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Managing Large-scale Disruptions in Supply Chain Networks

by Towfique Rahman

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Associate Professor Sanjoy Paul, Professor Renu Agarwal, Associate Professor Nagesh Shukla, and Dr. Firouzeh Taghikhah

University of Technology Sydney
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Certificate of Original Authorship

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Dedication

To My Beloved Family

My Parents
Md Abdur Razzaque and Latifa Khatun

My Wife
Iffat Jahan Srabonty

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Keywords

Supply chain

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Risk

Systematic literature review

Large-scale disruption

COVID-19

Pandemic

Multiple disruption

Simulation

Optimisation

Agent-based modelling

Panic-buying

Risk management

Viable supply chain

Resilience

Sustainability

Mitigation

Recovery

Abstract

Supply chain (SC) risk management is an emerging field that plays an important role in dealing with local and international SC disruptions. During the last decade, researchers have proposed several strategies related to characterisation, including resilient and sustainable SCs, strategising dimensions, and the justifications of strategies. However, there has been a lack of research in the development of SC resilience, adaptation, and viable strategies in tackling large-scale SC disruptions caused by catastrophic events and how the strategies improve and impact sustainability performances such as economic, social, and environmental performances of SCs during these unpredictable events. This study has several aims. Firstly, it conducts a critical literature review on SC resilience strategies, methodologies, and theories that justify them. Secondly, it investigates the impact of large-scale disruptions, such as COVID-19, on the SCs of essential product manufacturers. Thirdly, it proposes congruent SC strategies for essential product manufacturers to mitigate supply, demand, financial, and simultaneous disruptions caused by catastrophes, such as COVID-19. Finally, this study proposes an SC resilient model using system science methods to test the proposed resilience strategies to evaluate the improvement in SCs. The proposed model also evaluates the resilience and sustainable performances (economic, social, and environmental performances) of SCs in managing large-scale SC disruptions. The model includes integrated methods of qualitative (literature review, case study) and quantitative (system science methods) research methods. Quantitative methods are primary methods, while qualitative methods are used for supporting and contextualising quantitative research. Drawing on relevant literature and theoretical grounding, the typical and disrupted SC models are aimed to develop and test the proposed strategies and validate them using an exploratory case study for an Australian essential product SC (such as facemasks, ventilators, personal protective equipment, and toilet paper).

This research contributes to SC risk management literature theoretically, methodologically, empirically, and practically on three fronts. First, this research is one of the first studies that quantitatively assesses the efficiency of resilience, adaptation, and viable strategies adopted by firms for their recovery from large-scale disruptions caused by catastrophic events such as COVID-19. Second, it extends the scope of SC resilience models to incorporate supply and demand-side mitigation strategies, and simultaneous and dynamic impacts of the COVID-19

pandemic. Thirdly, it proposes a novel integrated agent-based model and optimisation method to study SC processes, model them, and then explore proposed strategies, which consequently will lead to an overall improved performance of SCs of essential products such as facemasks and toilet paper. The model also evaluates the resilience and sustainable performances of SCs while managing large-scale SC disruptions. Furthermore, SC managers will benefit from this research in understanding and implementing congruent SC resilience, adaptive and viable strategies to protect essential products' SCs effectively, and cope with large-scale disruptions caused by large-scale events like the COVID-19 pandemic.

The research has generated significant empirical and practical findings from its theoretical and methodological contributions. Firstly, the findings of the experiments of this research revealed that minimising the risk response time and maximising the production capacity helped essential item manufacturers meet consumers' skyrocketing demands and reduce financial shocks to firms. It was also found that delays in implementing recovery strategies could result in supply, demand, and financial shocks for manufacturers of essential items during large-scale disruptions. Secondly, due to increased production capacity through an optimal inventory and transportation strategy, the pandemic's multiple impacts on facemask production and delivery were reduced, leading to lower total SC costs and more product accessibility for consumers. Maintaining dynamically optimal reorder points and order sizes is crucial to minimise risks and maximise raw material supply and inventory levels. Thirdly, increasing production in decentralised manufacturing facilities and collaborating with third-party transporters can also help alleviate the effects of panic-buying in SCs, by increasing the supply of critical items. Further, increasing the frequency of orders to multiple and alternative suppliers can increase manufacturers' raw material supplies. Finally, regarding the sustainability performances of the SCs, the findings revealed that increased resilience in healthcare SCs improved economic and social sustainability while decreasing environmental performance. The findings can be further used as a guideline to manage large-scale disruptions in the SC network in future disruptions.

Lists of Publications

Journal Articles

1. Rahman, T., Paul, S. K., Shukla, N., Agarwal, R., Taghikhah, F., (2022). ‘Supply chain resilience strategies and initiatives: A systematic review’, *Computers & Industrial Engineering, 170,* 108317. <https://doi.org/10.1016/j.cie.2022.108317> (Based on Chapter 2)
2. Rahman, T., Taghikhah, F., Paul, S. K., Shukla, N., Agarwal, R., (2021). ‘An agent-based model for supply chain recovery in the wake of the COVID-19 pandemic’, *Computers & Industrial Engineering, 158,* 107401. <https://doi.org/10.1016/j.cie.2021.107401> (Based on Chapter 3)
3. Rahman, T., Paul, S. K., Shukla, N., Agarwal, R., Taghikhah, F., (2023). ‘Dynamic supply chain risks management plans for mitigating the impacts of the COVID-19 pandemic’, *International Journal of Systems Science: Operations & Logistics, 10(1), 2249815.* < https://doi.org/10.1080/23302674.2023.2249815 > (Based on Chapter 4)
4. Rahman, T., Paul, S. K., Agarwal, R., Shukla, N., Taghikhah, F., (2023). ‘A viable supply chain model for managing panic-buying related challenges: Lessons learned from the COVID-19 pandemic’, *International Journal of Production Research.* <https://doi.org/10.1080/00207543.2023.2237609> (Based on Chapter 5)
5. Rahman, T., Paul, S. K., Shukla, N., Agarwal, R., Taghikhah, F., (2022). ‘Managing panic buying-related instabilities in supply chains: A COVID-19 pandemic perspective’, *IFAC-Papers Online, Elsevier, 55(10),* 305-310. <https://doi.org/10.1016/j.ifacol.2022.09.405> (Based on Chapter 5)
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Conference Papers/Presentations

1. Rahman, T., Paul, S. K., Shukla, N., Agarwal, R., Taghikhah, F., (2022). ‘Managing panic buying-related instabilities in supply chains: A COVID-19 pandemic perspective’, *10th IFAC Conference on Manufacturing, Modelling, Management, and Control. (Received “Commended Paper Award”)* (Based on Chapter 5)
2. Rahman, T., Taghikhah, F., Paul, S. K., Shukla, N., Agarwal, R., (2021). ‘Recovery model for supply chains in the event of the COVID-19 pandemic’, *Australia-Korea Conference on Supply Chain Resilience.* <Abstract Presentation> (Based on Chapter 3)
3. Rahman, T., Paul, S. K., (2023). ‘Evaluating environmental sustainability performance in healthcare supply chains under demand surges’, *IEEE International Conference on Industrial Engineering and Engineering Management (IEEM).* (Based on Chapter 6)

Book Chapters

1. Rahman, T., Paul, S. K., (2022). ‘Reconfigurable strategies to manage uncertainties in supply chains due to large-scale disruptions’, *Supply Network Dynamics and Control. Springer Series in Supply Chain Management, 20,* 95-119. *Springer, Cham.* <https://doi.org/10.1007/978-3-031-09179-7_5>
2. Rahman, T., Paul, S. K., Agarwal, R., Sarker, R., (2023). ‘Overview of supply chain risk and disruption management tools, techniques, and approaches’, *Supply Chain Risk and Disruption Management: Latest Tools, Techniques, and Management Approaches, Springer.* <https://doi.org/10.1007/978-981-99-2629-9_1>
3. Rahman, T., Paul, S. K., (2023). ‘A review of computational tools, techniques, and methods for sustainable supply chains’, *Computational Intelligence Techniques for Sustainable Supply Chain Management. Elsevier* <Accepted>

Note: The chapters are a subset of the full published/submitted paper and any overlap with the other chapters has been eliminated from these chapters.

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Chapter 1

Introduction

This introduction chapter describes the background, rationale of this study, and the problem statement; and summarises the research questions, the research methodology and framework, the objectives, and the theoretical and empirical contributions.

1.1. Background to the research

Modelling supply chain (SC) networks to manage simultaneous and multiple impacts of large-scale disruptions is an extremely challenging research topic. A McKinsey study shows that global SCs are disrupted every 3.7 years on average (McKinsey & Company, 2020). The risks imposed on SCs are SC network- and industry-specific and depend on the merits of the disruptions. Large-scale disruptions are imposing unknown-unknown risks across the SC networks. These risks are unpredictable, assuming their complexity, timing, location of the occurrence, and simultaneous impacts as businesses are challenged to operate in a volatile, uncertain, complex, and ambiguous (VUCA) environment compared to small-scale disruptions (Ivanov & Sokolov, 2010).

The current COVID-19 pandemic has drastically disrupted the global SCs, the impact of which is yet to be fully revealed post-pandemic. Due to the time-to-time lockdowns, shutdowns, and border closures, global SCs faced supplier failure, production capacity degradation, restrictions in transportation, and a lack of sufficient inventory to meet the extra demand for essential products such as facemask, food, and toilet paper. On the other hand, manufacturers producing luxury and low-demand products, such as clothing, apparel, and automobiles, faced a considerable demand fall. As a result, businesses struggled to continue their livelihood. The long-established SCs have been unable to manage large-scale SC disruptions caused by the COVID-19 pandemic. In this context, the recent COVID-19 pandemic can be classified as a catastrophic event which has devastated the SC and business operations globally (Ivanov, 2020b).

Large-scale disruptions cause unlimited SC uncertainties (Fazli-Khalaf et al., 2020). The recently occurring COVID-19 pandemic has imposed environmental, economic, operational, and technical uncertainties and human thinking and decision-making uncertainties for the SCs of businesses worldwide. Environmental uncertainties due to large-scale disruption have impacted the global SCs the most. Most countries imposed strict lockdowns and shutdowns inside the country, restricting the border to a large extent. Some countries, like Australia, closed the border with almost all the nations with a minimal exemption (Antony et al., 2020). This strict restriction has severely impacted the supply of goods from one country's source to another's manufacturer. The manufacturers of essential products, such as food, personal protective equipment, and toilet paper, faced severe supply shortages (Poudel et al., 2020). As a result, fear spread among the general people about the shortage of essential products. People panic-purchased essential products such as food and toilet paper, and retailers struggled to meet the demand surge (Nicola et al., 2020). The pandemic also proved that the current technology of the manufacturing units could not increase production to meet the extra demand of consumers during such disruptions. Thus, large-scale disruption caused by COVID-19 has imposed severe environmental uncertainties on the global SCs. Due to the lockdowns and shutdowns imposed to control the spread of the COVID-19 virus, the world's economic activities slowed down, which turned into a severe global economic recession (Fernandes, 2020). The supplier failed to deliver the products to the manufacturers; because of this, the manufacturers could not ramp up the production capacity to fulfil the consumers' demand. The SCs of most industries faced an increased shortage cost because of high backorder levels and lost sales (Mehrotra et al., 2020). Thus, the large-scale disruption caused by COVID-19 impacted the turnover of the industries. The manufacturers' existent operational and technological strength could not allow them to ramp up the production capacity to meet the demand surge, especially the demand for consumers' essential products. Thus, the operational capacity and technological condition weaknesses are the significant uncertainties in SCs induced by the COVID-19 pandemic (Xu et al., 2020).

Moreover, the decision-makers of the industries struggled to adopt strategies to manage all levels of environmental, economic, operational, and technological uncertainties caused by the pandemic to bring balance to the SCs. The impacts of the pandemic are beyond ordinary human thinking; because of this, decision-makers were puzzled to adopt any reconfigurable strategies immediately to manage the impacts of the large-scale disruptions (Li et al., 2020). The task involved in SC large-scale disruption management modelling is not easy, especially when it is particularly sensitive to unexpected disruption due to the COVID-19 pandemic. The case becomes more complex when multiple disruptions, one after another, are considered. The most important task is to optimise the operational decisions, such as the plan of supply, production, inventory policy, and distribution, after the occurrence of each single or series of disruptions dynamically. Thus, developing appropriate methodologies to recover from both single and simultaneous disruptions will help decision-makers make accurate and prompt decisions during critical times.

1.2. Rationale of the research

During the pandemic, the global SCs faced severe demand fluctuation for high- and low-demand products. Suppliers failed to provide raw materials to the manufacturers in other countries; because of this, manufacturers could not ramp up the production capacity to meet the demand surge from consumers for high-demand products such as food, toilet paper, personal protective equipment, and facemask (Mehrotra et al., 2020). People panic-purchased the high-demand essential products and caused severe stockout in the super shops. In addition, the demand for low-demand luxury products such as apparel and automobiles dropped as economic activities slowed down due to lockdown and shutdown conditions. COVID-19 created severe demand disruption (Ivanov & Das, 2020). It has also imposed severe uncertainties and risks in the SCs of all industries of the world.

The sources of uncertainties in SCs can be divided into three: (i) internal organisation uncertainty, (ii) internal sources of SC uncertainties, and (iii) external sources of uncertainties (Hasani & Khosrojerdi, 2016). Environmental uncertainty refers to unpredictable changes that occur externally. These external changes cause instability in the environment of regular businesses, the degree of which is hard to understand, estimate, and make sense (Fazli-Khalaf et al., 2020). The SCs of the businesses cannot merely understand how an external environment might change, the potential impact of the changes, and what strategies they might initiate to manage the changes and make a balance within the SC networks. Environmental uncertainties consist of natural, behavioural, and goal uncertainties (Ivanov & Sokolov, 2010). Uncertainties regarding the reliability of the suppliers, variations in the choices and behaviours of consumers, the uncertain actions of the competitors, changes in the quality of the products, and volatility in inter-firm relationships are all examples of environmental uncertainties in SCs (Ang et al., 2017). As such, dynamic environments may be characterised by changes in product demand and supply, changes in consumer choices and preferences, and changes in technology (Kamalahmadi & Parast, 2017). Environmental changes should never be ignored within SC networks. In summary, major sources of environmental uncertainties within SC networks are consumers (demand), suppliers (supply), technology (infrastructure), and competitors (Li & Zobel, 2020). All these environmental uncertainties induce uncertainties in demand, supply, manufacturing process, and control within SC networks.

Internal and external economic uncertainties are major sources of uncertainties within SC networks. Changes in the inflation rate, world economic recession, and internal loss are all examples of economic uncertainties in the SCs (Açikgöz & Günay, 2020). In the global context, the global shutdown impacted by US/China trade war, Brexit, global lockdown and shutdown due to the pandemic caused by COVID-19, and the Russia-Ukraine war posed a severe economic impact on the global SCs (Fornaro & Wolf, 2020; Ivanov & Sokolov, 2013; Yaya et al., 2020). Businesses cannot control everything outside the organisations. SCs of businesses should be strategic, flexible, and dynamic in responding to external changes that might provide a timely solution.

SCs of businesses face various internal operational and technical uncertainties. Day-to-day production failure due to technical insufficiency and problems, and production failure due to operators' lack of experience, are examples of operational and technical uncertainties of SCs (Soren & Shastri, 2019). Operational and technical uncertainties may sometimes cause a capacity shortage for which the manufacturers cannot fulfil the demand surge of the consumers. This condition increases the shortage costs of the SCs (Datta et al., 2007). Manufacturers must invest more in high technology to foster the manufacturing process that may deal with operational and technical uncertainties timely.

Human thinking and decision-making uncertainties are other sources of uncertainties in SCs. Weak coordination, weak control of logistics, weak decision-making capability, lack of top management knowledge, and late top management decisions are examples of human thinking and decision-making uncertainties (Li & Zobel, 2020; Remko, 2020). In this time of artificial intelligence, human knowledge is also critical. Without the proper guidance of human intelligence, artificial intelligence in SCs may lead to disasters (Dwivedi et al., 2019). Thus, human intelligence and better decision-making capabilities are crucial to managing SC uncertainties due to large-scale disruptions. Uncertainties initiate risks, deviations, and disruptions in SCs. To mitigate SC disruptions, practitioners must understand SC uncertainties' sources.

The COVID-19 pandemic has resulted in severe environmental, economic, operational, technical, human thinking, and decision-making uncertainties and risks in SCs of all industries. As a result of the pandemic's uncertainties, supply, demand, manufacturing, logistics and supply support systems, inventory management, and many other areas have been adversely impacted. To successfully manage the large-scale disruption to SCs and ensure that SC systems continue functioning in the post-disruption era, a dynamic and targeted recovery plan is crucial; this research's significance is found in this consideration. Therefore, the following sections describe the problem statement and the overall goal and objectives of the current research to find a strategic and dynamic solution.

1.3. Problem statement and research questions

Globally, most countries implemented strict restrictions on their borders, imposed lockdowns, and closed systems inside their borders to slow the increase in COVID-19 cases. Consequently, due to this restriction, manufacturers struggled to receive raw materials from suppliers in quarantine zones (Chowdhury et al., 2021). Often, companies only have one supplier, and that supplier is based in a particular geographic location. The pandemic has adversely affected manufacturing companies with a single supplier or suppliers within quarantine zones (Chowdhury et al., 2020). Disruptions with the supply of raw materials affected manufacturing facilities. They could not increase production to meet the surge in consumer demand (Cai & Luo, 2020). Therefore, disruptions in the supply of raw materials significantly impacted the entire SC network.

Manufacturers could not increase production capacity because of disruptions in supply and demand. As a result of severe losses and debts, many industries have been forced to shut down manufacturing operations (Li et al., 2020). As the government of most countries imposed strict guidelines regarding social distancing to stop the spread of the virus, most manufacturers could not upgrade infrastructure to enable their employees to continue working. In addition, the manufacturing industry lost goodwill because it could not meet the consumers' demands for essential products (Mehrotra et al., 2020). There has been less research regarding the mitigation capabilities to normalise supply-demand disruption across the SCs during extreme disruption like the COVID-19 pandemic.

The products ordered by the consumers must be delivered promptly so SCs can eliminate backlogs of orders and associated costs. By delivering products to consumers on time, businesses can also maintain goodwill. As most countries have been in lockdown and have been closed down, two things happened in terms of transportation and delivery. First, businesses supplying high-demand and essential products had problems maintaining quick deliveries to consumers because of the low production capacities of manufacturers and strict lockdown conditions caused by an increasing COVID-19 infection rate (Guan et al., 2020; Y. Li et al., 2020). If they managed to increase the production capacity, they could not deliver the extra products to the consumers promptly due to a lack of transportation capacity (Sarmah, 2020). Secondly, the transportation and logistics support of businesses related to low-demand luxury products faced a downgrade in business because the demand for such luxury products dropped significantly. In both cases, transportation and logistics businesses faced severe disruptions, which required strategic and dynamic recovery plans to manage the disruptions (Queiroz et al., 2020).

Information related to the SC dynamics is essential in businesses based on which decision-makers decide to solve disruptions related to SCs (Govindan et al., 2020). The demand for essential products increased because of fear of lockdown due to the COVID-19 pandemic. The current global SCs of essential products struggled to obtain the information related to the exact demand of the consumers because of a lack of dynamic demand forecasting capability, technology, and infrastructure, which largely impacted the information management of the current global SCs (Ivanov, 2020c; Remko, 2020). Moreover, decision-makers could not take a timely decision to recover the SCs due to the lack of information regarding the extraordinary disruption caused by the COVID-19 pandemic.

SCs of manufacturers worldwide faced severe supply and demand disruptions throughout the pandemic caused by COVID-19. Manufacturers could not ramp up production capacity to meet the extra demand for the essential products of consumers. As a result, essential products' manufacturers faced severely increased shortage costs (Zhu et al., 2020). On the other hand, as the demand for luxury products declined, many of the manufacturers of luxury products had to limit production, which affected their revenue. During extreme lockdown cases because of community transmission of COVID-19 infections, manufacturers had to shut down their production for a while, severely affecting their SC financial conditions (Cai & Luo, 2020). Thus, large-scale disruption impacted the financial management of the global SCs extremely.

The COVID-19 pandemic has largely impacted all levels of SC networks, the impacts of which have severely downgraded the sustainability performances of the global SCs (Sharma et al., 2020). The environmental performance of the essential product manufacturers was severely affected. The essential manufacturers of personal protective equipment, such as facemasks, had to increase their production capacity to meet consumer demand (Wu et al., 2020). The government of most countries imposed strict regulations for people to wear a facemask to get rid of the COVID-19 virus as per the guideline published by the World Health Organisation (WHO) (Song & Karako, 2020). As a result, the waste of used facemasks and other personal protective equipment increased drastically, severely impacting the environment (Queiroz et al., 2020). Due to the lockdown and shutdown situation, the SCs faced increased shortage costs, and thus large-scale disruption caused by the pandemic impacted the economic performance of the SCs. Many employees lost their jobs due to the permanent shutdown of many manufacturers due to the drastic disruption and world economic recession caused by the pandemic. Thus, the social performances of the SCs of the manufacturers were impacted (Taqi et al., 2020). The reputation of most of the manufacturers was hampered as they could not ramp up their production capacity to meet the extra demand of the consumers when people panic-purchased essential products. Thus, the goodwill of the businesses was severely hampered (Chowdhury et al., 2021). In the literature, there has been less research to manage the multiple and simultaneous impacts of the COVID-19 pandemic in the SCs of almost all industries.

Considering the lack of research regarding the strategies for mitigating multiple and simultaneous impacts of the COVID-19 pandemic in the SCs, the present study aims to explore the following main research questions throughout the research:

1. What are the likely effects of large-scale disruptions caused by catastrophic events such as the COVID-19 pandemic on the SC network of essential products?
2. What strategies and dynamic plans for SC recovery can be designed to manage the impacts of large-scale disruptions on the SC network of essential products?
3. What tools, models, and methods can help SC decision-makers to assess the effectiveness of proposed strategies, select the practical strategies for moving towards resilience, and evaluate

the resilience and sustainability performances in SCs while managing large-scale SC disruptions?

The present study aims to explore a set of SC resilience, viable, and adaptation strategies for managing large-scale multiple disruptions of essential items SCs due to the COVID-19 pandemic.

1.4. Research methodology and framework

This research aims to adopt integrated methods of qualitative (literature review and case study) and quantitative (system science methods) research methods where quantitative methods are primary methods and qualitative methods are used for supporting and contextualising the quantitative research (Fearon & Laitin, 2008). Integrating qualitative and quantitative methods will support the validity and reliability of the research data and outcomes (Creswell, 2009). The methods will also enable the research to investigate particular theories, the network structure of SCs, strategies, and simulation and optimisation models using secondary and hypothetical data (Arvitrida, 2018).

To understand the strategies to manage and mitigate large-scale supply, demand, and financial shocks of SCs, and multiple and simultaneous long-term impacts caused by catastrophic events such as COVID-19, considering the behavioural dynamics of SC functions is necessary (Tan et al., 2020). Modelling the SC network is necessary to analyse the strategies and the SC behavioural aspects to recover from disruptions effectively (Tan et al., 2020). Thus, three aspects are very important while modelling SCs. Firstly, typical SC modelling defines the structure and behaviours of an SC network. Secondly, disruption modelling describes the characteristics of disruptive events. Finally, disruption management modelling assists the strategies to be tested to analyse the improvement in SCs (Behdani et al., 2019).

This research aims to model and strategise SC resilience for tackling large-scale supply, demand, and financial disruptions of essential product manufacturers and multiple and simultaneous long-term impacts caused by catastrophic events such as COVID-19 in the context of essential manufacturers. This research also evaluates the interaction between resilience and sustainability while managing large-scale SC disruptions. There are many essential products such as food, facemasks, personal protective equipment, toilet paper, and essential logistics service. This research aims to identify the relevant industry to get the data to test in the developed model to justify the proposed strategies. Thus, this research will test the proposed strategies in the SC simulation and optimisation models individually to evaluate the improvement in the SCs. This thesis integrates two types of data: secondary data, derived from academic journals and media with hypothetical data based on theoretical scenarios to minimize bias. Sensitivity analyses conducted in chapters 3 to 6 confirm the robustness and reliability of the models presented.

This research is based on several generic research processes. The research framework is illustrated in **Figure 1.1**. The generic steps of this research are discussed below.

Step 1: The research aims and objectives are identified. The research questions and objectives are discussed in detail in the previous section. A critical literature review is conducted to identify the research development and gaps on the studies of SC resilience strategies, methodologies, and theories.

Step 2: In this step, the research focuses on identifying the impacts of large-scale disruptions on SCs of essential products and identifying SC resilience, adaptation, and viable strategies from the literature to manage the disruptions.

Step 3: The next step is identifying the right strategies to mitigate macro-level supply, demand, manufacturing, information, transportation, and financial disruptions of SCs from the literature.

Step 4: In this step, the research focuses on large-scale supply, demand, financial disruptions, and multiple and simultaneous impacts on essential product manufacturers caused by catastrophic events such as COVID-19.

