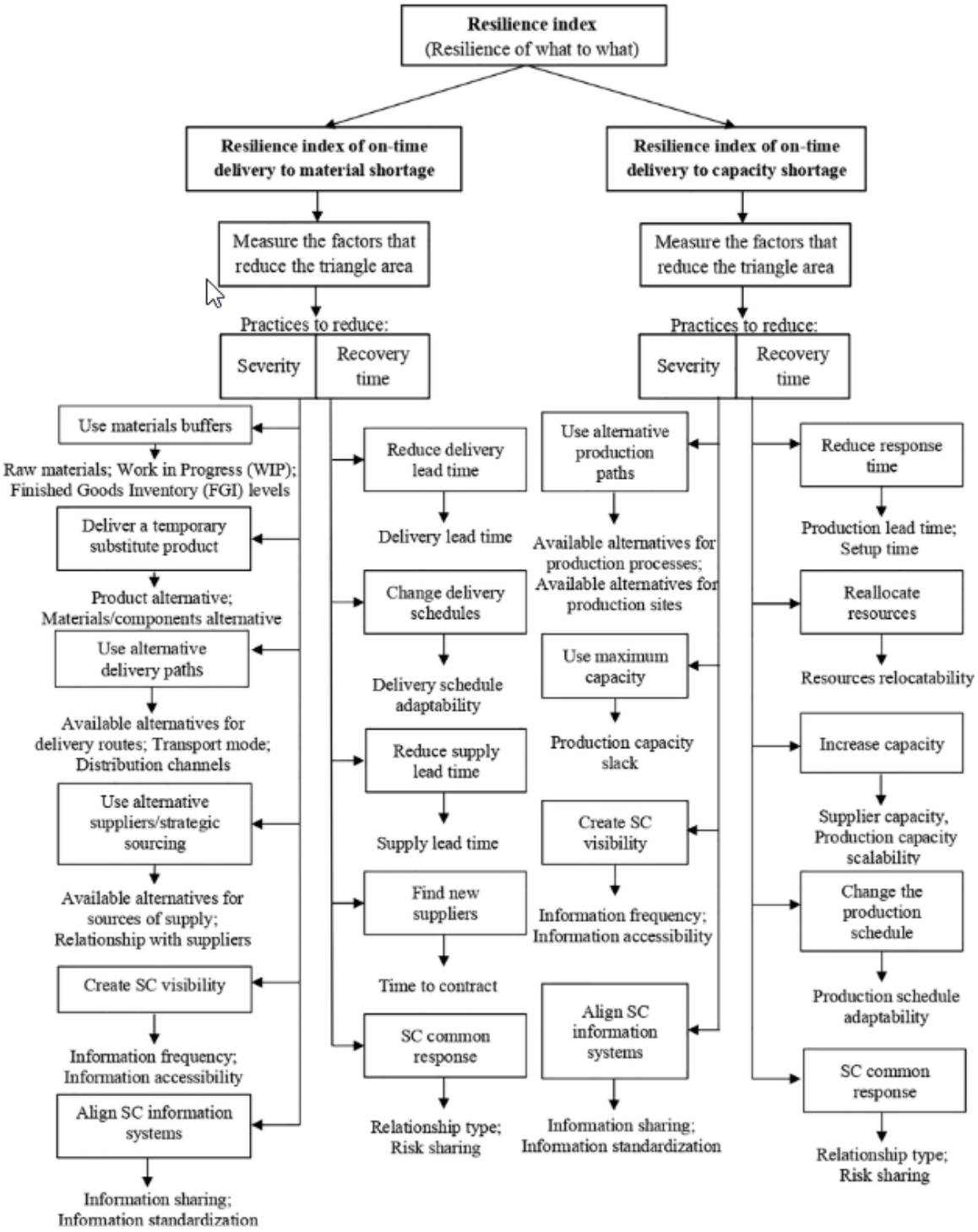

Fig. 3. Resilience practices and supply chain state variables used for modelling the resilience index.

Fig. 3. Resilience practices and supply chain state variables used for modelling the resilience index.[158]

[158] Carvalho et al.

Statement of Affirmation

I hereby declare that all parts of this thesis were exclusively prepared by me, without using resources other than those stated above. The thoughts taken directly or indirectly from external sources are appropriately annotated.

This thesis or parts of it were not previously submitted to any other academic institution and have not yet been published.

Dornbirn, [07.07.2023] Gaurav Pangarkar