Step 5: In this step, the research proposes congruent strategies to mitigate supply, demand, and financial disruptions as well as multiple and simultaneous impacts caused by catastrophic events such as the COVID-19 pandemic.

Step 6: In this step, the research develops SC simulation and optimisation models by system science methods such as agent-based modelling (ABM) to build a dynamic platform of a real-life SC structure and disrupted SC structure to test the strategies.

Step 7: In this step, the research aims to simulate and optimise the model by the proposed strategies to examine the improvement in SCs using secondary and hypothetical data.

Step 8: This research then aims to observe how the proposed models and strategies improve the typical SC networks and help to recover from large-scale disruptions caused by catastrophic events such as COVID-19. The research also focuses on how resilience and sustainability interact while managing large-scale disruptions.

Step 9: This research then evaluates the proposed models and strategies in real-world case applications and proposes managerial implications.

Step 10: Finally, this research evaluates the results, recommends further research scopes, and concludes.

These 10 steps are the generic steps of this research. The main objective of this research is discussed elaborately in the following section. The research framework for the thesis is illustrated in Figure 1.1.

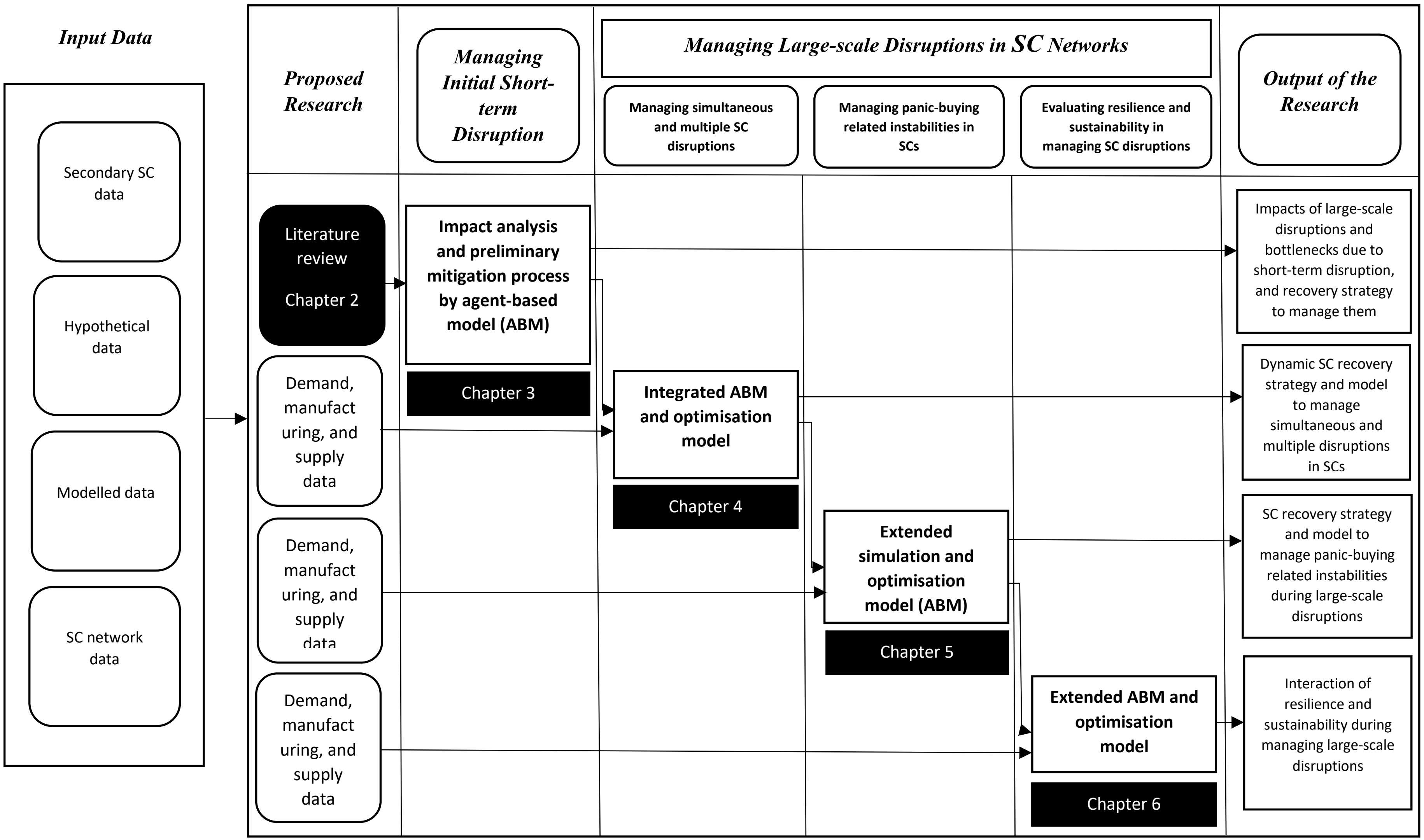

Figure 1.1: Proposed research framework

1.5. Objectives of the research

This thesis aims to develop quantitative decision support tools and reactive models to assess, manage, and mitigate disruptions within an SC due to large-scale disruptions like the COVID-19 pandemic. The tools consist of simulation and optimisation models developed by ABM techniques. A specific focus is given to the dynamic and simultaneous impacts of COVID-19 on SC networks, such as demand, supply, capacity disruption, and other multiple and simultaneous disruptions of SCs. Initially, the resilience, adaptation, and viable strategies are determined, followed by simulating and optimising the entire SC as a whole, and finally, determining the dynamic recovery plan if a system is experiencing both single and multiple disruptions on a real-time basis. Initially, the main objective was divided into five sub-objectives sequentially accomplished during this research. These sub-objectives and the steps needed to achieve them are described below.

Objective 1: Literature review on SC resilience strategies and initiatives **(Chapter 2)**.

- Study different resilience strategies and initiatives from the literature.
- Study different methodologies, tools, techniques, and theories from the literature that aid in managing SC disruptions.
- Identify the research gaps in the studies related to SC resilience initiatives and methodologies to manage large-scale SC disruptions.
- Identify the right strategies to manage single, multiple, and simultaneous long-term SC disruptions due to the large-scale SC disruption such as the COVID-19 pandemic.
- Identify the methodologies best suited to manage single, multiple, and simultaneous long-term SC disruptions due to the large-scale SC disruption such as the COVID-19 pandemic.

The following objectives are to develop various quantitative models to test the strategies to manage different levels of SC disruptions caused by large-scale disruptions.

Objective 2: An agent-based model for SC recovery in the wake of the COVID-19 pandemic **(Chapter 3)**.

- Develop an agent-based simulation model for studying the dynamic behaviour of the SCs for supply, demand, and capacity disruptions from the COVID-19 pandemic.

- Develop a solution approach to predict and solve the impacts and problems using a simulation model for managing short-term demand, supply, and capacity disruptions.
- Extend the solution approach for managing disruptions with different real-time recovery plans.
- Conduct experimental scenarios using different solution approaches to observe the best recovery plan.
- Perform sensitivity analysis.

Objective 3: Dynamic SC risk management plans for mitigating the impacts of the COVID-19 pandemic **(Chapter 4).**

- Develop a simulation and optimisation model using an ABM method by extending the previous model.
- Develop a dynamic solution approach to solve and manage the long-term multiple and simultaneous impacts of the large-scale SC disruptions by the ABM model.
- Extend the solution approach for managing multiple disruptions, parallel, or one after another disruptions as a series on a real-time basis.
- Conduct experimental studies using different disruption scenarios.
- Conduct experimental studies using different solution and recovery approaches.
- Conduct an optimisation experiment within the simulation model to optimise several parameters for the optimal solution.
- Perform sensitivity analysis.

Objective 4: A viable SC model for managing panic-buying-related challenges: Lessons learned from the COVID-19 pandemic **(Chapter 5).**

- Develop a simulation and optimisation model using an ABM method by extending the previous model.
- Develop a dynamic solution approach to solve and manage panic-buying-related instabilities in SCs by the ABM model.
- Extend the solution approach for predicting panic-buying-related impacts in SC resilience.
- Conduct experimental studies using different disruption scenarios.

- Conduct an optimisation experiment within the simulation model to optimise several parameters for the optimal solution for managing panic-buying-related instabilities.
- Perform sensitivity analysis.

Objective 5: Evaluating resilience and sustainable performance in managing large-scale SC disruptions **(Chapter 6).**

- Develop a simulation and optimisation model using an ABM method by extending the previous model.
- Develop a dynamic solution approach to solve and manage large-scale disruptions in SCs by the ABM model.
- Extend the solution approach for predicting the impacts of large-scale disruptions in SC resilience and sustainability.
- Conduct experimental studies using different disruption and solution scenarios.
- Conduct an optimisation experiment within the simulation model to optimise several parameters to obtain the optimal solution for evaluating resilience and sustainable performances in managing large-scale disruptions in SCs.
- Perform sensitivity analysis.

1.6. Contributions of the research

This research is expected to contribute to a new strand of literature on SC management, resilient and viable SC, and the studies of SC resilience strategies theoretically, empirically, and practically.

First, theoretically, this research provides a literature review on the studies of SC resilience strategies and initiatives. Second, this research is the first to critically investigate the SC resilience strategies to different levels of SC disruptions, and the methodological justification of the strategies to what extent they manage large-scale SC disruptions. Finally, this research aims to develop SC simulation and optimisation models to justify the resilience strategies in improving SCs. The newness and novel contributions of this research are summarised below.

The research has 11 theoretical, empirical, methodological, and practical contributions to the literature. The contributions of this research are summarised as follows:

Theoretical contributions (Two)

1. This research has conducted a critical literature review to identify SC resilience strategies, methodologies, and theories to support the strategies to tackle disruptions (Chapter 2). Several review papers in the past decade attempted to evaluate research on SC resilience strategies, but none reviewed the whole aspect of SC resilience strategies for preparedness, response, and recovery.
2. This research is the pioneer in strategising SC resilience, adaptation, and viable strategies for tacking large-scale supply, demand, and financial disruptions as well as simultaneous and multiple impacts of the essential manufacturers caused by catastrophic events such as COVID-19 to make the SCs resilient in the context of Australian healthcare manufacturers. This research also identified how resilience and sustainability interact while managing large-scale SC disruptions. Ali, Nagalingam and Gurd (2018) focused on SC strategies issues in the context of Australia, but they did not focus on strategising SC resilience and sustainability to tackle large-scale SC disruptions caused by catastrophic events such as the COVID-19 pandemic.

Methodological contributions (Four)

1. This research is the first that develops SC simulation models for essential product manufacturers by integrated ABM method and optimisation to justify the congruent strategies. Tan, Cai and Zhang (2020) determined and analysed strategies for SC resilience in SC networks by adopting discrete event and ABM methods. However, they did not focus on strategising SC resilience to tackle large-scale disruptions caused by catastrophic events such as COVID-19.
2. An SC simulation model by the ABM method was initially developed in Chapter 3 to predict the impacts of short-term disruptions in SCs during large-scale disruptions such as the COVID-19 pandemic. Strategies and recovery plans were implemented in the model to observe the improvement in the SCs.
3. The initial ABM simulation model was further extended, and later an integrated ABM and optimisation model was developed to predict multiple and simultaneous impacts of large-scale disruptions in SCs. Then strategies and recovery plans were implemented in the model to improve the SCs in Chapter 4. In Chapter 5, the model was further extended to observe the

impacts of panic-buying-related instabilities in SCs during large-scale disruptions. Strategies and recovery plans were also utilised in the model to observe the improvement in SCs.

4. Finally, the ABM model was further extended in Chapter 6. In this model, resilience and sustainability performances were evaluated while managing large-scale SC disruptions.

Empirical contributions (Two)

1. This research investigates the impact of large-scale multiple and simultaneous disruptions caused by catastrophic events such as the COVID-19 pandemic on SCs from literature and by developing SC simulation and optimisation models in Chapters 3–6. Chapter 3 investigates the impacts of short-term disruptions in supply, demand, and production capacity during the initial stages of large-scale disruptions in SCs. Chapter 4 investigates the impacts of multiple and simultaneous disruptions in SCs one after another during large-scale disruptions. The impacts of panic-buying-related instabilities in SCs, which is a consequence of multiple disruptions during the pandemic, have been investigated in Chapter 5. The impacts of the pandemic on the sustainability performances of SCs have been investigated in Chapter 6.
2. This research is the pioneer in investigating congruent strategies to tackle large-scale SC disruptions caused by catastrophic events such as COVID-19 for essential product manufacturers. Xu *et al.* (2020), Ivanov and Dolgui (2020), Gholami-Zanjani *et al.* (2020), Sharma *et al.* (2020), Zhu, Chou and Tsai (2020), and Ivanov (2020b) focused on strategising SC resilience to tackle large-scale disruptions caused by the COVID-19 pandemic. They focused on single disruption issues and limited strategic plans to manage them. This research focuses on managing short-term disruptions in Chapter 3, managing multiple and simultaneous impacts of the COVID-19 pandemic in Chapter 4, managing panic-buying-related instabilities in SCs in Chapter 5, and evaluating resilience and sustainability performances of SCs while managing large-scale SC disruptions in Chapter 6.

Practical contributions (Three)

1. A simulation model by the ABM method was developed in Chapter 3 to investigate the impacts of short-term disruptions in SCs. Two strategies and four recovery plans were adopted in the simulation model to observe the improvement of SCs and revealed that increasing production capacity could significantly improve the impacts of short-term disruptions in SCs of facemask manufacturers during the COVID-19 pandemic.

2. The model was further extended in Chapter 4 and was integrated with optimisation to observe the impacts of multiple and simultaneous impacts of pandemics in SCs. Four strategies and six recovery plans were tested in the model to observe the improvement in SCs. The study revealed that with increased production capacity through an optimal inventory and transportation strategy, the pandemic's multiple impacts on facemask production and delivery were reduced, leading to lower total SC costs and more product accessibility for consumers. Maintaining dynamically optimal reorder points and order sizes to minimise risks is crucial for maximising raw material supply and inventory levels. As an extended part of this research, the simulation and optimisation model in Chapter 5 investigated the impacts of panic-buying-related instabilities in SCs and revealed that increasing production in decentralised manufacturing facilities and collaborating with third-party transporters could also help alleviate the effects of panic-buying in SCs by increasing the supply of critical items to the market. Further, increasing the frequency of orders to multiple and alternative suppliers can contribute to increased raw material supplies for manufacturers.
3. Finally, in Chapter 6, the model of Chapter 5 was further extended and integrated the sustainability issues such as economic, social, and environmental performance-related aspects in the integrated ABM and optimisation model to evaluate resilience and sustainable performances in SCs while managing large-scale disruptions. The findings revealed that increased resilience in healthcare SCs improved economic and social sustainability while decreasing environmental performance during the pandemic.

With the above contributions, the research extends and makes novel contributions to making SCs resilient, adaptable, and viable. In the next section, the organisation of the whole thesis is summarised.

1.7. Organisation of the thesis

This thesis has seven chapters. The information flow and key contents of each chapter are depicted in Figure 1.2.

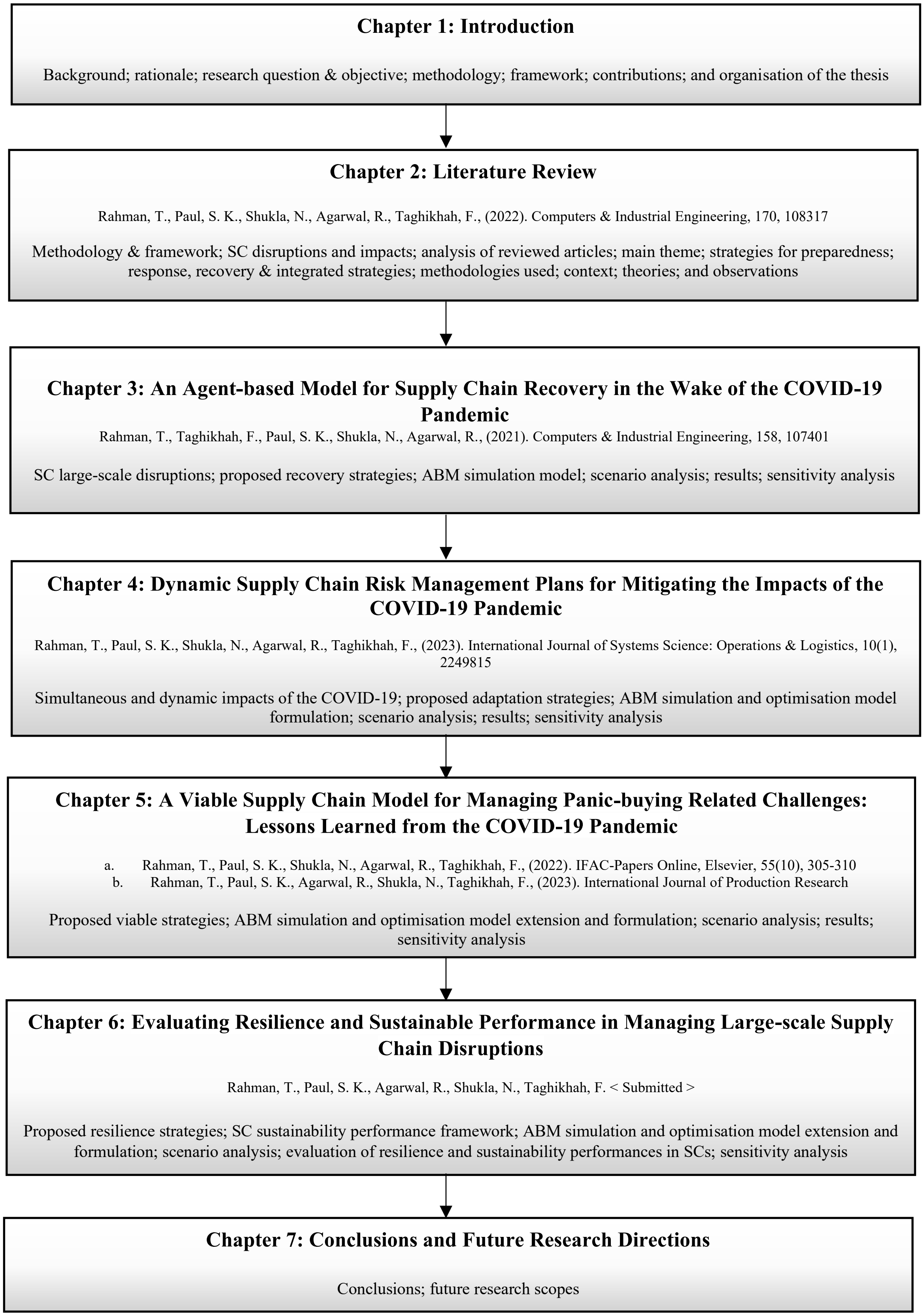

Figure 1.2: Organisation of the thesis

Chapter 2

Literature Review

Supply chain resilience (SCRES) is an emerging research area that is crucial in protecting supply chains (SCs) against small- to large-scale disruptions. Over the past few years, many researchers have focused on developing SCRES strategies that have significantly contributed to mitigating SC disruptions. While the number of papers on this subject has been gradually increasing, the absence of a literature review means that it is unclear which SCRES strategies for mitigating SC disruptions have already been studied and which issues still need to be investigated. Therefore, there is a need to conduct a literature review to provide a comprehensive overview of SCRES initiatives and strategies. For the review and synthesis in this chapter, 226 relevant articles were identified through a systematic search and selection of papers. First, the main themes of the SCRES strategies were categorised. The development of SCRES strategies for preparedness, response, and recovery aimed at mitigating SC disruptions was reviewed. Second, a detailed analysis of research developments in SCRES strategies was conducted, along with an investigation into the methodological, theoretical, and contextual justifications for tackling SC disruptions. Third, literature on SCRES strategies was synthesised for mapping and identifying potential research gaps. The analysis revealed a scarcity of simulation model-based and theoretically grounded studies to mitigate large-scale SC disruptions. Moreover, it was also found that most studies have identified SCRES strategies for low-demand luxury products, while high-demand essential products and services have been mainly ignored. Finally, based on the analysis, this article identifies research questions and future research directions for the field of SCRES research. These can guide academics and practitioners in designing and leading effective research.

2.1. Introduction

Over the past decade, various new types of disruptions have impacted manufacturing SCs. Micro disruptions, such as man-made disruptions, lead time increases, and production failures, impact day-to-day SC operations in the short-term (Chen *et al.*, 2020; Rezapour, Farahani, and Pourakbar, 2017). On the other hand, macro disruptions, such as natural disasters, epidemics, and pandemics, impact global SCs in the long term (Soni, Jain, and Kumar, 2014; Xu *et al.*, 2020; Ivanov, 2020b).

Recently, the COVID-19 pandemic has disrupted SCs globally, although the severity of this disruption is not yet fully understood post-disruption amid another global crisis caused by the Russia-Ukraine war (Ivanov, 2020b; Shih & Lin, 2022). Most manufacturing firms deal with extremely dynamic and simultaneous disruptions in supply, demand, production, inventory management, transportation, and distribution systems (Gholami-Zanjani et al., 2020). While many firms and SCs have been able to identify these issues and conduct risk assessments, most manufacturers struggle to identify appropriate SCRES strategies that allow them to recover from the disruptions caused by the COVID-19 pandemic (Zhu, Chou, and Tsai, 2020; Chowdhury *et al.*, 2021; Zalitis *et al*., 2022). Substantial research must be conducted to formulate SCRES strategies to address these interruptions and risks and to make SCs more resilient.

Many researchers have defined SCRES from different perspectives. Hohenstein *et al.* (2015) defined SCRES as an SC's preparedness for unexpected disruptions, which includes their ability to respond to and recover promptly from prospective disruptions and return to their normal state or improved state to enhance their consumer service, market share, and financial performance. Several other definitions of SCRES are listed in Table A1. Adopting appropriate resilient strategies is of utmost importance to make SCs more resilient during large-scale disruptions and post-disruptive periods (Chowdhury *et al.*, 2021). Research has previously been conducted on identifying strategies that make SCs sustainable (Bui *et al.*, 2021). Resiliency becomes vital whenever SCs are affected by large-scale disruptions like the COVID-19 pandemic (Golan *et al.*, 2020). Steps such as preparedness, responsiveness, and recovery are crucial to surviving such disruptions (Scala and Lindsay 2021). Thus, in response to the severe impact of disruptions on SCs, researchers are increasingly focusing on SCRES strategies.

Although SC risk management (SCRM) and resilience strategies have been extensively investigated in previous literature, no significant review comprehensively examines all aspects of SCRES strategies to the best of our knowledge. The recent methodological, theoretical, and contextual (geography and industry) aspects of resilience strategising have not been investigated sufficiently. Previous review articles have discussed particular aspects of SCRES strategies (Mandal, 2014; Altay & Pal, 2023). Thus far, very few review articles have attempted to identify SCRES strategies for preparedness, response, and recovery on a broad scale (Hohenstein *et al.,* 2015). Furthermore, these previous reviews lacked a comprehensive assessment of how the

SCRES strategies were justified from a methodological and theoretical perspective (Kochan and Nowicki 2018). In the literature on SCRM, previous review articles focused on the types and causes of risks, risk analysis techniques, risk-mitigation strategies, and risk-disruption modelling, but none of them addressed SCRES strategies for managing and mitigating disruptions to the best of our knowledge (Paul *et al*., 2016; Ho *et al*., 2015; Joshi *et al*., 2023). Therefore, a review of studies related to SCRES strategies is crucial to identify topics that are well understood and to highlight knowledge gaps that still exist in the literature. From the perspective of resilience, such a review can provide a concise summary of what we know, how we know it, and what needs to be done going forward to ensure that SCs can better handle the impact of external disruptions. The purpose of this literature review of this chapter is to narrow research gaps by screening and analysing the contents of all papers selected that cover the development of strategies for preparedness, response, and recovery, in conjunction with their associated methodologies, theories, and contexts. The research objectives for this literature review are as follows:

1. To identify SCRES strategies to mitigate the different aspects of SC disruptions.
2. To evaluate the methodologies, theories, and contexts used in the extant literature to present and justify the SCRES strategies.
3. To identify the gaps and future research scopes in the field of research on SCRES strategies.

Finally, the literature content is analysed to identify gaps and offer potential research directions in SCRES strategies.

To the best of our knowledge, this is the first literature review that analyses SCRES-related studies. This review has three contributions. First, it analyses SCRES strategies from the literature by categorising them into preparedness, response, and recovery strategies to mitigate SC disruptions. Second, it assesses the methodological, theoretical, and contextual bases of the justification of these strategies. Lastly, it highlights research gaps and proposes potential future research questions, which can assist the research community in identifying new opportunities regarding SCRES strategies. This article has undertaken a literature review to analyse the content of the selected articles on SCRES strategies. A review is beneficial for guiding decision-making and identifying flaws, biases, and gaps in knowledge and providing directions for future research (Chowdhury *et al.*, 2021). Hence, this review can help determine the strengths and weaknesses of resilience strategies as they relate to preparedness, response, and recovery, providing methodological, theoretical, and contextual explanations.

2.2. Analysing topics related to recent review articles

A few papers have recently reviewed the existing literature on studies related to SCRES strategies and SCRM. Using the keywords 'Supply chain', 'Risk', 'Resilience strateg*', and 'Resiliency' in Scopus, we found a few review papers that examined SCRES strategies and risk management to mitigate SC disruptions. Mandal (2014) reviewed 45 journal articles published between 2003 and 2012, which focused on SC vulnerabilities and the strategic management of such vulnerabilities. Hohenstein *et al.* (2015) reviewed 67 articles published between 2003 and 2013. They presented the definition of SCRES based on three categorisations: preparedness, response, and recovery. Various phases of SCRES, such as assessment and measurement, were also introduced in this study. Ali, Mahfouz, and Arisha (2017) utilised the citation network analysis method on 103 papers published between 2000 and 2015. They reviewed SCRES definitions and mapped its strategies under the categories of capabilities, elements, and practices. Pires Ribeiro and Barbosa-Povoa (2018) reviewed 39 peer-reviewed journal articles published between 2009 and 2016. They focused on SCRES definitions, resilience factors, and the synthesis of quantitative methods to support these factors. Kochan and Nowicki (2018) reviewed 228 papers published between 2000 and 2017, focusing on SCRES capabilities, vulnerabilities, theories, and methodologies. Hosseini, Ivanov, and Dolgui (2019) reviewed 168 articles published between 2002 and 2017, focusing on SCRES's approach in terms of analytical and mathematical modelling perspectives. Ali and Gölgeci (2019) reviewed 155 articles published between 2003 and 2018, focusing on the drivers, barriers, moderators, and mediators of SCRES, and the research methods employed in building SCRES. In a meta-analysis of extant empirical studies, Han *et al.* (2020) investigated the effects of three clusters of SC capabilities (organisational capability, SC flexibility, and SC integration) and their impact on firm resilience (proactive, reactive, or dynamic). Iftikhar *et al.* (2021) linked SCRES capabilities to performance metrics, offering a more straightforward conceptual framework to support SC management. Bier *et al*. (2020) reviewed 77 articles published between 2004 and 2018 and discussed the methods for mitigating SC disruptions, focusing on risk analysis techniques utilised in quantitative and conceptual models. Agrawal and Jain (2021) reviewed a large number of articles from the year 1996, with a focus on types of SC disruptions, SCRES strategies, and a framework for managing SC disruptions and resilience. To determine the current trends related to artificial intelligence (AI) and machine learning applications in the SC context and to identify gaps in existing research on resilience analytics, Golan *et al*. (2020) reviewed 141 articles from 2007 to 2019, also providing insight into the effects of the COVID-19 pandemic. Kamalahmadi and Parast (2016b) reviewed enterprise SCRES, in addition to the relevant principles and strategies, while Shekarian and Mellat Parast (2021) examined widely practised antecedents to strengthen SCRES. Katsaliaki *et al*. (2021) reviewed 250 articles published between 2004 and 2020, focusing on the types of disruptions, their impact, methods, and recovery strategies based on cost-benefit analysis to address disruptions. Shishodia *et al*. (2021) reviewed 771 articles from 1988 to 2020, discussing the drivers of risks, impacts, risk measurement, resilience approaches, and the quantification of SC networks.

Based on the search in Scopus, a few review papers focussed on SCRM. Though we focused on SCRES strategies, we also examined risk-management-related reviews to determine the gaps in studies related to SCRES strategies. Several review papers have discussed SCRM (Tang, 2006). In their review, Prakash *et al*. (2017) identified different types of risks and their causes in terms of SCRM. Ho *et al*. (2015) targeted risk definitions, risk types, factors, and risk mitigation strategies and methods. Kilubi (2016) reviewed the most frequently mentioned SCRM strategies and methods, specifically focusing on supply-demand-side risk sources. Paul *et al*. (2016) focused on SC risks and disruption modelling for production-inventory and SC networks, focusing on mathematical modelling to solve these issues. Vishnu *et al*. (2020) studied strategic capabilities for risk mitigation. Gurtu and Johny (2021) focused on SC risk factors in their review. Ghadge *et al*. (2012) discussed the types of risks, research methodologies, and their management approaches. Categories of SC risk related to location, scope, risk-management tools, and industry were examined by Bak (2018). Colicchia and Strozzi (2012) aimed to understand the complexity, uncertainty, practice, and tools for SCRM, in addition to the organisation of the SCRM process, SCRES, and robustness. SC disruptions, sourcing decisions, contracts and incentives, inventory, and facility locations for disruption mitigation were investigated by Snyder *et al*. (2016). Finally, Bui *et al*. (2021) identified indicators for disruption resilience and organisational ambidexterity.

Although the articles contributed significantly to the field of SCRES studies, five significant knowledge gaps are the motivations for conducting this literature review. First, each of the review papers focused on a particular issue related to SCRES strategies (summarised in Table 2.1), such as sourcing strategies (Mandal, 2014); elements and phases of SCRES strategies (Hohenstein et al., 2015); capabilities, elements, and practices of SCRES strategies (Ali, Mahfouz, and Arisha, 2017); SCRES factors (Pires Ribeiro & Barbosa-Povoa, 2018); effects of SC capabilities on firm resilience (Han *et al.*, 2020); and SCRES capabilities as performance metrics (Iftikhar *et al.*, 2021). None of these studies comprehensively covered all topics related to SCRES strategies, such as the methodological, theoretical, and contextual (geography and industry) aspects of strategising. Second, Hohenstein *et al.* (2015); Ali, Mahfouz, and Arisha (2017); and Hosseini, Ivanov, and Dolgui (2019) reviewed the elements, capabilities, and drivers of SCRES, but none of them reviewed or attempted to identify SCRES strategies for preparedness (i.e. proactive strategies), response (i.e. concurrent strategies), and recovery (i.e. reactive strategies). Third, Kochan and Nowicki (2018) and Hosseini, Ivanov, and Dolgui (2019) attempted to review the qualitative and quantitative methodologies, and the theories proposed in the literature, focusing only on SCRES capabilities and drivers. However, SCRES strategies are not justified using theories and methodologies from the literature. Fourth, most papers reviewed were published from 2000 to 2019, indicating a lack of more recent research. Finally, we found that the reviews on SC risk-management focused on the types of risks, causes of risks (Prakash *et al*., 2017), risk analysis techniques (Bier *et al*., 2020), risk-mitigation strategies (Ho *et al*., 2015), risk-disruption modelling (Paul *et al*., 2016), risk definitions (Gurtu and Johny, 2021), and complexity and uncertainty in SC risk-management (Colicchia and Strozzi, 2012). Nevertheless, these risk-management review papers did not consider the SCRES strategies to mitigate disruptions and risks. We did not find any systematic review paper on the development of SCRES strategies for preparedness, response, and recovery—along with associated methodologies, theories, and contexts—that was selected by search. Many papers have highlighted the importance of SCRES since the beginning of the COVID-19 pandemic, which has obviously been lacking in previous reviews but has significantly influenced the current review.

Table 2.1: Summary of the selected previous review articles on SCRES and SCRES strategies

Reference	**Summary**	**Year of publication**	**Timeline of publications reviewed**	**Number of papers reviewed**	**Focus area**

Colicchia and Strozzi (2012)	The literature review has closely examined SCRM and the issues emerging in this arena.	2012	1994–2010	55	Complexity, uncertainty, practice, in addition to SCRM tools, SCRM process organisation, and increased SCRES and robustness.
Ghadge *et al*. (2012)	This paper reviews the strategic changes in the SCRM field and discusses future research requirements and opportunities in SCRM.	2012	2000–2010	140	Types of risks, risk management, research methodologies, and risk management process and approaches.
Mandal (2014)	A comprehensive review of SCRES and several research issues were reported.	2014	2003–2012	45	SC vulnerabilities; strategic management of SC vulnerabilities.
Hohenstein *et al.* (2015)	This review article provided a thorough literature review of SCRES strategies in terms of preparedness, response, and recovery to the normal state.	2015	2003–2013	67	Appropriate definition of SCRES, various phases of SCRES, and assessment and measurement strategies for SCRES.
Paul *et al*. (2016)	This review presents a literature review on risk and disruption management, and models for production inventory and SC systems.	2015	Not limited	Not limited	SC risks and disruptions; modelling for production inventory and SC systems, focusing on mathematical models and the approaches used in solving these models.
Snyder *et al*. (2016)	The author has reviewed scholarly works on supply disruptions from the OR/MS literature.	2015	1994–2014	180	Evaluating supply disruptions, strategic decisions, sourcing decisions, contracts and incentives, inventory, and facility locations.
Kamalahmadi and Parast (2016b)	The article reviewed the literature on SCRES, discussed the evolution of SCRES, and examined different definitions and concepts relating to organisational resilience.	2015	2000–2015	100	Enterprise and SCRES definitions, SCRES principles, and SCRES strategies.

Kilubi (2016)	The review analyses various strategies for mitigating SC risks and proposes a framework for assessing SCRM resilience.	2016	2000–2015	86	Most frequently mentioned SCRM strategies and methods, and supply and demand side risk sources.
Ho *et al*. (2015)	The paper summarises the literature on SCRM over the past decade in a comprehensive manner.	2016	2003–2013	224	Development in SC risk definition, risk types, risk factors, and risk-mitigation strategies and methods.
Ali, Mahfouz, and Arisha (2017)	SCRES was analysed within a concept-mapping framework to seek conceptual clarity of its capabilities in this paper.	2017	2000–2015	103	SCRES definition, strategies, capabilities, elements, and practices.
Prakash *et al*. (2017)	The review article presented a risk-management-process-based classification method, content analysis, and current SC risk-management literature synthesis.	2017	2004–2014	343	Types of risks and causes of these risks.
Pires Ribeiro and Barbosa-Povoa (2018)	A systematic literature review was conducted on SCRES, focusing on analysing the formation of quantitative methods to support such decisions.	2018	2009–2016	39	Definitions of SCRES, resilience factors, and quantification of SCRES.
Kochan and Nowicki (2018)	A focused review of the SCRES literature analysing SC capabilities, their relationship to SCRES outcomes, and the concerned theoretical grounds of this relationship was presented in this paper.	2018	2000–2017	228	SCRES capabilities, vulnerabilities, and theories and methodologies.
Bak (2018)	The structured literature review evaluated the identification and development of categories that comprised the current SC risk literature and comprised the tools, location, and research methods used.	2018	1990–2015	114	Categories of SC risk related to location, scope, risk management tools, and industry.
Hosseini, Ivanov, and Dolgui (2019)	The systematic literature review identified resilience-enhancing features of SCs and	2019	2002–2017	168	SCRES approach from the analytical and mathematical modelling perspective.

	discussed analytical approaches, particularly the mathematical modelling of SCR issues.				
Ali and Gölgeci (2019)	The paper algorithmically and objectively investigated the previous literature on SCR and advanced theories by analysing new research domains.	2019	2003–2018	155	Drivers, barriers, theories, and moderators; mediators and research methods involved in forming SCR.
Bier *et al.* (2020)	The review attempted to provide an overview and categorisation of existing research on methods for mitigating SC disruptions for complex SCs.	2019	2004–2018	77	SC risk analysis techniques: quantitative and conceptual methods.
Vishnu *et al.* (2020)	The review paper presents a comprehensive and systematic literature review of strategic capabilities for mitigating SC risks.	2019	Not limited	648	Focused on strategic capabilities (flexibility, reliability, agility, resilience, robustness, agility, adaptability, and alignment) for risk mitigation.
Han *et al.* (2020)	This paper conducted a systematic literature review based on the principles of rigour, transparency, and replication required by the methodology.	2020	2003–2019	153	Measures for SCRES in the SCRES capabilities Performance Metrics Framework (SCPM) (readiness, response, and recovery).
Golan *et al.* (2020)	The review identifies emerging issues and trends related to using AI and machine learning applications in the SC context and a gap in existing research on resilience analytics of systemic threats, such as the COVID-19 pandemic.	2020	2007–2019	141	Modelling and quantifying resilience, and connecting the SC with other networks, including transportation, command, and control.
Bui *et al.* (2021)	In the study, a data-driven literature review is conducted on sustainable SC management trends in terms of ambidexterity and disruption.	2020	2008–2020	2402	Identifying indicators for disruption resilience and organisational ambidexterity.
Shekarian and Mellat Parast (2021)	An extensive literature review is conducted in the paper to assess the impact of the most widely known practices for strengthening resilience (flexibility, agility, redundancy, and	2020	2000–2017	98	Antecedents for SCRES (flexibility, agility, collaboration, redundancy, etc.).

	collaboration) on mitigating SC disruptions (demand, supply, process, control, and environmental disruptions).				
Iftikhar *et al.* (2021)	The systematic review aims to develop an in-depth theoretical framework and meta-analyses of available empirical studies on resilience, its antecedents, and firm performance.	2021	2000–2019	56	Three clusters of SC capabilities (organisational capability, SC flexibility, and SC integration) are examined in terms of the impact of firm resilience (proactive, reactive, and dynamic).
Agrawal and Jain (2021)	The paper uses a systematic literature review and data visualisation to discuss resilience strategies for SC disruptions.	2021	1996–2020	1084	Focused on types of SC disruptions (SCD) and SC resilience (SCR) strategies. A framework for SCD and SCR is proposed.
Gurtu and Johny (2021)	A review of the literature on SC risk factors in an uncertain and competitive business environment is presented in the paper.	2021	2010–2019	312	SC risk definitions, risk disruption, risk detection and mitigation, and risk management.
Katsaliaki *et al.* (2021)	The review examines recent publications in important journals on SC disruptions, and the latest developments in the field.	2021	2004–2020	250	Types of disruptions, impacts on SCs, and resilience methods in SC design and recovery strategies supported by cost-benefit analyses.
Shishodia *et al.* (2021)	The review analyses SCRES research and identifies nine important research areas, critically mapping the structural relationships between the SCRES dimensions, namely, vulnerabilities, capabilities, strategies, and performance metrics.	2021	1988–2020	771	Drivers of risks, impacts of risks, risk assessment, measuring resilience approach, resilience capabilities, quantification of SC networks, and developing robustness in SC networks.

2.3. Review methodology

This review analysed 226 journal papers selected. Figure 2.1 shows the review methodology used in this article. First, research aims were formulated to conduct the content-based review, as mentioned in Section 2.1. Second, the search criteria were identified. The keywords utilised in the search protocol were 'Supply chain OR Risk AND Resilience strateg* OR Resiliency'. Third, several academic databases, such as Google Scholar and Scopus, were used to identify and collect relevant journal articles from various publishers, including Elsevier/Science Direct, Wiley, Emerald, Taylor and Francis, Springer, IEEE, and MDPI. Only peer-reviewed journal papers written in English were selected to obtain the most relevant articles. On the contrary, book chapters, conference papers, notes, books, and thesis/dissertations were excluded from the search protocol. Fourth, inclusion and exclusion criteria were determined to filter out irrelevant articles. In terms of the inclusion criteria, titles and abstracts of the papers were scrutinised to identify those that studied one or more topics related to SCRES strategies, including SCRM, SCRES, SCRES strategies, SCRES methods, the methodological justification of SCRES strategies, and research gaps. The papers were excluded if they did not pass one of the filter (inclusion and exclusion) criteria. Fifth, after several initial and close inspections, the reference lists of the selected articles were also thoroughly scrutinised to ensure that no other relevant articles were excluded from the search. Finally, the content of each shortlisted article was carefully analysed to ensure that the articles were representative and fit into one of the contexts of the studies on SCRES strategies. This thorough investigation resulted in 226 journal articles to review.

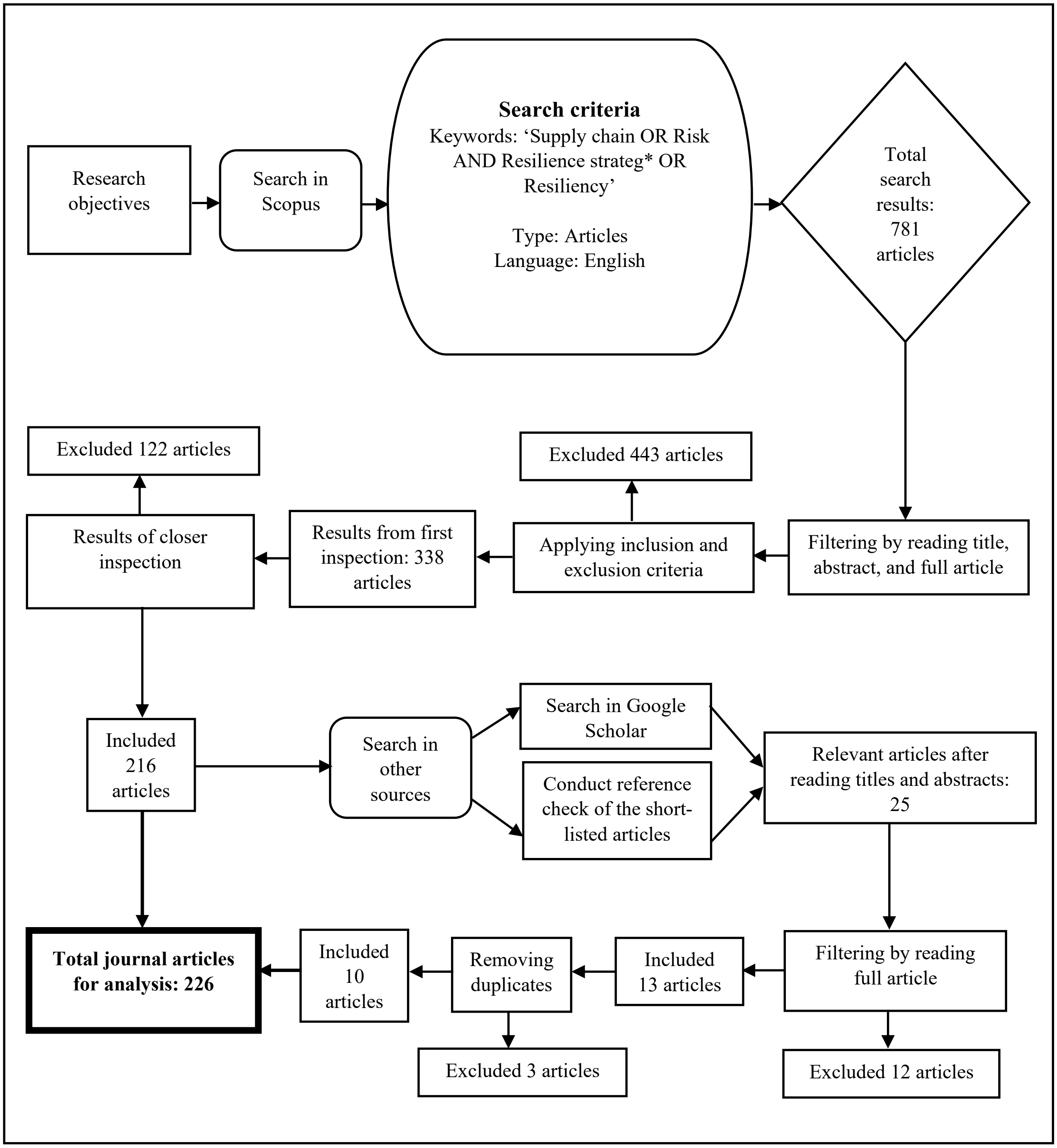

Figure 2.1: Flowchart of the review methodology

2.4. Analysing selected articles

2.4.1. Main themes in the existing research

Over the past decade, more research articles have been published on SCRES strategies, as shown in Figure 2.2. Table 2.2 lists the journal articles based on the source titles reviewed. To scrutinise these articles and to review SCRES strategies, a research framework for analysis was developed, as presented in Figure 2.3. In reviewing various research articles from the extant literature, it was found that there are three dimensions of SCRES strategies exist: preparedness (Chen et al., 2020), response (Amindoust, 2018), and recovery (Sabouhi, Pishvaee, and Jabalameli, 2018). Ali and Gölgeci (2019) defined preparedness as a proactive strategy (i.e. the ability to anticipate disruptions), responsiveness as a concurrent strategy (i.e. the ability to adapt and respond to during disruptions), and recovery as a reactive strategy (i.e. the ability to recover and learn). It was determined from the extant literature that the three dimensions of resilience strategies are formulated mainly for two levels of SCs: macro (Ivanov, 2020c) and micro (Tukamuhabwa, Stevenson, and Busby, 2017). National-level, industry-level, and network-level SCs are called macro-level SCs (Ivanov & Dolgui, 2020), whereas firm-level SCs are called micro-level SCs (Ali, Nagalingam, and Gurd, 2018; Liu, Song, and Tong, 2016). Furthermore, micro SCs can be divided into six sub-categories: supply (Chen *et al.*, 2020; Yavari and Ajalli, 2021), demand (Ni, Howell, and Sharkey, 2018), manufacturing (Leat & Revoredo-Giha, 2013), information (Papadopoulos et al., 2017), transportation (Liu & Lee, 2018), and financial (Yang & Xu, 2015) levels of SCs. SCRES strategies are mainly formulated to tackle SC disruptions in these seven layers of SCs in the extant literature. On the other hand, the impacts of disruptions are also categorised into the framework of the seven levels of SCs in the extant literature, namely, disruptions in the macro-level (Li & Zobel, 2020), supply (Soren & Shastri, 2019), demand (Fattahi, Govindan, and Keyvanshokooh, 2017), manufacturing (Leat & Revoredo-Giha, 2013), information (Papadopoulos et al., 2017), transportation (VanVactor, 2011), and financial (Yang & Xu, 2015) levels of SCs. The journal articles have been analysed and reviewed from a three-dimensional perspective, as presented in Figure 2.3, to understand the development of research and the gaps in the field of studies on SCRES strategies.

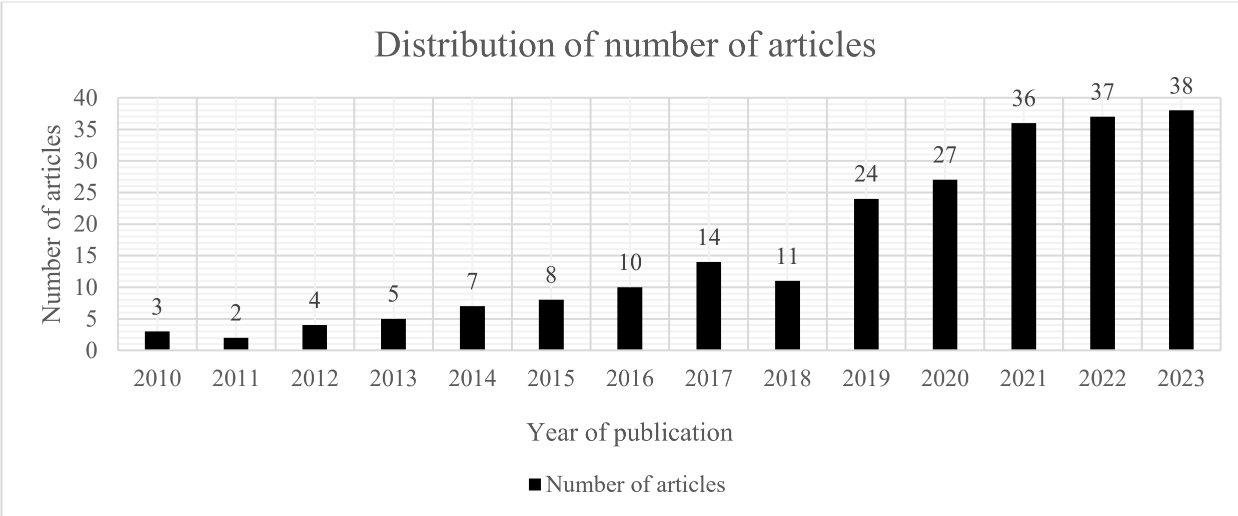

Figure 2.2: Distribution of the number of journal articles

Table 2.2: Selected lists of reviewed articles based on source titles

Selected source titles and publishers	Number of articles
International Journal of Production Research, Taylor & Francis	17
Computer and Industrial Engineering, Elsevier	16
Sustainability, MDPI	13
Supply Chain Management, Emerald	11
The International Journal of Logistics Management, Emerald	11
International Journal of Production Economics, Elsevier	9
Annals of Operations Research, Springer	8
Transportation Research Part E, Elsevier	8
International Journal of Operations & Production Management, Emerald	6
Benchmarking: An International Journal, Emerald	5
Journal of Business Research, Elsevier	5
Omega, Elsevier	5
Journal of Cleaner Production, Elsevier	5
Management Science, Informs	4
Journal of Manufacturing Technology Management, Emerald	4
Manufacturing & Service Operations Management, Informs	3
International Journal of Logistics Research and Applications, Taylor & Francis	3
Production and Operations Management, Wiley	3
European Journal of Operational Research, Elsevier	3
Sustainable Production and Consumption, Elsevier	3
Operations Management Research, Springer	3
Operations Research, Informs	2
Journal of Operations Management, Wiley	2
Journal of Industrial and Production Engineering, Taylor & Francis	2

International Journal of Management Science and Engineering Management, Taylor & Francis	2
International Journal of Information Management, Elsevier	2
Global Journal of Flexible Systems Management, Springer	2
Production Planning & Control, Taylor & Francis	2
Journal of Business Logistics, Wiley	2
International Journal of Physical Distribution & Logistics Management, Emerald	2
Technology in Society, Elsevier	2
Socio-Economic Planning Sciences, Elsevier	2
Cleaner Logistics and Supply Chain, Elsevier	2
Mathematics, MDPI	2
International Journal of Critical Infrastructure Protection, Elsevier	1
Food Control, Elsevier	1
IIE Transactions, Taylor & Francis	1
Operational Research, Springer	1
The American Review of Public Administration, Sage	1
International Journal of Systems Science, Taylor & Francis	1
British Food Journal, Emerald	1
Engineering Applications of Artificial Intelligence, Elsevier	1
Global Business Review, Sage	1
Decision science, Wiley	1
Journal of Manufacturing Systems, Elsevier	1
Technological Forecasting & Social Change, Elsevier	1
Journal of Strategic Marketing, Tylor and Francis	1
International Journal of System Assurance Engineering and Management, Springer	1
International Journal of Logistics: Research and Applications, Taylor & Francis	1
Resources, Conservation & Recycling, Elsevier	1
Measuring Business Excellence, Emerald	1
Maritime Policy & Management, Taylor and Francis	1
Management Decision, Emerald	1
Journal of Supply Chain Management, Wiley	1
Journal of Risk Research, Taylor & Francis	1
Journal of Operations Management, Elsevier	1
Journal of Modelling in Management, Emerald	1
Journal of Intelligent Manufacturing, Springer	1
International Journal of Quality & Reliability Management, Emerald	1
International Journal of Disaster Resilience in the Built Environment, Emerald	1
IISE Transactions, Taylor & Francis	1
IEEE Transactions on Engineering Management, IEEE	1
IEEE Engineering Management Review, IEEE	1
Flexible Services and Manufacturing Journal, Springer	1
Environment, Development and Sustainability, Springer	1
Energy, Elsevier	1

Energy Policy, Elsevier	1
Energy Report, Elsevier	1
Energies, MDPI	1
Journal of Business & Industrial Marketing, Emerald	1
Applied Sciences, MDPI	1
Electronic Commerce Research and Applications, Elsevier	1
Construction Innovation, Emerald	1
Computers and Chemical Engineering, Elsevier	1

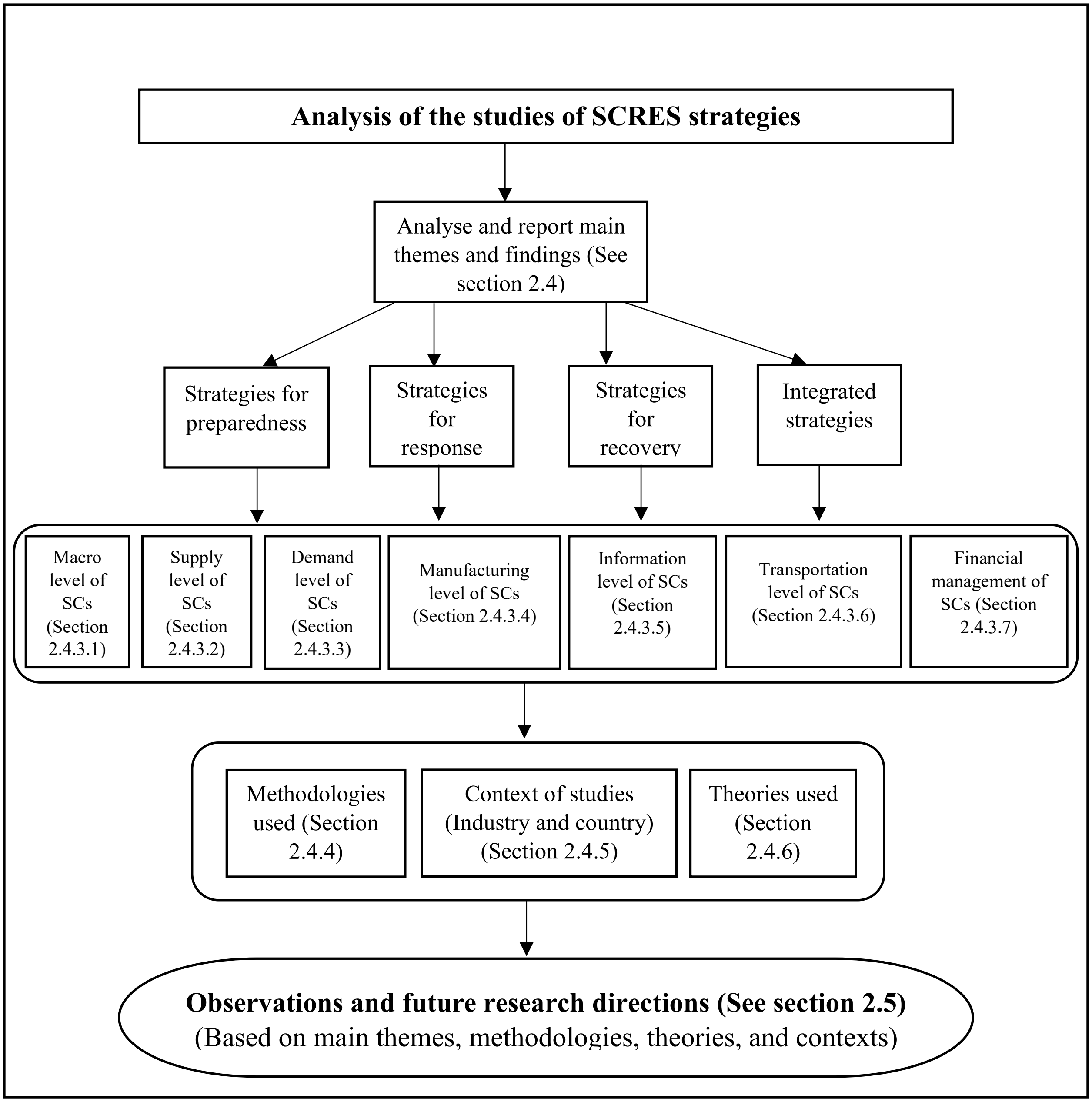

Figure 2.3: Framework of the analysis

2.4.2. SC disruptions and impacts

Several articles have described different types of disruptions related to SCs. Most studies examined low-frequency, high-impact, unpredictable, and macro- and micro-level disruptions that drastically affect SCs for an extended period, leading to global disruptions (Chen, Das, and Ivanov, 2019; Lee and Rha, 2016; Ivanov, 2020b; Mohammed *et al*., 2023). They also mentioned different types of natural disasters as macro-level disruptions, such as floods (Soren & Shastri, 2019), droughts (Soren & Shastri, 2019), tsunamis (Hosseini et al., 2019), earthquakes (Papadopoulos *et al.*, 2017; Yavari and Ajalli, 2021), fires (Sabouhi et al., 2020), volcanic eruptions (Jüttner & Maklan, 2011), hurricanes (VanVactor, 2011), climate change (Dubey *et al.*, 2019; Asada *et al*., 2023; Vicario *et al*., 2023), pandemics (Ivanov, 2020c), cyclones (Das & Lashkari, 2015), and tornados (Das & Lashkari, 2015).

Recently, a large number of articles (e.g. Xu *et al.* (2020); Ivanov and Dolgui (2020); Gholami-Zanjani *et al.* (2020); Sharma *et al.* (2020); Zhu, Chou, and Tsai (2020); Ivanov (2020b); Ivanov (2021b); Kumar and Kumar Singh (2021); van Hoek and Dobrzykowski (2021); Herold *et al*. (2021); Belhadi *et al*. (2021); Chopra *et al*. (2021); Rahman *et al*. (2021); Majumdar *et al*. (2021); Moosavi and Hosseini (2021); Shen and Sun (2021); Das *et al*. (2021); Dohale *et al*. (2021); Vecchi *et al*. (2020); and Khan *et al*. (2021)) discussed the severity of large-scale disruptions caused by the COVID-19 pandemic to global SCs. They have reported the impact of such disruptions on the macro-level of SCs. Micro-level disruptions are high-frequency, low-impact, day-to-day disruptions that hamper SCs for a short period and are predictable and can be easily recovered from (Dixit, Verma, and Tiwari, 2020). Many papers discussed different types of micro-level disruptions, such as a lack of resources (Polyviou, Croxton, and Knemeyer, 2019), product quality degradation (Ali, Nagalingam, and Gurd, 2018), pipeline failure (Ding et al., 2020), day-to-day operational disruptions (Fattahi, Govindan, and Keyvanshokooh, 2017; Arabsheybani and Arshadi Khasmeh, 2021), technological disruptions and financial constraints (Ni, Howell, and Sharkey, 2018), supplier disruptions (Lücker & Seifert, 2017), a lack of human skills (Dixit, Verma, and Tiwari, 2020), market volatility and institutional disruptions (Leat & Revoredo-Giha, 2013), demand fluctuation and process failures (Parast, 2020), inventory disruptions (Li & Zobel, 2020), production stoppages (Zahiri, Zhuang, and Mohammadi, 2017), counterfeit products (Machado, Paiva, and da Silva, 2018), unfair competition (Tukamuhabwa, Stevenson, and Busby, 2017), social conflicts and economic crises (Pereira, Christopher, and Lago Da Silva, 2014), issues with supplier-buyer relationships (Scholten & Schilder, 2015), regulatory issues (Ambulkar, Blackhurst, and Grawe, 2015), distribution center disruptions and service interruptions (Lu *et al*., 2015), and lead time and transportation delays (Azadeh et al., 2014; Abdolazimi *et al*., 2023).

Researchers have focused more on the direct and indirect impacts of micro-level disruptions on the supply side compared to the demand side of SCs. Simultaneous disruptions to supply and demand have significant impacts on all SC echelons (Soren and Shastri, 2019; Demirel *et al*., 2018; Ledwoch *et al*., 2018). The impact of disruption on manufacturing has been studied in several papers. The disruption of manufacturing processes significantly influences the supply and demand side of SCs (Soni, Jain, and Kumar, 2014; Amindoust, 2018; Hasani and Khosrojerdi, 2016; Arabsheybani and Arshadi Khasmeh, 2021). Further, transportation plays an important role in making the delivery process smooth; disruptions to this process lead to customer dissatisfaction and a loss of goodwill (Ali, Nagalingam, and Gurd, 2018; Song *et al.* 2022). Due to lockdowns, transportation restrictions, and a lack of appropriate strategies, manufacturers and retailers could not deliver their products to customers during the COVID-19 pandemic (Rahman *et al*., 2021; Bastas & Garza-Reyes, 2022). Surprisingly, few papers address these transportation disruptions (Zhen *et al*., 2016). Furthermore, information and financial management are crucial for the smooth operation of SCs (Yang and Xu, 2015; Papadopoulos *et al.*, 2017). Nevertheless, very few papers have emphasised the impact of disruptions on the information side of SCs. Further, few papers have discussed the financial management of SCs when disruptions occur. Some articles have discussed several micro- and macro-level man-made disruptions, such as labour strikes (Hosseini *et al.*, 2019; Werner *et al*., 2021), geopolitical instabilities (Asamoah, Agyei-Owusu, and Ashun, 2020), terrorist attacks (Sahu, Datta, and Mahapatra, 2016), counterfeit products (Machado, Paiva, and da Silva, 2018), industrial disputes (Aggarwal & Srivastava, 2019), cyber-attacks and intentional price hikes (Siva Kumar & Anbanandam, 2019), employee dishonesty (Tukamuhabwa, Stevenson, and Busby, 2017), and intentional fires in a plant (Dubey *et al.*, 2019). These micro- and macro-level disruptions impact all levels of SCs slightly and severely in the short- and long-term, respectively. To handle and mitigate the impact of disruptions on SCs, organisations and manufacturers need to implement SCRES strategies effectively and efficiently. Therefore, the next section will analyse the different dimensions of SCRES strategies for different levels of SCs found in the extant literature.

2.4.3. SCRES strategies

The strategies for the preparedness, response, and recovery, and integrated strategies to tackle disruptions in the macro-level, supply, demand, manufacturing, information, transportation, and financial management of SCs, are discussed in the following subsections.

2.4.3.1. Resilience strategies for the macro level of SCs

Preparedness strategies for the macro level: Among the papers that discussed strategies for preparedness, Chen *et al.* (2020); Soni, Jain, and Kumar (2014); Rajesh (2020); and Siva Kumar and Anbanandam (2020) proposed to create and establish a sense and understanding of risks, risk-management culture, and risk-sharing capabilities as robust strategies to tackle macro-level SC disruptions. However, they did not describe any methods or analytical frameworks to create such risk management and sharing capabilities, or techniques to quantify these benefits. Most researchers, such as Soni, Jain, and Kumar (2014); Pereira, Christopher, and Lago Da Silva (2014); Pettit, Croxton, and Fiksel (2013); Rajesh (2020); and Siva Kumar and Anbanandam (2020), emphasised connectedness, strategic collaboration, and collaborative activities within SC cultures, in addition to control-based SCs to make the SCs more resilient to disruptions. They argue that collaboration is an effective pre-disruption strategy to strengthen the resilience of SCs. The need to make SCs agile, sustainable, visible, adaptive, responsive, and flexible is stressed by most researchers as a general preparedness strategy (Chen *et al.*, 2020; Soni, Jain, and Kumar, 2014; Pereira, Christopher, and Lago Da Silva, 2014; Pettit, Croxton, and Fiksel, 2013; Michel-Villarreal *et al*., 2021; Majumdar *et al*., 2021; Um and Han, 2021; Nayeri *et al*., 2023; Ghanei *et al*., 2023). Rajesh (2020) focused on contingency planning, SC intelligence, continuity management, flexible and efficient postponement, and the standardisation of products for disruption preparedness. However, they did not quantify their benefits using any methodology. The importance of the postponement of products was highlighted by Dohale *et al*. (2021). In contrast, Das and Lashkari (2015) and Siva Kumar and Anbanandam (2020) argued for the formation of a task force to take initiative action as part of their strategy for pre-disruption events and developed customised training for employees to handle disruptions efficiently and effectively.

Response strategies for the macro level: Many researchers, such as Amindoust (2018); Rajesh (2019); Zainal Abidin and Ingirige (2018); and Liu and Lee (2018), emphasised cooperation, connectedness among SC partners, collaborative planning, dispersion collaboration, internal and external collaboration, and internal integration among the SC partners to respond to disruptions efficiently, whereas Rajesh (2019) focused on enhancing the level of knowledge created and shared among SC partners to make the SCs more resilient and enable them to respond to macro-level disruptions. However, none developed any analytical framework of collaborative planning for responding to macro-level disruptions effectively. Amindoust (2018) and Liu and Lee (2018) emphasised risk-reduction capabilities and risk allocation as effective strategies for responding to macro-level disruptions. Some general strategies—such as responsiveness, agility, robustness, flexibility, developing sensing capabilities, and developing visible and adaptive SCs—were suggested by other researchers, such as Amindoust (2018), Mohammed (2020), Rehman and Ali (2021), Modgil *et al*. (2021), and Zainal Abidin and Ingirige (2018). According to Kumar and Kumar Singh (2021), poor access to essential SCs is the main hindrance during disruptions such as the COVID-19 pandemic. Collaboration, sharing of information, and joint planning can aid in extending access to essential SCs for better survivability under such conditions.

Recovery strategies for the macro level: Many papers have focused on recovery strategies for SCs at the macro level. Chen, Das, and Ivanov (2019); Polyviou, Croxton, and Knemeyer (2019); Vanpoucke and Ellis (2019); Jafarnejad *et al.* (2019); and Sharma *et al.* (2020) suggested vertical and horizontal collaboration, internal collaboration, the exchange of tacit knowledge, expertise and labour, swift coordination and decision making after disruptions, and sharing risk and outcomes as effective recovery plans at the macro level. The positive side of collaboration among SC partners to recover from disruptions is further supported by Machado, Paiva, and da Silva (2018). They also suggested collaborating with international organisations and government agencies to facilitate quick recovery from the disrupted state. Some congruent recovery strategies, such as improving SC visibility, initial information analysis and decisions, emergency team formation, preventive planning and stabilisation, assessment and execution of contingency planning, and adaptive strategies, were suggested by Chen, Das, and Ivanov (2019). Vanpoucke and Ellis (2019) focused on implementing quality management programs for quick recovery. Some general recovery strategies, such as agility, robustness, building trust among actors, and building sensing capability, are suggested by Jafarnejad *et al.* (2019) and Azadeh *et al.* (2014). On the other hand, Ivanov (2020b) focused on implementing Industry 4.0 for better growth after recovery from disruptions.

Integrated strategies for the macro level: Several SCRES strategies have been suggested as integrated strategies to tackle macro-level SC disruptions, such as SC network optimisation (VanVactor, 2011); mapping SC vulnerabilities; monitoring and tracking SC performance (Gunasekaran *et al*., 2015); building social capital; increasing innovativeness (Piprani, Jaafar, and Mohezar Ali, 2020); risk hedging (Rajesh, 2020b); employing a multiskilled workforce and the cross-training of employees (Ali, Nagalingam, and Gurd, 2018; Rajesh, 2020b); lobbying and influencing constitutional changes (Hendry et al., 2019); scenario analysis and simulation (Siva Kumar & Anbanandam, 2019); building security against theft, terrorism, and infiltration (Tukamuhabwa, Stevenson, and Busby, 2017); staff training; risk emergency management; non-hierarchical communication; maintaining a culture of trust and accountability; increasing environmental and social awareness (Hsu *et al*., 2021; Peters *et al*., 2023); making SC systems more cognitive (Omer et al., 2012); shortening the SC and increasing SC visibility through a monitoring system; investing in a long-term SC continuity plan (Abe and Ye, 2013; Rajesh, 2020b); collaboration, joint planning, and coordination (Dohale *et al*., 2021; Bygballe *et al*., 2023; Gupta *et al*., 2023); fine-tuning SC design (Rajesh, 2020b); and the merging of business-to-business and business-to-consumer schemes (Zhu, Chou, and Tsai, 2020; Kent *et al*., 2022). Werner *et al*. (2021) suggested integrating resilience capabilities such as agility, collaboration, trust, flexibility, and robust SC design to make the SC more resilient. Bimpikis *et al*. (2019) emphasised the importance of forming an optimally beneficial endogenous equilibrium SC for upstream and downstream suppliers to reduce supply-side disruptions. Government support is a major factor that can help eliminate SC issues during pandemic scenarios (Das et al., 2021). Dohale *et al*. (2021) prioritised flexibility and postponement for reducing SC risks. Further, SCRES and responsiveness positively affect SC risk management performance (Can Saglam *et al*., 2020; Vali-Siar & Roghanian, 2022).

The recent COVID-19 pandemic has proven that global SCs are not resilient to most large-scale disruptions. From the literature review, it is clear that no significant research has been conducted concerning resilience strategies to mitigate large-scale SC disruptions. Vertical collaborative strategies, such as inter-firm collaboration, or horizontal collaborative strategies, such as intra-firm collaboration and collaboration with the government, may aid manufacturers in articulating rapid action to respond to global disruptions, such as COVID-19. Collaboration with government agencies and international organisations could help arrange emergency aid to help SCs recover from disruptions. A firm should focus on operational flexibility and collaboration beyond the SC when dealing with outbreaks of COVID-19 (Shen and Sun, 2021; Amoozad Mahdiraji *et al*., 2023; Di Paola *et al*., 2023). Further investigation is required to understand how and to what extent collaborative strategies can help SC practitioners alleviate large-scale disruptions' impacts.

2.4.3.2. Resilience strategies for the supply level of SCs

Preparedness strategies for the supply level: In terms of the preparedness strategies for the supply level of SCs, most articles focused on supply-side disruptions for SCRES preparedness strategising. Chen *et al.* (2020) and Pereira, Christopher, and Lago Da Silva (2014) emphasised strategic reserves, storage, and internal stock as SCRES strategies for preparedness in supply-side disruptions. However, none developed any methodological framework to quantify the benefits of strategic storage capabilities for the manufacturers. Ding *et al.* (2020); Dixit, Verma, and Tiwari (2020); Valipour Parkouhi and Safaei Ghadikolaei (2017); Aldrighetti *et al*. (2019); and Kamalahmadi *et al*. (2021) discussed new, parallel, alternative, back-up, and even multiple routes, sources, suppliers, and contracts with back-up suppliers as strong preparedness SCRES strategies to make the supply side resilient. Ding *et al.* (2020) also mentioned selecting sources and suppliers close to the manufacturing location or country as a viable strategy.

It is advantageous for manufacturers to have suppliers close to the manufacturing units or country during any disruption. Valipour Parkouhi and Safaei Ghadikolaei (2017); Pereira, Christopher, and Lago Da Silva (2014); and Pettit, Croxton, and Fiksel (2013) discussed suppliers' business continuity plans, the fortification of suppliers, strategic sourcing, flexibility in sourcing, and order fulfilment as strategies for preparedness for disruptions. Establishing a strong supply base has been stressed by Pereira, Christopher, and Lago Da Silva (2014); Rajesh (2020); and Siva Kumar and Anbanandam (2020). Pereira, Christopher, and Lago Da Silva (2014) and Thomas *et al.* (2015) emphasised strong supplier relationships and supplier collaboration to make supply-side SCs more resilient. Developing and selecting qualified and cost-effective suppliers have been stressed by Pereira, Christopher, and Lago Da Silva (2014) and Das and Lashkari (2015). Tucker *et al.* (2020) introduced the idea of 'failure to supply penalties' as a preparedness strategy to handle supply-side disruptions. However, research based on evidence is essential to quantify the benefits of penalties for suppliers who fail to supply goods and services.

Response strategies for the supply level: Some authors, such as Amindoust (2018) and Li *et al.* (2017), emphasised surplus inventory, holding back-up emergency stock at distribution centres, and storing back-up emergency stock for trans-shipment to all distribution centres as effective strategies. Other authors, such as Rajesh (2019), Sabouhi *et al.* (2020), Namdar *et al*. (2021), Sabouhi *et al*. (2021), Moosavi and Hosseini (2021), Kumar *et al*. (2014), Mu *et al*. (2021), and Razavian *et al*. (2021) emphasised contracting with back-up or alternative suppliers and multiple sourcing locations for making SCs resilient to supply-side disruptions. Rezaei *et al*. (2021) further emphasised the need for backup suppliers, increased capacity, emergency stock, and geographic separation to deal with supply interruptions. Chen, Das, and Ivanov (2019) and Amindoust (2018) focused on disruptions during the design and planning of procurement and geographical segregation of suppliers to avoid disruptions in the supply side. These strategies were suggested to make the SCs resilient to supply-side disruptions. Public procurement requires innovation, focusing on the strategic role of procurement and the importance of public-private partnerships, where both would be prioritised by public agencies if they were sophisticated buyers (Vecchi *et al*., 2020). Finding a dependable and proactive supplier will significantly improve the chances of a smooth supply (Vecchi *et al*., 2020; Kayani *et al*., 2023).

Recovery strategies for the supply level: A majority of the papers that discussed strategies for recovery focused on the supply level. Researchers such as Yang and Xu (2015); Sabouhi, Pishvaee, and Jabalameli (2018); Rezapour, Farahani, and Pourakbar (2017); Li and Zobel (2020); Jüttner and Maklan (2011); Vanpoucke and Ellis (2019); Ivanov (2020a); Sharma *et al.* (2020); Tan, Cai, and Zhang (2020); Kaviani *et al.* (2020); Ivanov (2020b); Mehrjerdi and Shafiee (2021); and Salama and McGarvey (2021) focused on contingent sourcing, backup suppliers, dual and multiple sourcing, flexible sourcing and order fulfilment, a backup subcontractor to supply products, and backup sourcing for quick recovery from supply-side disruptions. The benefits of backup and multiple suppliers are flexibility in the backup system to recover from supply-side disruptions, which is supported by Machado, Paiva, and da Silva (2018); Saghafian and Van Oyen (2012); and Zhao *et al*. (2019). Saghafian and Van Oyen (2012) further suggest that a contracted recourse option can reduce supply-side disruptions. Schmitt *et al*. (2017) proposed dynamic order-up-to policies to obtain raw materials smoothly. Jüttner and Maklan (2011) discussed that by switching to cheaper sources for supplying raw materials, SCs could accelerate production to recover from supply-side disruptions. Vanpoucke and Ellis (2019) suggested avoiding risk by discontinuing relationships with risky suppliers to avoid further supply-side disruptions. In contrast to this strategy, Chen, Das, and Ivanov (2019) suggested ranking suppliers based on their performance to identify and avoid supply-side risks. Rezapour, Farahani, and Pourakbar (2017); Vanpoucke and Ellis (2019); and Ivanov (2020a) emphasised using emergency stock from retailers, backup capacity and safety stock reserved at suppliers, and risk-mitigation inventories at distribution centers as a means to recover from supply-side disruptions. When reserved raw materials are scarce at the supplier's, retailer's, or manufacturer's end, Li and Zobel (2020) suggested preparing emergency planning to promote recovery from supply-side disruptions. Sabouhi, Pishvaee, and Jabalameli (2018) suggested providing quantity discounts to purchase raw materials. However, none of them postulated any framework for emergency sourcing and did not quantify the benefits of such strategies. Sharma *et al.* (2020) suggested that suppliers' capabilities could be improved by giving them aid, incentives, and training to supply products more smoothly. Decision-makers should favour using a variety of suppliers over monopoly sourcing to boost firm resiliency. They should aim to store more inventory in warehouses to maintain robustness and avoid supply-side interruptions (Arabsheybani and Arshadi Khasmeh, 2021). Companies should wait to place orders for unreliable suppliers until they have monitored their disruption status (Saghafian and Van Oyen, 2012). In the event that the manufacturers find the previous supplier to be unreliable, they must switch to another supplier to recover from disruptions (DuHadway *et al*., 2019).

Integrated strategies for the supply level: To make the supply side of SCs more resilient, integrated strategies provide some congruent SCRES strategies, such as providing incentives to suppliers in disruptive situations (Ni, Howell, and Sharkey, 2018), the expansion of supplier capacity, resource investment for faster supplier recovery (Hosseini et al., 2019), product flexibility through similar purchased components (Wang and Webster, 2021), collaborative supplier relationships, collaboration among franchises to exchange required materials (Pereira et al., 2020), repeated change of order allocation among existing suppliers (Kumar & Anbanandam, 2019), supplier diversification (Xu *et al.*, 2020; Abe and Ye, 2013), system approaches for inventory management (Boone et al., 2013), spot purchases (Namdar et al., 2018), flexibility in either primary or backup suppliers (Wang and Webster, 2021), having better contract terms with suppliers (Bimpikis *et al*., 2018; Gao, 2015), selecting suppliers on the basis of risk criteria rather than on pure cost minimisation (Abe and Ye, 2013), strengthening supply bases, flexible supply contracts (Rajesh, 2020b; Dohale *et al*., 2021), and establishing bonded warehouses (Colicchia, Dallari, and Melacini, 2010). Yavari and Ajalli (2021) advocated a new mitigation strategy: coalitions with other suppliers considering both environmental impacts and economic objectives to resolve supply shortages. Multiple sourcing may slightly improve the downstream SC performance (Yavari and Ajalli, 2021). Demirel *et al*. (2018) suggested contingent supplier pricing, flexible sourcing, penalties for delayed deliveries, keeping back-up suppliers, and a commitment to sole sourcing to reduce supply disruptions. When each supplier announces a single (wholesale) price, a conflict of incentives will occur, and this scenario is not realistic in most real-world settings (Li et al., 2022). A contingent-pricing game reflects a more intuitive practical relationship (Demirel *et al*., 2018). Ledwoch *et al*. (2018) suggested that inventory mitigation increases the fill rate more than contingent rerouting, regardless of the network topology, and applying inventory mitigation to the most disrupted suppliers is only effective when the network suffers frequent interruptions. In the case of random capacity uncertainty, Wang *et al*. (2010) suggest improving suppliers' reliability as supplier cost heterogeneity increases, while dual sourcing is favoured if reliability heterogeneity is high. If suppliers are unreliable and/or capacity is low compared to the demand, a combined strategy (improvement and dual sourcing) can provide significant value (Wang et al., 2010). The importance of dual sourcing and suppliers' process improvements is further backed by Tang *et al*. (2014), who found that direct buyer investment in suppliers' improvement efforts was superior to indirect incentives, and dual sourcing might give the buyer a higher profit at the same wholesale price. Thus, using dual sourcing and appropriate inventory management through optimal order quantities can reduce raw-material supply disruptions significantly (Iakovou *et al*., 2010).

An uninterrupted supply of raw materials from the suppliers to the manufacturers is critical to sustain SC networks. During the recent global pandemic, global manufacturers faced severe supply failures due to lockdowns, shutdowns, and border closures. This showcased the drawbacks of having a single supplier from a single geographical location. Diversifying suppliers can be a game-changer in elevating such supply disruptions. Some other SC re-structuring strategies, such as re-shoring, back-shoring, near-shoring, and localising, have been suggested by several researchers, but the benefits and other consequences of such re-structuring strategies are yet to be investigated (Belhadi *et al*., 2021; Alikhani *et al*., 2023; Yılmaz *et al*., 2023).

2.4.3.3. Resilience strategies for the demand level of SCs

Preparedness strategies for the demand level: Among the studies that discussed preparedness strategies for the demand level, Ding *et al.* (2020); Dixit, Verma, and Tiwari (2020); Tucker *et al.* (2020); Haldar *et al.* (2014); Das and Lashkari (2015); Dohale *et al*. (2021); and Sazvar *et al*. (2021) emphasised increasing national demand storage and mandatory redundancy (safety stock), holding strategic inventory and stocks for crises, and additional stock in distribution centres to better equip SCs and enable them to face any demand-side disruptions. Dong *et al*. (2018) and Macdonald *et al*. (2018) emphasise the importance of storing extra inventory to reduce shortages and losses of goodwill. Additionally, resilience-inducing investment in buffer stock is essential to improving SC performance (Macdonald *et al*., 2018; Ash *et al*., 2023). Ding *et al.* (2020) additionally mentioned reducing the dependency on foreign aid, which is an excellent approach for manufacturers to become more self-sufficient. Fazli-Khalaf *et al.* (2020) and Tucker *et al.* (2020) focus on establishing more processing facilities, decentralising manufacturing networks, and maintaining multiple suppliers. Tucker *et al.* (2020) argued the validity of increasing the prices of essential products as a preparedness strategy to tackle demand disruptions, attributing the shortage of products to the low prices of essential products. On the other hand, Pettit, Croxton, and Fiksel (2013) and Rajesh (2020) argued that forecasting the demand and anticipating the associated risks can help tackle demand disruptions. Das and Lashkari (2015) discussed taking products from other plants for strategic stock as a preparedness strategy. However, they did not quantify the benefit of pooling from other plants to justify its impact. Increasing customer interactions from the retailer perspective was stressed by Siva Kumar and Anbanandam (2020) as a means to understand the variations in demand before demand disruption occurs. Siva Kumar and Anbanandam (2020) emphasised that flexible contracts with suppliers could provide a smooth supply of products to tackle any demand disruptions. Shen and Sun (2021) suggest that an intelligent forecast platform and a smart replenishment platform can be used by SCs to mitigate demand disruption in disruptive times.

Response strategies for the demand level: Many papers have discussed SCRES strategies in response to demand-side disruptions. For example, Rajesh (2019) and Liu and Lee (2018) emphasised the importance of forecasting, effective communication, and coordination to understand customer demand and, thus, make SCs more resilient to demand disruptions. However, they did not quantify the benefits of forecasting demand. Sahu, Datta, and Mahapatra (2016) and Li *et al.* (2017) used holding strategic inventory, stocks for crises, and reserving excess capacity in the facilities to make SCs more resilient to demand-side disruptions. On the other hand, Rajesh (2019) and Li *et al.* (2017) suggested reducing the pipeline time to respond to fluctuating demand and arranging virtual stockpiling to respond to demand surges effectively. Soren and Shastri (2019) emphasised the need to consider disruptions during demand forecasting. However, they did not develop any analytical framework to integrate the disruption during demand forecasting and did not quantify the benefits of doing so. Ivanov (2021a) urged manufacturers to increase their production capacity after disruption to meet the demand for essential products. Hasani (2021) emphasised the importance of backup resources and safety stocks to respond to additional demand. Shen and Sun (2021) discussed the value of flexible support via digital platforms, coordinating with suppliers, and creating promotional offers to manage demand fluctuations. A dynamic pricing and promotion plan can ensure that more demand can be met (Sameer Kumar et al., 2014; Vann Yaroson *et al*., 2023).

Recovery strategies for the demand level: Lücker and Seifert (2017); Tan, Cai, and Zhang (2020); and Ivanov (2020b) proposed that the stock from additional risk-mitigation inventory, safety stock, or inventory buffers be used to mitigate demand as an initial recovery plan. An optimal risk-mitigation inventory can significantly help meet extra demand during disruptions (Lücker *et al*., 2019; Rujeerapaiboon *et al*., 2023). Jüttner and Maklan (2011) suggested that a quick response to unpredictable demand changes is required to recover from demand disruptions. Tan, Cai, and Zhang (2020) also discussed the benefits of expediting orders to support a swift recovery from demand disruptions. However, they did not quantify the benefits of expediting these orders. Several other researchers, such as Chen, Das, and Ivanov (2019); Sharma *et al.* (2020); and Kaviani *et al.* (2020), emphasised the importance of gathering accurate information about the demand, in addition to correct anticipation and forecasting, to understand the demand level and mitigate instances of high demand. During extreme disruptions, such as the COVID-19 pandemic, Rahman *et al*. (2021) suggested increasing production capacities.

Integrated strategies for the demand level: The following were proposed as congruent SCRES strategies for making the demand side of SCs more resilient: negotiation with customers regarding orders (Ni, Howell, and Sharkey, 2018); information sharing among internal customers and suppliers (Pereira et al., 2020); emergency cyclic and seasonal safety stock (VanVactor, 2011); inventory flexibility; responsive pricing strategies (Rajesh, 2020b); assortment planning (Sameer

Kumar et al., 2014); centralised demand (Rajesh, 2020b); optimal inventory allocation across the SCs (Gao *et al*., 2019); monitoring unethical pricing practices (Das et al., 2021); collaborative forecasting; inventory hedging (Gao, 2015); and silent product rollovers (Tukamuhabwa, Stevenson, and Busby, 2017; Rajesh, 2020b).

The surge in demand for essential products, such as food, medical equipment, and personal protective equipment (i.e. face masks), has been acute during the COVID-19 pandemic. In contrast, the demand for luxury products has declined. To the best of our knowledge, no significant research has been undertaken to determine the bottlenecks of the demand disruption during the COVID-19 pandemic; thus, research needs to be conducted to identify these bottlenecks, such as supply or production failures. Accordingly, suitable strategies to mitigate such disruptions should also be studied. More focus should also be given to understanding customer purchasing psychology/behaviours in the event of disruptions. Panic buying is a significant cause of demand surges during lockdowns and shutdowns (Rahman *et al.*, 2022). Several studies discuss panic buying but do not consider the context of SCRES; more research could be linked to operational research theories to reduce the impact of panic buying, focusing on resilience strategies.

2.4.3.4. Resilience strategies for the manufacturing level of SCs

Preparedness strategies for the manufacturing level: Many papers have focused on preparedness strategies for manufacturing disruptions. Chen *et al.* (2020); Dixit, Verma, and Tiwari (2020); and Haldar *et al.* (2014) emphasised increasing the production capacity and efficiency, increased production, overcapacity, and investing in a capacity buffer to prepare for production disruptions. Product substitution, new product development, and product flexibility have been stressed by Chen *et al.* (2020); Pereira, Christopher, and Lago Da Silva (2014); and Thomas *et al.* (2015) as viable solutions. Researchers such as Pereira, Christopher, and Lago Da Silva (2014); Pettit, Croxton, and Fiksel (2013); and Das and Lashkari (2015) discussed the introduction of redundancies concerning critical components and the importance of capacity flexibility in preparing SCs to tackle disruptions. Pereira, Christopher, and Lago Da Silva (2014); Thomas *et al.* (2015); and Das and Lashkari (2015) emphasised establishing a quality plant with improved technology, such as 3D printers and computer-aided technologies. Lean and agile production, six sigma, total productive maintenance, SC re-engineering, the elimination of functional silos, and controlled production risks have been discussed as effective preparedness strategies for manufacturing risks by several researchers, such as Thomas *et al.* (2015) and Rajesh (2020). Multiple product lines in manufacturing facilities can help prevent disruptions in production and may serve to satisfy customer demand in disruptive times (DuHadway *et al*., 2019; Hamidu *et al*., 2023).

Response strategies for the manufacturing level: Amindoust (2018); Sahu, Datta, and Mahapatra (2016); Zainal Abidin and Ingirige (2018); and Sabouhi *et al.* (2020) focused on building restorative capacity, investing in capacity buffers, and increasing the production capacity in factories as effective strategies for response. Abidin and Ingirige (2018) suggested producing outputs with minimum resources as an effective strategy to tackle production disruptions under extraordinary circumstances. Li *et al.* (2017) suggested using substitute facilities in the SC network to back up primary facilities during disruptions. The value of this strategy is unknown as the authors did not assess the benefits. Rajesh (2019) introduced a parallel process in production facilities, reflecting a concurrent process instead of a sequential one. Rajesh (2019) claimed that a parallel process reduces bottlenecks in production facilities; however, neither quantitative analysis nor applications in a case study was provided in the study. Soren and Shastri (2019) suggested considering disruption issues during the design and planning of material flow to make the SCs more resilient to manufacturing disruptions.

Recovery strategies for the manufacturing level: Lücker and Seifert (2017); Sabouhi, Pishvaee, and Jabalameli (2018); Zahiri, Zhuang, and Mohammadi (2017); and Tan, Cai, and Zhang (2020) suggested establishing a second manufacturing site and contracting with backup facilities and plants to foster the necessary production to recover from manufacturing disruptions. On the other hand, Lücker and Seifert (2017); Sabouhi, Pishvaee, and Jabalameli (2018); Jüttner and Maklan (2011); Ivanov (2020a); Azadeh *et al.* (2014); and Tan, Cai, and Zhang (2020) emphasised taking resources from a prepositioned emergency inventory at the primary site, utilising the reserved capacity of the other plants owned in neighbouring regions, and adding extra capacity at potential points to increase the production capacity following manufacturing disruptions. Ivanov (2020b) also supported using a capacity buffer to recover from disruptions. Lücker *et al.* (2019) suggested maintaining a reserve capacity to reduce manufacturing disruptions. Chen, Das, and Ivanov (2019) and Sabouhi, Pishvaee, and Jabalameli (2018) suggested expanding production capacities by initiating pilot production to recover from a crisis quickly. Machado, Paiva, and da Silva (2018) and Namdar *et al*. (2021) emphasised process and production flexibility to foster the recovery of manufacturing disruptions. Risk-sharing between manufacturers and suppliers, the optimisation of capacity and collaboration, horizontal collaboration among producers, vertical collaboration with the processor and retailer, and coordinated production ordering were stressed by Jüttner and Maklan (2011); Leat and Revoredo-Giha (2013); and Tan, Cai, and Zhang (2020) as ways to accelerate the manufacturing process and recover from disruptions more quickly. Ivanov and Rozhkov (2020) recommend coordinating production-ordering contingency policies for smooth production. Furthermore, several researchers, such as Sabouhi, Pishvaee, and Jabalameli (2018); Machado, Paiva, and da Silva (2018); Ambulkar, Blackhurst, and Grawe (2015); Kungwalsong *et al.* (2022); and Tan, Cai, and Zhang (2020), emphasised the fortification of facilities, quick SC redesign, and resource re-configuration to strengthen the manufacturing recovery processes. The reconfiguration of resources was also prioritised by Hsu *et al*. (2021), while the importance of facility fortification was further supported by Ivanov (2020b). Parast (2020); Zahiri, Zhuang, and Mohammadi (2017); Machado, Paiva, and da Silva (2018); Tan, Cai, and Zhang (2020); and Ivanov (2020b) focused on strengthening the technological aspect of manufacturing units, such as the implementation of research and development (R&D), smart manufacturing using robots, backup technologies for production to switch to another level of technology to continue production, tracking products using Radio Frequency Identification (RFID) to avoid counterfeit products, and mitigating redundant structures to accelerate the recovery processes. To fulfil extended demand, product diversification and substitution, as suggested by Ivanov (2020b), are excellent strategies to accelerate production, which allows manufacturers to recover from disruptions quickly. However, they did not quantify the benefits of product diversification and substitution through any method or case study. Van Hoek and Dobrzykowski (2021) highlighted the importance of reshoring manufacturing facilities to recover from future large-scale SC disruptions, such as COVID-19. Improving product design and equipment can reduce manufacturing disruptions (Hsu *et al.*, 2021). Further, process automation in manufacturing facilities can significantly improve production under disruptive conditions (Khan *et al*., 2021). Companies with the most advanced technological manufacturing processes suffered the least during COVID-19 (Khan *et al*., 2021).

Integrated strategies for the manufacturing level: Several SCRES strategies for the manufacturing level of SCs, such as emergency equipment purchases, annual contracts with backup facilities (Ni, Howell, and Sharkey, 2018), the flexibility to change product weight or main characteristics, product substitution (Pereira et al., 2020), semi-manufactured products, alternative bill of materials (BOMs) (Hasani & Khosrojerdi, 2016), the design of generic products, just-in-time production (Adobor & McMullen, 2018), the frequent launch of new technologies, changes to the manufacturing process and mixtures, the synchronisation of production planning with SC partners, process automation and AI (Modgil et al., 2021; Belhadi *et al.*, (2022), quality assurance (Kumar and Anbanandam, 2019; Rajesh, 2020b; Das *et al.*, 2021), the production of cheap products to capture a market quickly (Dubey *et al.*, 2019), flexible supply contracts and manufacturing processes (Rajesh, 2021), back-up production systems (Peng *et al.*, 2021), manufacturing and capacity flexibility, agile operation (Rajesh, 2020b), production and support linking (Hsu *et al.*, 2021), and the diversification of production plants in countries near the source as a plus-one theory (Zhu, Chou, and Tsai, 2020), were commonly suggested in the integrated strategies to make the manufacturing side of SCs more resilient.

During large-scale disruptions such as COVID-19, manufacturers of essential products faced severe supply failures. Owing to this, manufacturers could not ramp up their production capacity to meet the extra demand. Many researchers suggest collaborating with similar manufacturers to share resources, planning for an emergency supply of raw materials, collaborating with government agencies to provide incentives, and diversifying manufacturing facilities to increase their production capacity. Investigations are yet to be conducted to identify the benefits and consequences of such strategies to manage manufacturing disruptions during large-scale disruptions.

2.4.3.5. Resilience strategies for the information level of SCs

Preparedness strategies for the information level: Few papers have discussed preparedness strategies to address information disruptions. Soni, Jain, and Kumar (2014); Pereira, Christopher, and Lago Da Silva (2014); Siva Kumar and Anbanandam (2020); and Namdar *et al*. (2021) proposed seamless information sharing as an effective preparedness strategy in response to disruptions. Making the SCs visible and transparent by investing in ICTs (i.e. blockchain technology and digital technologies) was stressed by Pettit, Croxton, and Fiksel (2013); Siva Kumar and Anbanandam (2020); Lohmer *et al*. (2020); (Furstenau *et al*., 2022); and Michel-Villarreal *et al*. (2021). Shen and Sun (2021) and Ambrogio *et al.* (2022) suggested intelligent investments in digital technologies to improve the information technology (IT) sector of SCs. Khan *et al*. (2021) emphasised blockchain technology's importance in reducing information-related disruptions in SCs.

Response strategies for the information level: Rajesh (2016) suggested predicting SC performance using big data to assess SC indicators, such as flexibility, responsiveness, quality, productivity, and accessibility, which could make the SCs more resilient. To make the SCs resilient to information disruptions, Rajesh (2019) also emphasised the importance of having a detailed view of SC inventories and other SC parameters. Liu and Lee (2018) emphasised information sharing to tackle any information disruptions, which is further supported by Li *et al.* (2017).

Recovery strategies for the information level: Papadopoulos *et al.* (2017); Polyviou, Croxton, and Knemeyer (2019); Machado, Paiva, and da Silva (2018); Jafarnejad *et al.* (2019); and Gruzauskas *et al*., 2023 emphasised information and knowledge sharing, big data for quality information sharing, sharing databases, and predictive capacity to make the SCs more resilient to information disruptions. Machado, Paiva, and da Silva (2018) emphasised early warning communication to recover from disruptions effectively. Azadeh *et al.* (2014) claimed that having a transparent view of upstream and downstream inventories, demand and SC conditions, and production and purchasing schedules makes the SCs of manufacturers more resilient to disruptions. Sharma *et al.* (2020) and Ivanov (2020b) discussed that digital data-driven SCs (Tseng *et al*., 2022; Ahmed *et al*., 2023; Kumar *et al*., 2023), big data (Bag *et al.,* 2022; Hsu *et al.*, 2022; Alhalalmeh, 2022), Internet of Things (IoT) (Njomane & Telukdarie, 2022), data analytics, and blockchains (Li *et al.,* 2022; Alabaddi *et al*., 2023; Kazancoglu *et al*., 2023) make SCs more resilient, such that the manufacturers can receive correct and timely information, enabling them to recover from disruptions efficiently.

Integrated strategies for the information level: To make the SCs resilient to information disruptions, several strategies, such as sharing operational information with key suppliers and customers, implementing an integrated database in internal SCs (Chunsheng et al., 2019; Li *et al*., 2023), using big data analytics (Singh and Singh, 2019; Vergara *et al*., 2023) or business data analytics (Khan *et al*., 2021), frequent information exchange with customers (Siva Kumar & Anbanandam, 2019), and enhancing vertical information processing capacity (Dubey, Gunasekaran, Childe, Fosso Wamba, et al., 2019), have been suggested in different research papers.

SCs face severe supply, demand, and production capacity disruptions during large-scale disruptions. A substantial amount of information or data related to supply, demand, and capacity is required to mitigate these disruptions. The literature lacks insight into formulating frameworks and identifying strategies to mitigate SC disruptions by big data.

2.4.3.6. Resilience strategies for the transportation level of SCs

Preparedness strategies for the transportation level: Few papers have focused on preparedness strategies for transportation disruption. A quick response to delivery delays and reductions in non-value-adding time were the strategies studied by Pereira, Christopher, and Lago Da Silva (2014); Rajesh (2020); and Haldar *et al.* (2014). Ding *et al.* (2020) emphasised establishing backup routes for a smooth delivery process, which can prevent transportation disruptions. However, they did not quantify the benefit of alternative routes. Moreover, Shen and Sun (2021) suggest integrating distributed network optimisation systems with SCs to prevent transportation disruptions. It is important to choose reliable distribution centers and hold extra inventory at the distribution centres to avoid transportation-related delivery disruptions (Taleizadeh *et al*., 2020). Furthermore, hedging the location of a distribution centre or warehouse will safeguard transportation and distribution in the event of a disruption (Sameer Kumar et al., 2014). Kumar *et al*. (2014) recommended multimodal transportation, multicarrier transportation, and multiple routes to avoid transportation-related disruptions.

Response strategies for the transportation level: Establishing a more fortified warehouse close to the customer zones was suggested by Fattahi, Govindan, and Keyvanshokooh (2017) to make the transportation side of SCs more resilient. Liu and Lee (2018) emphasised internal and external logistics collaboration to respond to transportation disruptions. Scala and Lindsay (2021) also supported that collaboration is a key mechanism for SCRES during any large-scale disruption, such as the COVID-19 pandemic. Other researchers, such as Amindoust (2018); Liu, Song, and Tong (2016); and Sabouhi *et al.* (2020), emphasised several SCRES strategies as a response, such as rerouting, virtual trans-shipment, multiple transport routes, lateral trans-shipment between distribution centres, and allowing the direct shipment of products from factories to customers, to make SCs more resilient. Herold et al. (2021) stressed operational flexibility, digitisation, data management, and the optimisation of logistics infrastructure and personnel capacity to respond to transport disruptions. When pandemic-like disruptions occur, Zhang *et al*. (2021) and Chopra *et al*. (2021) recommend using omni-channels to ensure smooth consumer delivery. Shen and Sun (2021) suggested redistributing the logistics network and modifying the last-mile delivery process to address transportation and delivery instabilities.

Recovery strategies for the transportation level: Very few papers discussed strategies for recovery to mitigate transportation disruptions. Establishing new primary and local or regional distribution centres, in addition to establishing smart warehouses, were strategies suggested by Zahiri, Zhuang, and Mohammadi (2017); Jüttner and Maklan (2011); and Ivanov (2020b) to make the transportation side more resilient in the event of disruptions. Machado, Paiva, and da Silva (2018) emphasised the flexibility of distribution channels to promote a quick recovery from transportation disruptions. In this light, Sharma *et al.* (2020) and Tan, Cai, and Zhang (2020) emphasised just-in-time delivery and trans-shipment; however, they did not quantify the benefits of these methods. Further, backup transportation reduces the loss of profit, thereby leading to less pressure on the distribution centre's transportation recovery (Zhen *et al*., 2016; Xu *et al*., 2023).

Integrated strategies for the transportation level: Several SCRES strategies for the transportation level of SCs have been suggested by researchers, such as using air transport, flexibility to change delivery routes (Pereira et al., 2020), excess capacity in transport, changing the delivery mode (Siva Kumar & Anbanandam, 2019), and the use of multiport and a mixture of sea and air freight for maritime transportation (Colicchia, Dallari, and Melacini, 2010). The importance of logistics flexibility is supported by Rajesh (2020b). The consequences of ignoring disruption correlation could be significant losses in key factors, such as source disaster probabilities, disruption propagation effects, and service interruption penalties (Lu *et al*., 2015). Accordingly, Lu *et al*. (2015) suggest developing a distributionally robust, reliable facility location for distribution centres to ensure a better delivery support system. Multiple distribution channels can reduce risks in the delivery support system (Abe and Ye, 2013) while optimising transportation modes and routes can significantly reduce delivery disruptions (Hsu *et al*., 2021; Kogler & Rauch, 2023).

During large-scale disruptions, such as those seen during the COVID-19 pandemic, SCs faced severe supply-demand disruptions (Frieske & Stieler, 2022; Alva Ferrari *et al*., 2023). The surge in demand for essential products requires extra delivery options to meet consumers' demands. The literature lacks insight into the benefits and consequences of resilience strategies, such as diversifying delivery options, increasing transportation, and collaboration between transporters to meet the extra demand of consumers. To what extent diversifying transportation modes and collaboration between transporters help meet the additional demand of consumers during large-scale SC disruptions is a potential future research direction.

2.4.3.7. Resilience strategies for the financial management of SCs

Preparedness strategies for the financial level: Only a few papers have emphasised preparedness for the financial disruption of SCs. Soni, Jain, and Kumar (2014) focused on revenue sharing as a preparedness strategy to tackle any future financial disruptions. Pereira, Christopher, and Lago Da Silva (2014) and Pettit, Croxton, and Fiksel (2013) stressed the importance of establishing financial strength and security. Regularly checking the market position can be a good preparedness strategy to prevent future financial disruptions (Pettit, Croxton, and Fiksel, 2013; Phan *et al*., 2023; Juan & Li, 2023). Serpa and Krishnan (2017) suggested that business insurance policies and contractual incentives will reduce financial shocks in the long run. By reducing the problems created by free-rider companies, insurance can increase the efficiency of risk management efforts, guarding SCs against adverse financial consequences (Dong *et al*., 2018; Aldrighetti *et al*., 2023).

Response strategies for the financial level: Zainal Abidin and Ingirige (2018) studied resilience strategies (response strategies) at the financial level using their knowledge of market positions to secure the financial strength of SCs.

Recovery strategies for the financial level: Few papers have discussed recovery strategies to mitigate SC's financial disruptions. Yang and Xu (2015) suggested that companies seek government aid to recover from financial disruptions. Papadopoulos *et al.* (2017) emphasised building public-private partnerships (PPPs) to foster the recovery processes. Ivanov (2020b) and Abe and Ye (2013) also supported PPPs, suggesting the benefits of a business-government collaboration to accelerate the recovery process. Several other recovery strategies, such as securing and checking the market position, building financial strength, and reserving liquidity, have been suggested by Kaviani *et al.* (2020) and Ivanov (2020b) to strengthen the recovery processes. Zhen *et al*. (2016) suggested integrating business interruption insurance policies that cover the extra expense incurred to reduce profit loss in the event of a disruption, which could be seen as an incentive to restore services.

Integrated strategies for the financial level: Revenue sharing among SC partners (Siva Kumar & Anbanandam, 2019) was emphasised to make the financial side of SCs more resilient. Dong and Tomlin (2012) proposed integrating business interruption insurance coverage into the SC structure to reduce financial shocks during disruptions. The inventory value can be increased by insurance, reducing financial shocks by increasing the value of emergency sourcing overall. Insurance becomes more valuable when disruptions are rare (Dong and Tomlin, 2012; Rajesh, 2020b) while also boosting the SC partners' confidence, allowing them to launch new product developments while the market remains buoyant (Rajesh, 2020b). Automating transaction systems can reduce financial disruptions (Hsu *et al*., 2021; Yang & Yin, 2023).

During large-scale disruptions, such as the COVID-19 pandemic, SCs faced severe supply, demand, and capacity disruptions. Many researchers have suggested revenue sharing and PPPs as options to alleviate the financial disruptions of SC networks. However, the literature fails to identify the challenges of implementing such strategies to alleviate the financial disruptions of SCs during large-scale disruptions.

A consolidated summary of the SCRES strategies derived from the reviewed articles is presented in Table A2.

2.4.4. Methodologies used

Following the analysis of the 226 selected papers, the papers were divided into two types: (i) quantitative and (ii) qualitative. The summaries of the quantitative and qualitative methods are presented in Tables 2.3–2.5 to justify the SCRES strategies from the literature.

Quantitative methods (individual): The reviewed papers used different types of individual analytical and empirical quantitative methods.

Analytical methods (individual): Several papers used mathematical modelling and optimisation methods. Soren and Shastri (2019) used a multi-objective optimisation model to reduce the total SC cost by mitigating shortfalls in production. They argued the merits of considering disruptions during production and procurement planning. Yang and Xu (2015) tried to mitigate supply disruption using a backup supplier in a multi-objective mathematical modelling method. Fattahi, Govindan, and Keyvanshokooh (2017) and Ade Irawan *et al.* (2022) analysed meeting customer demands and reducing lead times, while Tucker *et al.* (2020) analysed reducing product shortages; both used a multi-stage stochastic programming method to justify their analyses. On the other hand, Ni, Howell, and Sharkey (2018) investigated how unmet demand affects customers, and Namdar *et al.* (2018) and Kamalahmadi *et al*. (2021) analysed sourcing strategies to achieve SCRES by using a two-stage stochastic programming model. Using a stochastic programming approach, Peng *et al*. (2021) evaluated the resilience of a physical internet-enabled integrated production-inventory-distribution system under various disruption risks.

By establishing a sub-chain of nodes from the same region, Salama and McGarvey (2021) maximised SC profit using a stochastic mixed-integer linear programming model in a pandemic setting. Sazvar *et al*. (2021) and Sabouhi *et al*. (2021) used a multi-objective mathematical and optimisation model, while Razavian *et al*. (2021) used a two-stage stochastic programming model to design resilient, sustainable SC models, revealing that resilience improves SC performance and reduces total costs. Other researchers, such as Lücker and Seifert (2017), attempted to reduce product shortages using an operational metric mathematical modelling method. To mitigate upstream automobile supply disruption, which affects the downstream, Rezapour, Farahani, and Pourakbar (2017) utilised a mixed-integer non-linear method to justify the analysis. Gholami-Zanjani *et al.* (2020) researched mitigating supply and demand disruptions through appropriate location allocation and inventory replenishment, and they quantified the analysis using two-stage mixed-integer mathematical modelling. Fazli-Khalaf *et al.* (2020) tried to maximise the coverage of customer demand by using a mixed fuzzy possibilistic flexible programming method.

On the other hand, to mitigate demand disruptions, Liu, Song, and Tong (2016) proposed a virtual stockpile pooling system to manage emergency stock, and quantified and justified the strategy by using a multi-location stochastic inventory model. Das and Lashkari (2015) proposed risk-readiness strategies for production and transportation, justifying them using a mixed-integer programming model. Moreover, Yavari and Ajalli (2021) explored a green-resilient SC network design by introducing a new concept of 'coalition' between suppliers in a bi-objective mixed-integer linear program to reduce the total cost and carbon emissions. Dong and Tomlin (2012) investigated business interruption insurance, inventory management, and emergency sourcing strategies to manage disruption risks using a mathematical endogenous insurance pricing model. Zhen *et al*. (2016) also presented a mathematical and optimisation model to justify business interruption insurance and backup transportation strategies to reduce financial losses in SCs. Serpa and Krishnan (2017) developed another mathematical model to describe the importance of business insurance and contractual incentives for financial liabilities. Additionally, Dong *et al*. (2018) proposed another mathematical and optimisation model to examine inventory, preparedness, and insurance in a two-stage production chain that may be affected by disruptions upstream or downstream. Lu *et al*. (2015) presented a model for correlated disruptions with uncertain joint distributions, using distributionally robust optimisation to minimise the expected cost under the worst-case distribution with marginal disruption probabilities. Demirel *et al*. (2018) designed a mathematical and optimisation model to evaluate the costs and benefits of flexible sourcing. Bimpikis *et al*. (2019) presented a mathematical and optimisation model for analysing endogenous SC networks and structures that maximise profits for suppliers and downstream retailers. Wang *et al*. (2010) developed a mathematical and optimisation model to examine two mitigation strategies—dual sourcing and process improvement—in SC networks. Tang *et al*. (2014) presented a series of mathematical models that shed light on how buyers and suppliers can mitigate disruption risks in a decentralised setting. Wang and Webster (2021) developed a normative model to separately examine the importance of flexibility with primary and backup suppliers. Bimpikis *et al*. (2018) constructed a mathematical model to investigate the sourcing decisions of firms. Gao (2015) studied dynamic risk-management in SCs by first capturing demand volatility through a Markov model and then introducing it into dynamic programming for inventory hedging. Iakovou *et al*. (2010) proposed a single period stochastic inventory decision-making model to trade-off inventory policies and disruption risk management for an unreliable dual-sourcing supply network. Lücker *et al*. (2019) developed a mathematical model to analyse optimal inventory and reserve capacity decisions. Saghafian and Van Oyen (2012) developed a quantitative methodology using the 'Newsvendor' model to quantify the value of using a secondary flexible backup supplier.

Several papers used individual simulation methods to justify different SCRES strategies among other analytical methods. Chen *et al.* (2020) analysed the resiliency of oil imports under shock using a system-dynamics simulation. On the other hand, a discrete-event simulation method was used by Ivanov (2020a) to investigate the structural and operational vulnerabilities in securing the demand and inventory side of SCs. Ivanov (2021a) also used the discrete-event simulation method to study the impact of the COVID-19 pandemic on SCs and identify strategies to improve SCs. Macdonald *et al*. (2018) employed another discrete-event simulation to clarify how disruptions affect the performance of SCs. Other simulation-based frameworks were used by Colicchia, Dallari, and Melacini (2010) to make the inbound SCs resilient by analysing the phenomena of the distance between the source and final market, in addition to their uncertainty in lead time and delivery. Rahman *et al*. (2021) developed an agent-based simulation model to predict and manage the COVID-19 pandemic's effects. To measure SCRES, Moosavi and Hosseini (2021), Schmitt *et al.* (2017), Aldrighetti *et al*. (2019), and Lohmer *et al*. (2020) employed different simulation models, including agent-based and discrete-event modelling. Ledwoch *et al*. (2018) developed an agent-based simulation model to explore the link between the topological characteristics of supply networks and their ability to recover through inventory mitigation and contingent rerouting strategies. In addition, Zhao *et al*. (2019) developed an agent-based simulation model to demonstrate how firms' adaptive behaviours can leverage the competitive relationship within a SC network. Mu *et al*. (2021) used a Monte Carlo simulation to assess food-safety resilience. Longo *et al.* (2022) proposed a simulation-based framework for manufacturing design and resilience assessment.

Among other analytical methods, Li and Zobel (2020) adopted SC network structure analysis to determine factors in resilient SC networks to secure the supply, demand, and inventory sides of SCs. In contrast, Omer *et al.* (2012) used a networked infrastructure resiliency assessment framework to propose several schemes to improve the transportation side of SCs. Shen and Sun (2021) examined quantitative operational data to assess the impact of the COVID-19 pandemic on SCs.

Few papers used classic multi-criteria decision-making models (MCDMs) and fuzzy methods to justify different SCRES strategies. Piprani, Jaafar, and Mohezar Ali (2020) used an analytical hierarchy process (AHP) to assess and prioritise SCRES capabilities. Aggarwal and Srivastava (2019) used the Grey-based DEMATEL model to explore the benefits of collaboration in SCs to recover from disruptions. To understand the resilience level of industries, Kumar and Anbanandam (2019) adopted the Delphi-fuzzy logic approach. To improve and rank the SCRES factors, Shin and Park (2019) used an interpretive structural model (ISM). Majumdar *et al*. (2021) prioritised risk-mitigation strategies for environmentally sustainable clothing SCs using fuzzy TOPSIS. Dohale *et al*. (2021) used fuzzy AHP to evaluate risk-mitigation strategies to overcome prominent SC risks.

Researchers have also used some other individual analytical methods. Rajesh (2016) and Qi *et al.* (2022) used Grey's prediction method to analyse and predict firm resiliency from secondary data to make the supply and manufacturing sides more resilient. Sharma *et al.* (2020) used a step-wise weight assessment ratio analysis (SWARA) method to analyse factors for increasing resiliency in SCs during and after COVID-19 regarding supplier-buyer relationships. Rajesh (2020) used advanced analysis of Grey incidences to understand, measure, and improve SCRES.

Empirical methods (individual): Among individual quantitative methods, some papers used different empirical quantitative methods.

Among them, Liu and Lee (2018) used partial least squares structural equation modelling (PLS-SEM) to analyse logistics resilience strategies. On the other hand, Dubey *et al.* (2019) also used PLS-SEM to analyse the role of data analytics in improving SCRES. Saglam *et al*. (2020) examined the relationship between proactive risk-mitigation strategies of SC flexibility, resilience, and responsiveness by using PLS-SEM. Vanpoucke and Ellis (2019) used structural equation modelling (SEM) to analyse supply-side risk-mitigation strategies. Similarly, Chunsheng *et al.* (2019) used this method (SEM) to analyse the benefits of internal and external integration in SCs to enhance SCRES by implementing risk-management culture and flexibility. Lee and Rha (2016) also adopted SEM to analyse building SCRES using dynamic capabilities. On the other hand, Ambulkar, Blackhurst, and Grawe (2015) used SEM to analyse factors in SCRES. Um and Han (2021) used the SEM method to examine the relationships between global SC risks, SCRES, and mitigation strategies. Singh and Singh (2019) used covariance-based structural equation modelling (CB-SEM) to address how firms can build resilient SCs by improving their data analytics capabilities. Khan *et al*. (2021) also investigated the effectiveness of business data analytics (BDA) and technological innovation (TI) on a firm's performance during COVID-19 by using CB-SEM.

Researchers have used some other statistical empirical methods. Asamoah, Agyei-Owusu, and Ashun (2020) used exploratory factor analysis to interpret the relationship between social network relations, SCRES, and customer-oriented performance. Hierarchical regression analysis was used by Dubey *et al.* (2019) to analyse SCRES in terms of behavioural aspects. Other empirical quantitative methods, such as longitudinal field studies, were used by Boone *et al.* (2013) to analyse the SCRES strategies and improve inventory management. On the other hand, Kaviani *et al.* (2020) utilised fuzzy hypothesis tests to evaluate SCRES by assessing SC vulnerabilities and capabilities in the automotive sector. A synopsis of individual quantitative methods is presented in Table 2.3.

Table 2.3: Synopsis of individual quantitative methods

Individual quantitative methods	References
1. Analytical methods	
Mathematical programming	
Mathematical and optimisation model	Soren and Shastri (2019), Yang and Xu (2015), Sazvar *et al*. (2021), Sabouhi *et al*. (2021), Dong and Tomlin (2012), Zhen *et al*. (2016), Serpa and Krishnan (2017), Dong *et al*. (2018), Lu *et al.* (2015), Demirel *et al*. (2018), Bimpikis *et al*. (2019), Wang *et al*. (2010), Tang *et al*. (2014), Wang and Webster (2021), Bimpikis *et al*. (2018), Gao (2015), Lücker *et al*. (2019), Nayeri *et al.* (2022), Z. Li *et al.* (2022), Kungwalsong *et al.* (2022), Ade Irawan *et al.* (2022), Alikhani *et al.* (2023), Aldrighetti *et al.* (2023), Li *et al.* (2023), Rujeerapaiboon *et al.* (2023), Ghanei *et al.* (2023), Yılmaz *et al.* (2023)
Multi-stage stochastic programming	Fattahi, Govindan, and Keyvanshokooh (2017), Tucker *et al.* (2020), Salama and McGarvey (2021)
Two-stage stochastic programming model	Ni, Howell, and Sharkey (2018), Namdar *et al.* (2018), Peng *et al*. (2021), Razavian *et al*. (2021)
Operational matric mathematical modelling	Lücker and Seifert (2017)
Mixed-integer non-linear method	Rezapour, Farahani, and Pourakbar (2017)
Two-stage mixed-integer mathematical model	Gholami-Zanjani *et al.* (2020), Kamalahmadi *et al*. (2021)
Mixed-fuzzy possibilistic flexible programming method	Fazli-Khalaf *et al.* (2020)
Multi-location stochastic inventory model	Liu, Song, and Tong (2016)
Mixed-integer programming model	Das and Lashkari (2015)
Bi-objective mixed-integer linear programming model	Yavari and Ajalli (2021)
Single-period stochastic inventory decision-making model	Iakovou *et al*. (2010)
Newsvendor model	Saghafian and Van Oyen (2012)
Other analytical methods	
System dynamics simulation	Chen *et al.* (2020)
Other simulation models	Schmitt *et al*. (2017), Aldrighetti *et al*. (2019), Longo *et al*. (2022), Gruzauskas *et al.* (2023)
Agent-based simulation model	Rahman *et al*. (2021), Lohmer *et al*. (2020), Ledwoch *et al*. (2018), Zhao *et al*. (2019), Rahman & Paul (2022)
Monte Carlo simulation	Mu *et al*. (2021)
SC network structure analysis	Li and Zobel (2020)
Grey's prediction method	Rajesh (2016)
Analytical hierarchy process	Piprani, Jaafar, and Mohezar Ali (2020)

Grey-based DEMATEL	Aggarwal and Srivastava (2019), Raj *et al.* (2022)
Delphi–fuzzy logic approach	Kumar and Anbanandam (2019), Tseng *et al.* (2022)
Fuzzy TOPSIS	Majumdar *et al*. (2021)
Discrete-event simulation	Ivanov (2020a), Ivanov (2021a), Moosavi and Hosseini (2021), Macdonald *et al*. (2018), K.E.K *et al*. (2022), Kogler & Rauch (2023)
Networked infrastructure resiliency assessment framework	Omer *et al.* (2012)
Simulation-based framework	Colicchia, Dallari, and Melacini (2010)
Stepwise weight assessment ratio analysis (SWARA) method	Sharma *et al.* (2020), Joshi *et al.* (2023)
Interpretive structural modelling	Shin and Park (2019), Sonar *et al*.(2022)
Advanced analysis of Grey incidences	Rajesh (2020)
Measuring quantitative operational data	Shen and Sun (2021)
Fuzzy AHP	Dohale *et al*. (2021)
2. Empirical methods	
Exploratory factor analysis	Asamoah, Agyei-Owusu, and Ashun (2020)
Partial least squares structural equation modelling (PLS-SEM)	Liu and Lee (2018), Dubey, Gunasekaran, Childe, Fosso Wamba, *et al.* (2019), Can Saglam *et al*. (2020), Bag *et al.*, (2022), Hamidu *et al.* (2023)
Structural equation models	Vanpoucke and Ellis (2019), Chunsheng *et al.* (2019), Lee and Rha (2016), Ambulkar, Blackhurst, and Grawe (2015), Um and Han (2021)
Covariance-based structural equation modelling	Singh and Singh (2019), Khan *et al*. (2021), G. Li *et al.*, (2022)
Hierarchical regression analysis	Dubey, Gunasekaran, Childe, Papadopoulos, *et al.* (2019), Chen *et al*. (2022)
Longitudinal field study	Boone *et al.* (2013)
Fuzzy hypothesis tests	Kaviani *et al.* (2020)

Quantitative methods (integrated): The rest of the reviewed papers used different variations of integrated analytical and empirical quantitative methods.

Analytical methods (integrated): Hosseini *et al.* (2019) used a probabilistic graphical model and a stochastic bi-objective mixed-integer programming model to assess resilient strategies for supplier selection to recover from supply-side disruptions. Hasani and Khosrojerdi (2016) analysed resilient strategies for robust global SC network design using a mixed-integer non-linear model, parallel hybrid Taguchi-based memetic algorithm, fitness landscape analysis, and LAGRANGIAN relaxation heuristic methods. Similarly, Zahiri, Zhuang, and Mohammadi (2017) also analysed strategies for pharmaceutical resilient SC networks using a multi-objective integrated sustainable-resilient mixed-integer linear programming model, fuzzy possibilistic-stochastic programming model, and Pareto-based lower bound method (NP-hard). On the other hand, Sabouhi *et al.* (2020) analysed the same objective (i.e. designing resilient SC operation) under random disruption; however, they used different methods, such as a two-stage stochastic optimisation model, a multi-cut shaped solution method, and a classical benders decomposition algorithm. Li *et al.* (2017) investigated the importance of information sharing in three echelons of SCs by using system dynamics and multi-objective simulation-based optimisation methods. Using two-stage mixed probabilistic-stochastic programming models with FDEMATEL and FANP, Namdar *et al*. (2021) designed a resilient SC network under uncertainties. They found that when funding is constrained, SCs must first address long-term disruptions closest to the customer. Kumar and Kumar Singh (2021) utilised the best-worst method and quality function methods to explore the impact of the COVID-19 pandemic on agri-food SCs, finding that poor accessibility was the main hindrance for most SCs during the pandemic. The optimal order allocation process was determined using nonlinear mixed integer programming, FMEA, and AHP by Rezaei *et al*. (2021). Healthcare SCs need to be aware of Industry 4.0, multiple sourcing, risk awareness, agility, and the global diversification of suppliers, markets, and operations, as Rehman and Ali (2021) identified using fuzzy AHP, fuzzy TOPSIS, and fuzzy QFD. In a closed-loop SC, Mehrjerdi and Shafiee (2021) examined sustainability and resilience simultaneously using a multi-objective mixed-integer programming model and fuzzy TOPSIS. Hasani (2021) proposed a fuzzy multi-objective mathematical programming model for designing global SC networks using the fuzzy best-worst method and VIKOR methodology. Mohammed *et al*. (2021) used DEMATEL-TOPSIS and possibilistic bi-objective programming models to investigate resilience pillars and companies' abilities to cope with uncertain demand. Gao *et al*. (2019) developed a mathematical model using the integrated worst-case conditional value at risk (CVaR) and conic programming to determine the optimal inventory allocation strategy to minimise lost sales. Arabsheybani and Arshadi Khasmeh (2021) developed a robust bi-objective and multiple-product mathematical model to simultaneously analyse resiliency and uncertainty in multi-period, multiple-item SC networks. Taleizadeh *et al.* (2020) used integrated game theory and decomposition algorithms to analyse resilient SC strategies, such as stocking up on inventory at distribution centres and considering reliable distribution centres.

Several papers used simulation-based methods with other analytical methods. Dixit, Verma, and Tiwari (2020) assessed and evaluated the resilience strategies of SC networks pre- and post-disaster by using the conditional value at risk (CVaR), simulation-based methods, and structural network design. Ivanov and Rozhkov (2020) used discrete and agent-based models to explore write-off risks and resilience under SC planning with capacity disruption considerations.

Jafarnejad *et al.* (2019) investigated key factors affecting the SCRES of medical equipment manufacturers by using the hesitant fuzzy Delphi method and system dynamic simulations to examine the dynamic relationship among SCRES factors. On the other hand, Azadeh *et al.* (2014) analysed resilience strategies to recover from transportation disruption by using visual simulation language for analogue modelling (SLAM) and fuzzy data envelopment analysis (FDEA). On the other hand, Tan, Cai, and Zhang (2020) determined and analysed strategies for SCRES in an SC network by adopting discrete-event and agent-based modelling (ABM) methods. Cavalcante *et al*. (2019) employed a combined simulation and machine learning approach to enable data-driven decision-making in resilient supplier selections. They found that combining supervised machine learning with simulation increases delivery reliability. Sonar *et al.* (2022) also attempted to find resilient suppliers using the interpretive structural model (ISM).

Furthermore, some papers adopted mixed MCDMs, fuzzy algorithms, and data envelopment methods. Soni, Jain, and Kumar (2014) analysed SC enablers using a graph theory and ISM for SCRES for better preparedness during disruptions. Parkouhi and Ghadikolaei (2017) analysed resilience strategies for robust global SC networks' design using the fuzzy analytic network process (ANP) and Grey-VIKOR methods. Rajesh (2019) adopted the resilient fuzzy index and performance fuzzy index methods to identify critical attributes affecting SCRES. Several papers used different methods to study the best supplier selection (Sonar *et al.*, 2022). Amindoust (2018) used the hybrid intelligent method, fuzzy interface system, and data envelopment analysis methods, while Sabouhi, Pishvaee, and Jabalameli (2018) used data envelopment analysis and mathematical programming modelling methods. Mohammed (2020) used VIKOR and DEMATEL; Sahu, Datta, and Mahapatra (2016) used fuzzy-VIKOR and fuzzy-TOPSIS; Hosseini and Khaled (2019) used AHP, predictive analytics models, and ensemble methods; and Haldar *et al.* (2014) used fussy TOPSIS and aggregated fuzzy weight (AFW) methods to select the best and most resilient suppliers to make the supply side more resilient. Rajesh (2020b) utilised integrated Grey theory and a layered analytical network process to analyse resilience strategies in electronic SCs. Das *et al*. (2021) identified critical factors affecting global SCs and evaluated strategies to reduce risk in the SC network during the COVID-19 pandemic with a model integrating AHP and DEMATEL. Hsu *et al*. (2021) used the integrated quality function deployment (QFD) approach, the house of quality (HOQ), KJ method/affinity diagram, failure modes and effects analysis

(FMEA), the finite difference method (FDM), and VIKOR to explore the resilience of fashion SCs by taking into account the SC risk, resilience capabilities, and resilience-enhancing features.

Some other authors, such as Ding *et al.* (2020), used the network construction model, topological property analysis, and structural modification approaches to assess the resilience of natural gas imports. Pettit, Croxton, and Fiksel (2013) analysed SCRES measurement through SCRES capabilities using the SCRES assessment and management (SCRAM) tool and the mixed-method triangulation method.

Empirical methods (integrated): Several papers used mixed empirical methods to analyse SCRES strategy issues.

Abidin and Ingirige (2018) used the Mann–Whitney U and Kruskal–Wallis tests to assess SC's critical vulnerabilities and capabilities that lead to SCRES. Ali, Nagalingam, and Gurd (2018) used exploratory factor analysis (EFA) and confirmatory factor analysis (CFA) to develop models that take the relationship among cold chain logistics risk, resilience, and firm performance into account in perishable product SCs. Rajesh (2021) also used EFA and CFA methods to examine the flexible business strategies at the demand, supply, and process levels of SCs, as they contribute to resilience. Brandon-Jones *et al.* (2014) used multiple regression analysis and hierarchical moderation tests to understand the relationship between specific resources (i.e. information sharing, connectivity, capabilities, and performance) in terms of SCRES. On the other hand, Jain *et al.* (2017) used MCDM and SEM mixed methods (i.e. ISM, MICMAC analysis, and the structural equation model) to develop a hierarchical-based model for SCRES, explaining the dynamic relationship between various catalysts. A synopsis of the integrated quantitative methods is presented in Table 2.4.

Table 2.4: Synopsis of integrated quantitative methods

Integrated quantitative methods	**References**
1. Analytical methods	
Network construction, topological property analysis, and structural modification	Ding *et al.* (2020)
Graph theory and interpretive structural modelling (ISM) approach	Soni, Jain, and Kumar (2014)
Hybrid intelligent method, fuzzy interface system, and data envelopment analysis	Amindoust (2018)
Data envelopment analysis and mathematical programming modelling	Sabouhi, Pishvaee, and Jabalameli (2018)

VIKOR and DEMATEL	Mohammed (2020)
Probabilistic graphical model and stochastic bi-objective mixed-integer programming model	Hosseini *et al.* (2019)
Conditional value at risk (CVaR), simulation-based approach, and structural network design	Dixit, Verma, and Tiwari (2020)
Fuzzy analytic network process and Grey VIKOR method	Parkouhi and Ghadikolaei (2017)
Mixed-integer non-linear model, parallel hybrid Taguchi-based memetic algorithm, fitness landscape analysis, and Lagrangian relaxation heuristic	Hasani and Khosrojerdi (2016)**,** Vali-Siar & Roghanian (2022)
Multi-objective integrated sustainable-resilient mixed-integer linear programming model, fuzzy possibilistic-stochastic programming approach, and Pareto-based lower bound method (NP-hard)	Zahiri, Zhuang, and Mohammadi (2017)
Resilient fuzzy index and performance fuzzy index	Rajesh (2019)
Fuzzy-VIKOR and fuzzy-TOPSIS	Sahu, Datta, and Mahapatra (2016)
Hesitant fuzzy Delphi method and system dynamic simulation	Jafarnejad *et al.* (2019)
Visual simulation language for analogue modelling (SLAM) and fuzzy data envelopment analysis (FDEA)	Azadeh *et al.* (2014)
AHP, predictive analytics models, and ensemble methods	Hosseini and Khaled (2019)
System dynamics and multi-objective simulation-based optimisation	Li *et al.* (2017)
FDEMATEL–FANP and novel two-stage mixed possibilistic-stochastic programming (TSMPSP) model	Namdar *et al*. (2021)
BWM and quality function method (QFD)	Kumar and Kumar Singh (2021)
Nonlinear mixed integer programming, failure modes and effects analysis (FMEA), and AHP	Rezaei *et al*. (2021)
Fuzzy AHP, fuzzy TOPSIS, and fuzzy quality function deployment (QFD)	Rehman and Ali (2021), Gupta *et al.* (2023)
Multi-objective mixed-integer programming model and fuzzy TOPSIS	Mehrjerdi and Shafiee (2021)
A fuzzy multi-objective mathematical programming model, fuzzy best-worst method and augmented ε-constraint method, and VIKOR technique	Hasani (2021)
DEMATEL-TOPSIS and possibilistic bi-objective programming model	Mohammed *et al.* (2021)
Supply chain resilience assessment and management (SCRAM) and mixed-method triangulation	Pettit, Croxton, and Fiksel (2013)
Fuzzy TOPSIS and aggregate fuzzy weight (AFW)	Haldar *et al.* (2014)
Two-stage stochastic optimisation model, a multi-cut L-shaped solution method, and classical benders decomposition algorithm	Sabouhi *et al.* (2020)
Discrete event- and agent-based model (ABM)	Tan, Cai, and Zhang (2020)**,** Ivanov and Rozhkov (2020)
Worst-case conditional value at risk (CVaR) and conic programming	Gao *et al.* (2019)
Grey theory and layered analytical network process	Rajesh (2020b)
Bi-objective multi-period robust optimisation model, ε-constraint method, fuzzy analytic hierarchy process (AHP), and fuzzy multi-objective optimisation based on ratio analysis (MOORA)	Arabsheybani and Arshadi Khasmeh (2021)
Simulation and supervised machine learning (SML)	Cavalcante *et al.* (2019)

AHP and DEMATEL	Das *et al.* (2021)
Integrated quality function deployment (QFD) approach, the house of quality (HOQ), KJ method/affinity diagram, failure modes and effects analysis (FMEA), finite difference method (FDM), and VIKOR	Hsu *et al.* (2021)
Stackelberg game model, two-phase bi-level mixed integer programming approach, and decomposition-based algorithm	Taleizadeh *et al.* (2020)
Fuzzy systems, Wavelet Neural Networks (WNN), and Evaluation based on Distance from Average Solution (EDAS)	Belhadi *et al.* (2022)
House of Quality and MCDM (HOQ-MCDM)	Hsu *et al.* (2022)
TOPSIS and grey prediction model	Qi *et al.* (2022)
2. Empirical methods	
Mann–Whitney U and Kruskal–Wallis tests	Abidin and Ingirige (2018)
Exploratory factor analysis (EFA) and confirmatory factor analysis (CFA)	Ali, Nagalingam, and Gurd (2018)**,** Rajesh (2021)
Multiple regression analysis and hierarchical moderation tests	Brandon-Jones *et al.* (2014)
ISM and MICMAC analysis, and structural equation model (SEM)	Jain *et al.* (2017)

Qualitative methods (individual): Among the individual qualitative methods, Chen, Das, and Ivanov (2019); Pereira *et al.* (2020); Jüttner and Maklan (2011); and Leat and Revoredo-Giha (2013) conducted interviews to investigate post-disruption stages and SCRES strategies to identify the key capabilities that purchasing and supply management functions develop to enhance SCRES in the supply side of buying firms, conceptualise SCRES, and identify their relationship with SC vulnerabilities and SC risk-management. Further, they investigated the key risks and challenges in developing SCRES in agri-food SC systems. Herold *et al*. (2021) interviewed experts to determine how logistics service providers maintained their SCs in response to the COVID-19 pandemic. Modgil *et al*. (2021) interviewed experts on the use of AI and the potential for AI to enhance SCRES through visibility, sourcing, and distribution. On the other hand, Parast (2020) used the dynamic capability theory to evaluate how R&D affects SCRES. VanVactor (2011) and Scholten and Schilder (2015) used a case study to analyse healthcare SC's preparedness and mitigation strategies and how collaboration influences SCRES. In addition, Scala and Lindsay (2021) conducted a case study on how this resilience is evident in healthcare SC. They found that collaboration is the key to success in extraordinary disruptions. A rigorous case study by van Hoek and Dobrzykowski (2021) showed the importance of reshoring to recover from future SC disruptions similar to COVID-19. Zhang *et al*. (2021) conducted a case study on how omnichannel strategies can be used in stable and turbulent environments. Werner *et al*. (2021) conducted a case study using non-financial key performance indicators on organisational resilience. Abe and Ye (2013) discuss how global SCs can enhance natural disaster risk mitigation by analysing a recent case study of natural disasters in Japan and Thailand. Vecchi *et al*. (2020) recommend procurement lessons learned from disasters like the COVID-19 pandemic. Similarly, a case study by Kumar *et al*. (2014) provided an organisation with a framework for managing SC risk. Adobor and McMullen (2018) studied frameworks on resilience types in SC networks from a complex adaptive systems perspective. Pereira, Christopher, and Lago Da Silva (2014) studied the role of procurement in SCs through a systematic literature review. On the other hand, Ivanov and Dolgui (2020); Mackay, Munoz, and Pepper (2019); and Zhu, Chou, and Tsai (2020) theorised conceptual frameworks for digital SCs, conceptual strategies to improve post-disruption system performance, and a framework for SCRES in light of the COVID-19 pandemic. Manning and Soon (2016) presented a conceptually innovative framework for driving business performance in the food SC by considering strategic business resilience. Gunasekaran *et al*. (2015) presented a conceptual framework and discussed how global sourcing affects SCs. Al-Haidous, Al-Breiki, *et al.* (2022) used SWOT analysis to evaluate LNG SCRES. Hohenstein (2022) proposed strategies and empirical lessons for improving transportation services.

Qualitative methods (integrated): Papadopoulos *et al.* (2017) investigated the use of big data for evaluating resilience in SC networks in terms of sustainability by collecting data and surveying social media. Hendry *et al.* (2019); Polyviou, Croxton, and Knemeyer (2019); Machado, Paiva, and da Silva (2018); and Tukamuhabwa, Stevenson, and Busby (2017) interviewed individuals and used case studies to investigate how local SCs prepare and respond to constitutional changes, which allowed them to explore resources and capabilities that help medium-sized firms to be resilient, investigate how companies develop mitigation strategies to reduce the negative aspects of counterfeiting, and investigate the process of building SCRES in developing countries, respectively. Xu *et al.* (2020) analysed SC disruptions caused by the COVID-19 pandemic and ways to build SCRES using a case study and critical review. Thomas *et al.* (2015) proposed a conceptual fitness model called the ‘Fit Operation Model’, which is a resilience model for SC, by obtaining data from surveys. Sabahi and Parast (2020) studied the relationship between innovativeness, SCRES, and SC innovative capabilities by conducting a literature review, preposition development, and conceptual framework. Kumar and Anbanandam (2020) extended the understating of SCRES-building capabilities and improvements using a situation actor process–learning action performance (SAP–LAP) analysis and a case study. Finally, Ivanov (2020b) and Ivanov (2021b) theorised a concept for viable SCs and the relationship between resiliency and viability in SCs using the dynamic system theory and SC structural dynamics control approach. A synopsis of the qualitative methods is presented in Table 2.5.

Table 2.5: Synopsis of the qualitative methods used

Qualitative methods (individual and integrated)	**References**
Individual qualitative methods	
Interview	Chen, Das, and Ivanov (2019), Pereira *et al.* (2020), Jüttner and Maklan (2011), Leat and Revoredo-Giha (2013), Herold *et a*l. (2021), Modgil *et al*. (2021), Belhadi *et al*. (2021), Furstenau *et al.* (2022), Cohen *et al.* (2022), Bastas & Garza-Reyes (2022), Vicario *et al.* (2023)
Survey	Bender *et al*.(2022), Shih & Lin (2022), Kent *et al.* (2022)
Delphi method	Seuring *et al.* (2022), Grzybowska & Tubis (2022)
Dynamic capability theory	Parast (2020), Raj *et al.* (2022)
Case study	VanVactor (2011), Scholten and Schilder (2015), Scala and Lindsay (2021), van Hoek and Dobrzykowski (2021), Zhang *et al.* (2021), Michel-Villarreal *et al*. (2021), Werner *et al*. (2021), Abe and Ye (2013), Vecchi *et al*. (2020), Kumar *et al.* (2014), Hohenstein (2022)
Complex adaptive systems perspective	Adobor and McMullen (2018)
Systematic literature review	Pereira, Christopher, and Lago Da Silva (2014)
Theorising	Ivanov and Dolgui (2020), Mackay, Munoz, and Pepper (2019), Zhu, Chou, and Tsai (2020), Ivanov (2021b), Chopra *et al.* (2021), DuHadway *et al.* (2019)
Conceptual	Manning and Soon (2016), Gunasekaran *et al*. (2015), Ambrogio *et al.* (2022), Song *et al.* (2022), Altay & Pal (2023), Naim & Gosling (2023)
Comparative research approach	Njomane & Telukdarie (2022)
SWOT analysis	Al-Haidous, Al-Breiki, *et al.* (2022)
Integrated qualitative methods	
Data collection and surveys from social media	Papadopoulos *et al.* (2017), Choksy *et al*. (2022)
Interview and case study	Hendry *et al.* (2019), Polyviou, Croxton, and Knemeyer (2019), Machado, Paiva, and da Silva (2018), Tukamuhabwa, Stevenson, and Busby (2017)
Case study and critical review	Xu *et al.* (2020), Di Paola *et al.* (2023)
Survey and conceptual fitness model	Thomas *et al.* (2015)
Literature review, preposition development, and conceptual framework	Sabahi and Parast (2020)
Situation actor process–Learning action performance (SAP–LAP) analysis and case study	Kumar and Anbanandam (2020)
Dynamic systems theory and SC structural dynamics control approach	Ivanov (2020b)

2.4.5. Context of the studies

Industry focus: Products and services can be divided into two major types: **1.** high-demand essential products and services and **2.** low-demand luxury products and services (Sabouhi, Pishvaee, and Jabalameli, 2018; Boone *et al.*, 2013; Azadeh *et al.*, 2014; Zhang *et al*., 2021; Sazvar *et al*., 2021). Very few papers focused on high-demand essential products and services industries, such as products—food, pharmaceutical, vaccine, medical equipment, personal care products—and services—cold chain logistics, hospital logistics, and other logistics, and maritime and port services (Yang and Xu, 2015; Lücker and Seifert, 2017; Papadopoulos *et al.*, 2017; Pettit, Croxton, and Fiksel, 2013; Ivanov, 2021a; Rehman and Ali, 2021; Michel-Villarreal *et al*., 2021; Rahman *et al*., 2021; Yavari and Ajalli, 2021). On the other hand, most papers have focused on low-demand luxury products and services industries—for example, the ICT, electrical and electronic, automotive, aircraft, textiles, plastic, metal, fashion, tire, and apparel industries (Chen, Das, and Ivanov, 2019; Amindoust, 2018; Boone *et al.*, 2013; Belhadi *et al*., 2021; Mehrjerdi and Shafiee, 2021; Rajesh, 2021; Werner *et al*. 2021; Rajesh, 2020b; Dohale *et al*., 2021; Hsu *et al*., 2021; Choksy *et al.*, 2022).

Geographical locations of applications: The reviewed studies were conducted in different regions of the world. Xu *et al.* (2020), Das *et al.* (2021), Abe and Ye (2013), and Ivanov (2020b) focused on global SCs. Chen, Das, and Ivanov (2019); Amindoust (2018); Dixit, Verma, and Tiwari (2020); Papadopoulos *et al.* (2017); Sazvar *et al.* (2021); Razavian *et al*. (2021); Rajesh (2021); Majumdar *et al*. (2021), Moosavi and Hosseini (2021); Yavari and Ajalli (2021); Shen and Sun (2021); Rajesh (2020b); Dohale *et al*. (2021); and Hsu *et al.* (2021) focused on the following nine regions in Asia: Taiwan, China, Iran, India, Nepal, the Middle East, Pakistan, Malaysia, and South Korea. Asamoah, Agyei-Owusu, and Ashun (2020) and Tukamuhabwa, Stevenson, and Busby (2017) focused on the following two countries in Africa: Ghana and Uganda. Lu *et al*. (2015); van Hoek and Dobrzykowski (2021); Ni, Howell, and Sharkey (2018); Michel-Villarreal *et al*. (2021); Schmitt *et al*. (2017), Kumar *et al*. (2014); and Tucker *et al.* (2020) focused only on the three countries in North America (i.e. the USA, Mexico, and Canada). Similarly, Pereira *et al.* (2020), Khan *et al*. (2021), and Hasani and Khosrojerdi (2016) focused on the following two countries in South America: Brazil and Ecuador. Zhang *et al*. (2021), Ivanov (2021a), Hendry *et al.* (2019), Aldrighetti *et al*. (2019), Scala and Lindsay (2021), and Leat and Revoredo-Giha (2013) focused on the following five countries in Europe: France, Germany, Italy, the UK, and the Netherlands. Ali, Nagalingam, and Gurd (2018) and Rahman *et al*. (2021) focused on Australia when researching SCRES strategies.

The details of the contexts of the studies are summarised in Table A3 and Table A4.

2.4.6. Use of theories

The reviewed articles used different theories to assess, define, measure, and analyse all aspects of SCRES strategies. Dynamic capital theory, social capital theory, contingent resource-based theory, relational view theory, information processing theory, and complexity theory were used to justify the SCRES strategies for preparedness by Siva Kumar and Anbanandam (2020) and Pu *et al*., 2023. Parast (2020); Polyviou, Croxton, and Knemeyer (2019); and Ivanov (2020b) used dynamic capability theory, internal social capital theory, and dynamic system theory, respectively, to justify the SCRES strategies for SC recovery processes. Summarised in Table 2.6, several other theories were used to justify different variations of integrated SCRES strategies.

Table 2.6: Summary of theories used by researchers

Theories	**References**
Bayesian network theory	Hosseini *et al.* (2019)
Dynamic capability theory	Parast (2020), Hendry *et al.* (2019), Lee and Rha (2016), Sabahi and Parast (2020), Kumar and Anbanandam (2020), Bag *et al*. (2022), G. Li *et al.*, (2022), Song *et al.* (2022), Hohenstein (2022), Pu *et al.* (2023)
Social capital theory	Asamoah, Agyei-Owusu, and Ashun (2020), Kumar and Anbanandam (2020)
Contingency theory	Ali, Nagalingam, and Gurd (2018), Song *et al.* (2022)
Resource-based theory	Ali, Nagalingam, and Gurd (2018)
Internal social capital theory	Polyviou, Croxton, and Knemeyer (2019)
Organisational theory and organisational culture theory	Chunsheng *et al.* (2019), Majumdar *et al*. (2021)
Resource orchestration theory	Chunsheng *et al.* (2019)
Organisational ambidexterity theory	Lee and Rha (2016)
Contingent resource-based theory	Brandon-Jones *et al.* (2014), Kumar and Anbanandam (2020)
Organisational information processing theory	Dubey *et al.* (2019), DuHadway *et al*. (2019)
Relational view	Kumar and Anbanandam (2020)
Information processing theory	Kumar and Anbanandam (2020), Jain *et al.* (2017)
Complexity theory	Kumar and Anbanandam (2020)
High-reliability theory	Jain *et al.* (2017)

Social exchange theory	Jain *et al.* (2017)
Dynamic system theory	Ivanov (2020b)

Finally, an annotated bibliography of the reviewed articles is presented in Table A5.

2.5. Observations and future research directions

The reviewed articles reveal several aspects available for future research in SCRES strategies. Several articles have been published, but well-grounded studies—both methodologically and theoretically—related to SCRES strategies are scarce. Based on an analysis of the main theme of the review presented in section 2.4 and considering existing literature on the studies of SCRES strategies in this section, some potential avenues are proposed that still require research. Table 2.7 highlights potential future research questions and opportunities in different areas of SCRES strategy research.

Table 2.7: Summary of future research questions and scopes

Themes of the studies	**Research questions and future scopes**	**Other recommendations for future research**
SCRES strategies-focused (preparedness, response, recovery, and integrated strategies)	a. What are the congruent strategies to mitigate combinatory supply, demand, and financial disruptions of SC networks during large-scale disruptions? b. What is the best combination of strategies to mitigate large-scale SC disruptions? c. What will be the differences between preparedness strategies, response strategies, and recovery strategies to mitigate SC disruptions (i.e. supply, demand, manufacturing, transportation, information, and financial disruptions of SCs)? d. How does the restructuring of SCs impact global SCs? e. What strategies could be considered to ramp up production during extraordinary disruptions? f. What are the strategies to meet the demand surge caused by panic buying during disruptions? How could studying consumer psychology/behaviour facilitate the adoption of suitable strategies to reduce the impacts caused by panic-buying tendencies on SCs? g. What will the global effects of implementing SCRES strategies, such as re-shoring, back-shoring, and near-shoring, be? What are the challenges and how can they be overcome? h. What are the benefits and challenges of diversifying manufacturing units to mitigate production	Theory for strategising: a. Theorising during the conceptualisation of the research b. Theorising during the design and synthesis of the studies c. Building theory on disruption management using SCRES strategies

	disruptions? How could diversifying manufacturing units help mitigate capacity shortages during large-scale disruptions? i. What are some appropriate strategies to diversify the delivery options to consumers and what are the challenges in implementing such strategies? j. How could the information within the SCs be safeguarded? k. How could collaborative strategies help to mitigate supply, demand, capacity, inventory, transportation, and financial disruptions in SC networks? l. Why do business insurance policies play a significant role in managing large-scale disruptions? m. In what ways can facility locations be selected to minimise SC disruptions? n. How can improvements in the SC process help manage large-scale SC disruptions? o. How should combined strategies for managing the simultaneous and dynamic impacts of the COVID-19 pandemic be applied? p. What is the resilience-sustainability nexus in mitigating SC disruptions? q. How do SCRES strategies impact and improve the sustainability of SCs? What are the pros and cons of implementing SCRES strategies to make SCRES more sustainable?	
Types of disruptions, with a focus on strategising	a. What are the impacts of large-scale disruptions (such as the COVID-19 pandemic) on the dynamics of SCs? b. How do large-scale disruptions (such as the COVID-19 pandemic) impact the SCs of high-demand essential products and low-demand luxury products? c. Which industry and area of SCs are most affected by large-scale disruptions, such as the COVID-19 pandemic? d. What are the differences between the effects of previous large-scale disruptions and the effects of disruptions caused by the COVID-19 pandemic on SCs? e. Which area of SCs is most disrupted by the COVID-19 pandemic—supply or demand, or both? What are the challenges and strategies used to mitigate supply-demand disruptions caused by the COVID-19 pandemic? f. What are the short-term, medium-term, and long-term effects of large-scale SC disruptions on SCs? g. What are the strategies to manage the simultaneous and dynamic impacts of the COVID-19 pandemic in the SCs of essential manufacturers? h. What are some possible post-disruption strategies to recover from large-scale disruptions caused by the COVID-19 pandemic, and what precautionary strategies can be implemented to help face such disruptions in the future?	

Methodological justification, with a focus on strategising	a. What tools, models, and methods can help SC decision-makers assess the effectiveness of proposed resilience strategies and select practical strategies for achieving resilience? b. Which methods can be used to anticipate and identify the impacts of large-scale disruptions (such as the COVID-19 pandemic) on the dynamics of SCs? c. Which methods could be used to observe the behavioural aspects within SCs when disruptions occur? d. Which methods could be used to model the SCs to observe improvements in the conditions during a disrupted situation? e. What are the benefits of system science methods, such as agent-based modelling, over conventional mathematical and optimisation modelling to model SCs and test the strategies and improve the conditions?	
Industry and geographical location of applications, with a focus on strategising	a. What are the impacts of large-scale disruptions on the dynamics of the SCs of high-demand essential products and low-demand products? Which industry is most affected by large-scale disruptions, such as COVID-19? b. What would be the differences between the strategies to mitigate disruptions in the SCs of high-demand essential products and low-demand products? c. What are the geographical location-based differences regarding the impacts of disruptions on SCs? How could a case study in one geographical location help understand the impacts on the SC dynamics in other geographical locations?	

2.5.1. SCRES strategy focus

Several strategies for managing SC disruptions have been discussed in existing literature, including those related to preparing for, responding to, and recovering from disruptions. Most articles reviewed discuss SCRES strategies for recovery, while very few papers discuss strategies for preparedness and responses to aid recovery. SCs can become more resilient if they recover from disasters faster (Yang and Xu, 2015; Ni, Howell, and Sharkey, 2018; Piprani, Jaafar, and Mohezar Ali, 2020; Dong *et al.*, 2018). The actual disruption conditions are uncertain; therefore, the recovery processes and strategies have been focused on more than strategies for preparing and responding to disruptions (Lücker and Seifert, 2017; Rezapour, Farahani, and Pourakbar, 2017; Hosseini *et al.*, 2019; Piprani, Jaafar, and Mohezar Ali, 2020; Zhen *et al.*, 2016). Hosseini *et al.* (2019) claimed that SCs should improve the performance of recovery strategies in the event of a disruption, since higher pre-disaster resilience strategies do not deliver a higher restoration rate. Further, there has been minimal research on companies' strategies to respond to disruptions, making it difficult for them to thrive (Soren and Shastri, 2019; Fattahi, Govindan, and Keyvanshokooh, 2017). SCs must adopt strategies for responding to a disruption to speed up the recovery process (Shen and Sun, 2021). The topic of supply and demand disruptions has received the most attention (Khan *et al*., 2021). Such disruptions result in disruptions at all other levels of SCs. SCs are rarely discussed in terms of integrated supply, demand, manufacturing, inventory management, transportation, and financial disruption strategies (Chowdhury *et al.*, 2021). A few articles have discussed the strategies for responding to individual supply, demand, manufacturing, inventory management, transportation, or financial disruptions of SCs. However, relatively few papers have focused on strategies to mitigate the combined effects of supply, demand, manufacturing, inventory management, transportation, and financial disruptions. During the COVID-19 pandemic, essential manufacturers experienced severe supply-demand disruptions, resulting in shortages in their production capacity (Xu et al., 2020). As a result, manufacturers could not meet the surge in demand for essential products during lockdowns. Due to a lack of supply and capacity, the SCs of the manufacturers of essential products and services suffered severe shortages (Zhu, Chou, and Tsai, 2020). Owing to disruptions in the supply and demand, they suffered from severe financial losses (Gholami-Zanjani et al., 2020). It was difficult for the manufacturers to maintain adequate inventories and to deliver items to retailers (Rahman et al., 2021b). In this context, strategies to mitigate the combined financial, supply, and demand disruptions, in addition to the simultaneously and dynamically occurring effects of the COVID-19 pandemic, are crucial for SCs. There is a dire need to prepare SCs to deal with large-scale disruptions. Future large-scale disruptions, similar to the COVID-19 pandemic, require SCs to be adequately prepared (Seuring *et al.*, 2022). Few preparedness strategies to deal with such large-scale disruptions are present in the existing literature. Research is required to develop resilience strategies to allow SCs to cope with large-scale disruptions. From Section 2.4.3, it is clear that resilience strategies relating to combinatory supply, demand, and financial disturbances, as well as simultaneous and dynamic disturbances, have been focused on less in the literature, which is a research gap that needs bridging.

The most prevalent theme in the literature is the development of strategies for SCs to recover from disruptions. Additionally, disruptions in supply and demand are interconnected in SC networks.

As a result of disruptions in the supply and demand sides of the SC networks, production capacity declines, and manufacturers cannot meet the surge in demand from consumers and retailers (Xu et al., 2020). Furthermore, this slows down the delivery process, consequently increasing shortage costs. Combinatory strategies should be developed to mitigate disruptions in supply and demand due to large-scale disruptive events. Increasing the production capacity to meet the demand surge may be necessary. Several papers have proposed that emergency supplies of raw materials can be arranged through collaboration with other suppliers (Jüttner and Maklan, 2011). There is a need to conduct more research to develop strategies to increase the production capacity to meet the demand surge. Manufacturers may need to increase their emergency stock and work vertically or horizontally to receive more raw materials. Additionally, they should work closely with governments to receive aid and negotiate a relaxed import policy for suppliers from other countries to ensure a continuous supply (Soni, Jain, and Kumar, 2014). To the best of our knowledge, neither a comprehensive study nor a framework for analysing the efficacy of collaborative strategies has been proposed to mitigate disruptions in large-scale SC networks.

Panic-buying contributed significantly to the surge in demand for essential products during lockdowns and shutdowns caused by the COVID-19 pandemic. More emphasis should be placed on understanding customers' purchasing psychology/behaviour when disruptions occur. Applying operational research theories could reduce the impact of panic buying during disruptions. The importance of collaborative strategies for helping manufacturers increase production capacity in response to panic buying must be investigated further. Several researchers have suggested nearshoring, reshoring, and back-shoring strategies to recover from supply-side disruptions to restructure SC networks (Chen *et al.*, 2022; Fernández-Miguel *et al.*, 2022). It has yet to be determined what effect such restructuring strategies have on global SCs as there is a lack of studies to justify such strategies. Research needs to be conducted to understand the advantages and consequences of restructuring in SC networks. Automating and improving processes in manufacturing facilities can significantly improve outputs during a disruptive period (Khan et al., 2021). Further, the diversification of manufacturing units can ensure production capacity and safeguard the economy in times of disruption (Hasani and Khosrojerdi, 2016). To understand the effects of diversifying manufacturing units on SC dynamics, more research is required.

It is important to investigate the impact of supply, demand, and capacity disruptions on the transportation and delivery side of SCs, as well as techniques to mitigate them. As a result of lockdowns and shutdowns caused by the COVID-19 pandemic, the product delivery process was affected. In the literature, there is a lack of evidence for mitigation strategies for transportation disruptions resulting from large-scale disruptions. Research is needed on methods to optimise the delivery process to meet the demand surge for essential products during major disruptions. A robust, reliable distribution centre considering disruption correlations is necessary to build an efficient and effective delivery support system (Lu et al., 2015). A greater understanding of the benefits of blockchain technology in SCs is needed to secure the information within SCs (Papadopoulos *et al.*, 2017; Li *et al.*, 2022). As part of SC reengineering, blockchain technology can enhance transparency and visibility, automate processes, eliminate intermediaries, and enable real-time tracking through traceability, privacy, and data-management techniques (Sharma *et al.* 2020). Serpa and Krishnan (2017) suggest that business insurance policies and contractual incentives can reduce financial shocks in the long term. It is necessary to conduct empirical and evidence-based research to understand how business insurance policies can contribute to managing large-scale disruptions, such as the COVID-19 pandemic. The collaborative strategies to mitigate the supply, demand, manufacturing, transportation, and financial disruptions of SCs need to be scrutinised. Research needs to be conducted to observe to what extent these collaborative strategies (i.e. vertical and horizontal collaboration with other facilities or even the government) make SCs more resilient and sustainable. The resilience-sustainability nexus to mitigate SC disruptions needs to be identified; the extent to which the resilience strategies make the SCs sustainable needs to be determined (Nayeri *et al.*, 2022; Al-Haidous, Govindan *et al.*, 2022; Ghufran *et al.,* 2022). Identifying the resilience-sustainability nexus for mitigating SC disruptions is a potential research avenue. More research needs to be conducted to observe to what extent resilience strategies impact and improve the sustainability of SC networks.

2.5.2. Types of disruptions, with a focus on strategising

A majority of the reviewed articles discussed and investigated SCRES issues on micro-level disruptions and their impact on SCs, such as day-to-day SC operational disruptions in production, temporary resource unavailability, supply failures, temporary technological disruptions, degradations in product quality, and delivery delays (Chen *et al.*, 2020; Scholten and Schilder, 2015; Liu, Song, and Tong, 2016) (discussed in subsection 2.4.2). Several papers have discussed macro-level disruptions for strategising SCRES, including earthquakes, tsunamis, floods, and epidemics (Vanpoucke and Ellis, 2019; Gholami-Zanjani *et al.*, 2020; Ivanov, 2020b). Some papers focused on micro- and macro-level man-made disruptions and their impacts on SCs, such as labour strikes, terrorist attacks, and cyber-attacks (Sahu, Datta, and Mahapatra, 2016; Aggarwal and Srivastava, 2019). The impacts of micro-level disruptions are predictable and can be quickly recovered from, while the impacts of macro-level disruptions are much more unpredictable and take a long time to recover from (Rajesh, 2016; Sharma *et al.*, 2020; K.E.K *et al.*, 2022). Large-scale disruptions caused by a pandemic, such as COVID-19, affect SCs the most, the severity of which has led to global SC disruptions (Ivanov, 2020c). All levels of SCs have been disrupted by the COVID-19 pandemic due to lockdowns, shutdowns of SC operations, and border closures, leading to a global economic recession (Xu et al., 2020; Naim & Gosling, 2023). An Institute for Supply Chain Management survey claimed that approximately 75% of the companies worldwide faced capacity disruption in their SCs due to COVID-19-related transportation restrictions (Zhu, Chou, and Tsai, 2020). The supply and demand sides of SCs have been severely disrupted due to these restrictions, which have led to financial shocks (Gholami-Zanjani et al., 2020). While a large number of papers have recently focused on disruptions caused by COVID-19 in relation to SCRES strategies, it is still clear that there is a significant lack of understanding regarding the overall impact of the COVID-19 pandemic on the SCs and strategies to normalise them. Gholami-Zanjani *et al.* (2020) and Sharma *et al.* (2020) proposed models to mitigate the supply-demand disruptions caused by the COVID-19 pandemic, while Xu *et al.* (2020); Ivanov and Dolgui (2020); Zhu, Chou, and Tsai (2020); and Ivanov (2020b) only presented conceptual theories and recommendations to recover from catastrophic disruptions. They did not quantify any of the strategies they proposed by recognised methods. The details of the disruptions and their impact on SCs are discussed in subsection 2.4.2. Limited research focuses on identifying the impact of large-scale SC disruptions caused by catastrophic events, such as the COVID-19 pandemic, and strategies to mitigate their impacts.

The impact of large-scale disruptions, such as COVID-19, on the dynamics of SCs is yet to be identified (Bender *et al.*, 2022). Existing literature lacks demonstrations of the impacts of extraordinary disruptions on SC networks. Research needs to be conducted to determine the impacts of large-scale disruptions on the dynamics of SCs broadly. Several industries provide high-demand essential products and low-demand luxury products. These industries are not similarly affected by large-scale disruptions. The COVID-19 pandemic has had a significant effect on essential manufacturers (Zhu, Chou, and Tsai, 2020). The demand surge for essential items (i.e. food, medical equipment, and face masks) is an example of such disruptions. On the other hand, the demand for low-demand products, such as clothes, cooking items, and other household items, declined because of limited economic activities. Research should be conducted to identify which areas of SCs were most affected by the COVID-19 pandemic and how congruent strategies can mitigate such disruptions. Due to COVID-19, most countries imposed restrictions on border movement and lockdowns. Economic activity declined due to lockdowns and shutdowns resulting from the COVID-19 pandemic. On the other hand, the demand for essential items surged. Manufacturers of essential items could not ramp up their production capacity due to supply shortages (Ivanov, 2020c). This condition increased the shortage costs of the SC networks. This situation, caused by the COVID-19 pandemic, significantly differs from other large-scale disruptions that occurred previously. Continuous research needs to be undertaken to understand the volatility, uncertainty, complexity, and ambiguity (VUCA) of such large-scale disruptions on global SC networks in comparison to large-scale disruptions that occurred previously (Grzybowska & Tubis, 2022; Babaei *et al*., 2023). Demand and supply disruptions are the worst in this pandemic, leading to severe production-capacity shortages (Gholami-Zanjani et al., 2020). Panic buying resulted from such demand-supply disruptions during the COVID-19 pandemic (Xu et al., 2020). As a result of the lockdown and capacity constraints during the pandemic, manufacturers experienced difficulties in maintaining optimal inventory levels and delivering goods to retailers and customers (Rahman et al., 2021b). Identifying the bottlenecks of supply, demand, and capacity disruptions is important to facilitate smooth production, inventory management, and distribution and delivery support. More effort should be invested in developing mitigation strategies to minimise supply, demand, and capacity disruptions, along with the simultaneous and dynamic impacts of the COVID-19 pandemic on the SC networks (Zalitis *et al.*, 2022). The effects of the disruptions of SCs caused by the COVID-19 pandemic are short-, medium-, and long-term. More research needs to be conducted to develop post-disruption strategies to mitigate such long-term disruptions caused by the COVID-19 pandemic (Raj *et al*., 2022).

2.5.3. Methodologies focused on the justification of strategies

Some of the most widely used quantitative methods to justify the advantages of SCRES strategies are mathematical modelling and optimisation methods, simulations, MCDMs and fuzzy approaches, network analysis, and empirical methods (i.e. structural equation models and statistical empirical methods) (Colicchia, Dallari, and Melacini, 2010; Sabouhi *et al.*, 2020; Jain *et al.*, 2017). Mathematical modelling and optimisation tools are very powerful methods used to justify SCRES strategies, while MCDMs and fuzzy approaches are classical methods, which offer fewer advantages in terms of justifying the SCRES strategies (Mohammed, 2020; Fazli-Khalaf *et al.*, 2020). Simulation methods that use mathematical modelling or other simulation approaches, without mathematical modelling, such as the agent-based modelling method, discrete event methods, and system dynamics, are very powerful tools for understanding and analysing the SC network and justifying SCRES strategies (Tan, Cai, and Zhang, 2020). Tan, Cai, and Zhang (2020) used integrated simulation methods, such as discrete-event and agent-based modelling based on a graph model of an SC network, to justify strategies to recover from large-scale disruptions, demonstrating the methodological strength of strategising SCRES. Very little research has been conducted to quantify the impact of large-scale SC disruptions (such as the COVID-19 pandemic) and justify strategies to mitigate SC disruptions through simulation modelling. Further, very little research has been conducted to justify the SCRES strategies to mitigate large-scale disruptions by empirical methods. Empirical analyses are challenging as they are time-consuming and require a significant amount of data from industry; at times, this is very difficult (Liu and Lee, 2018; Jain *et al.*, 2017).

The SC is a complex dynamic structure (Wu, Blackhurst, and O'Grady, 2007; Singh *et al*., 2023). Most previous research has focused on strategising SCRES using quantitative methods, such as mathematical modelling and optimisation (e.g. linear programming, mixed-integer programming, goal programming, stochastic programming, and fuzzy programming), empirical methods (e.g. structural equation modelling methods and classical multi-criteria decision-making (MCDM) tools), and other methods (Soren and Shastri, 2019; Yang and Xu, 2015; Fattahi, Govindan, and Keyvanshokooh, 2017; Aggarwal and Srivastava, 2019; Gholami-Zanjani *et al.*, 2020; Asamoah, Agyei-Owusu and Ashun, 2020; Mohammed, 2020; Ali, Nagalingam, and Gurd, 2018). Optimisation methods (i.e. linear and non-linear optimisation algorithms), dynamic programming, heuristics, and meta-heuristics also perform well, but they fail to model the behavioural aspects of SCs that are bounded rational (Taghikhah et al., 2021). Classical MCDMs cannot reflect the dynamics of the behavioural aspects of SCs. More research needs to be conducted to identify appropriate methodologies to anticipate the impacts of large-scale disruptions caused by COVID-19 on SC networks. System science methods, such as agent-based modelling (ABM) and the discrete event method (DEM), are capable of simulating the non-physical or intangible issues of SCs effectively and efficiently (Behdani, Lukszo, and Srinivasan, 2019). They can analyse the interactions among various SC stages, facilitating an understanding of the dynamic mechanism of SC partners over time. They can also provide continuous feedback on key aspects of SC partners with limited information (Tan, Cai, and Zhang, 2020). It is necessary to consider the behavioural dynamics of SC functions to understand the strategies used to mitigate the large-scale supply, demand, and financial shocks of SCs caused by catastrophic events such as COVID-19 (Tan, Cai, and Zhang, 2020). Modelling the SC network is imperative to analyse the strategies and SC behavioural aspects, such that SCs may recover from disruptions effectively (Tan, Cai, and Zhang, 2020). As such, three aspects are very important when modelling SCs: first, typical SC modelling, which defines the structure and behaviours of an SC network; second, disruption modelling, which describes the characteristics of disruptive events; and third, disruption-management modelling, using which strategies can be tested to analyse improvements in SCs (Behdani, Lukszo, and Srinivasan, 2019). Agent-based modelling (ABM) is considered to be one of the best methods for this as it provides a platform to integrate the entire SC as a network system of independent echelons, where various actors of SCs employ different decision-making procedures (Datta, Christopher, and Allen, 2007; Rahman & Paul, 2022). Although ABM is a powerful tool to simulate SC dynamic behaviour, it has been used in SC research only very recently (Datta, Christopher, and Allen, 2007). Simulation models, such as discrete event modelling (DEM), are powerful tools for analysing SC networks (Tan, Cai, and Zhang, 2020). In the case of ABM and DEM, an SC network is prototyped as a network or system of agents, where each entity or set-up in the SC network is considered an agent. Each agent prototypes or models each entity's functioning and operational behaviour individually in the SC network. DEM methods are used to execute the communication between agents, where agents in the simulation process communicate and interact by passing events to each other (Tan, Cai, and Zhang, 2020). In this manner, ABM and DEM can analyse the critical interactivities between entities, enabling observing the behaviours arising from the entire SC system (Tan, Cai, and Zhang, 2020; Das and Hanaoka, 2014). The entry of such simulation models into research on SC management is in its nascent stages. Chen *et al.* (2020) analysed the resilience of oil imports under shock by using a system dynamics simulation. On the other hand, a DEM method was used by Ivanov (2020a) to investigate the structural and operational vulnerabilities to secure the demand and inventory sides of SCs. Tan, Cai, and Zhang (2020) determined and analysed strategies for SCRES in an SC network by adopting discrete-event and ABM methods. However, no significant research has been undertaken in the reviewed literature to identify the impact of large-scale disruptions, such as COVID-19, on global SC networks, or to justify the SCRES strategies used to mitigate the impacts using such simulation methods (agent-based modelling, discrete-event modelling, etc.). Research is required to observe the benefits of such system science methods over conventional mathematical and optimisation methods for modelling SCs, and to test the strategies to observe improvements in SC network conditions. Integrating mathematical and system science methods (such as agent-based models and discrete-event models) can help justify strategies to deal with SC disruptions and provide possible solutions.

It should also be noted that very few empirical research studies have been undertaken to understand the impacts of large-scale disruptions, such as COVID-19, on global SCs. Such empirical research will provide a more realistic idea of how to predict and adopt strategies necessary to combat such extraordinary disruptions. From the qualitative research perspective, no significant research (i.e. primary data collection), such as a case study or interview, was conducted in the reviewed literature to understand the real-life impacts of large-scale disruptions caused by COVID-19 on the SC networks and possible SCRES strategies to mitigate them. More research on real-life case studies needs to be conducted through interviews to observe the real-life impacts of such large-scale disruptions caused by COVID-19 on global SCs, in addition to the possible strategies that can be used to recover from the disrupted condition.

2.5.4. Industries and geographical locations of application, with a focus on strategising

From subsection 2.4.5, it can be seen that most of the studies focused on modelling and strategising SCRES on low-demand luxury products and the services industry, whereas fewer papers focused on high-demand essential products and services. The scarcity of essential products, such as food, medicines, medical equipment, and personal protective equipment, has recently occurred due to global SC disruptions caused by the COVID-19 pandemic (Zhu, Chou, and Tsai, 2020; Ivanov, 2020b). Limited research has been conducted on developing SCRES strategies for essential products and services industries, which can be considered a potential research gap. A majority of research related to strategising SCRES has been conducted based in Asian countries, which includes the nine countries mentioned in subsection 2.4.5, whereas a few papers researched SCRES issues based in developed countries: North American countries, South American countries, and Australia. Very few papers focused on SCRES strategies based in Australia (Ali, Nagalingam, and Gurd, 2018; Rahman *et al*., 2021; Rahman & Paul, 2022). A majority of research on developing SCRES strategies was conducted in Asian countries, whereas the region least researched is Australia. Developing SCRES strategies for these regions requires significant attention.

Most research, such as that conducted by Hasani and Khosrojerdi (2016); Polyviou, Croxton, and Knemeyer (2019); Jafarnejad *et al.* (2019); Xu *et al.* (2020); Pettit, Croxton, and Fiksel (2013); Amindoust (2018); Rezapour, Farahani, and Pourakbar (2017); Hosseini *et al.* (2019); Chen, Das, and Ivanov (2019); and Chunsheng *et al.* (2019) focused on strategising SCRES for low-demand product manufacturers. None of these studies focused on the large-scale disruptions caused by the COVID-19 pandemic and their impacts on various SC networks. More research could be conducted to identify the various impacts of large-scale disruptions on high-demand essentials and low-demand product manufacturers. Different suitable strategies must be developed to mitigate large-scale disruptions within both industries. Most research has been conducted in Asian countries, whereas only Ali, Nagalingam, and Gurd (2018) focused on resilient SCs in the context of developed countries, such as Australia. However, Ali, Nagalingam, and Gurd (2018) did not research strategising SCRES to tackle large-scale disruptions caused by catastrophic disruptions, such as COVID-19. During the COVID-19 pandemic, severe supply-demand disruptions for essential products, including toilet paper, face masks, and other medical equipment, were observed in developed countries such as Australia (Rahman & Paul, 2022). More research should be conducted to identify congruent strategies to mitigate large-scale supply-demand disruptions caused during the delivery of essential products in developed countries, and other developing and under-developed countries. It is also necessary to understand how strategies to mitigate large-scale disruptions in one geographical location could help mitigate SC disruptions in other geographical locations, and the geographical effects of the dynamics on SC networks. A comprehensive summary of the critical literature review of this thesis is described in the following sub-section.

2.6. Chapter summary

A thorough literature review and content-based analysis were undertaken on the 226 papers that dealt with SCRES strategies. A three-dimensional review of the development of SCRES strategies and different levels of SCs has been conducted. This review article has presented these strategies, identified them in the selected papers, and described the methodologies used to justify them. According to the analysis, a lack of simulation-model-based and theoretically grounded studies has been identified to mitigate large-scale disruptions in SCs. Furthermore, the analysis reveals that most studies have focused on SCRES strategies for low-demand luxury products, while high-demand essential products and services have been substantially ignored. Therefore, this research on strategising SCRES will significantly improve our understanding of SCRES issues. Strategising SCRES to tackle SC disruptions caused by catastrophic events will positively impact industries and, eventually, society.

To the best of our knowledge, this is the first critical literature review that explores SCRES strategies in an integrated manner. This review will help academicians and practitioners understand the current level of research on SCRES strategies that aid in mitigating SC disruptions. The methodological, theoretical, and contextual aspects of strategising that are discussed will help identify the strengths and weaknesses of these strategies, and the methodological techniques to justify them. This research forms the basis to explore more issues related to SCRES strategies to mitigate SC disruptions. The recent COVID-19 pandemic shook global SCs; therefore, the need to enhance the resilience of SCs is a dire issue. This review article will provide a guideline regarding the weaknesses and strengths of strategies to mitigate large-scale disruptions, such as the COVID-19 pandemic, along with providing methodologies to justify their use. The research scope identified in this review article, related to SCRES strategies to mitigate large-scale disruptions, provides a guideline for academicians and practitioners.

The theoretical and practical contributions of this review article are summarised as follows:

1. This chapter has identified SCRES strategies from the literature and classified them into three categories—preparedness strategies, response strategies, and recovery strategies—to mitigate macro-level, supply, demand, manufacturing, information, transportation, and financial disruptions of SCs.

2. This chapter has also analysed the strengths and weaknesses of the methodological justification of the strategies, the geographical and industrial contextual analyses of which are also discussed.
3. This chapter has identified potential research gaps based on several observations and proposed future research recommendations to help academicians and researchers conduct further studies on SCRES strategies.

This review has certain limitations, which are three-fold. First, only peer-reviewed articles were considered, while book chapters, conference papers, and doctoral dissertations were excluded. Second, this research focused on a broad overview of studies on SCRES strategies. A more specific research agenda should be considered for further systematic literature reviews. Third, in our search for articles, we used Scopus and Google Scholar, but did not use individual publisher websites such as Wiley and Elsevier. It is also possible that some other articles, which were not included in the databases we used, were omitted from the review. Searching individual publishers' websites is necessary to collect more relevant papers. Nevertheless, this literature review article of this chapter provides baseline guidance for scholars in designing further research in the field of SCRES strategies.

Chapter 3

An Agent-based Model for Supply Chain Recovery in the Wake of the COVID-19 Pandemic

The current COVID-19 pandemic has hugely disrupted supply chains (SCs) in different sectors globally. The global demand for many essential items (e.g. facemasks and food products) has been phenomenal, resulting in supply failure. SCs could not keep up with the shortage of raw materials, and manufacturing firms could not ramp up their production capacity to meet these unparalleled demand levels. This chapter aimed to examine congruent strategies and recovery plans to minimise the cost and maximise the availability of essential items to respond to global SC disruptions. Using the agent-based modelling method, we used facemask SCs as an example and simulated the current state of its supply and demand. We proposed two main recovery strategies for building emergency supply and extra manufacturing capacity to mitigate SC disruptions. Our findings revealed that minimising the risk response time and maximising the production capacity helped essential item manufacturers meet consumers' sky-rocketing demands and timely supply while reducing financial shocks to firms. This chapter suggested that delayed implementation of the proposed recovery strategies could lead to supply, demand, and financial shocks for essential item manufacturers. This chapter scrutinised strategies to mitigate the demand-supply crisis of essential items. It further proposed congruent strategies and recovery plans to alleviate the problem in the exceptional disruptive event caused by COVID-19.

3.1. Introduction

New research from the McKinsey Global Institute states that SC disruptions lasting a month or longer occur every 3.7 years on average (McKinsey & Company, 2020). The risks imposed on SCs are industry-specific and depend on exposure to different shock types (Mizgier et al., 2013). In this context, the recent COVID-19 pandemic can be classified as a catastrophic event, devastatingly impacting the SCs and operations of businesses globally (Ivanov, 2020b). Most manufacturing firms, especially those related to producing essential items, dealt with extreme supply and demand fluctuations (Control Center of Disease, 2020). For example, the demand for facemasks surged once the World Health Organization (WHO) reported them as essential protective equipment to control the disease's spread (Wu et al., 2020). Retailers and pharmacies worldwide have faced a stockout of facemasks as manufacturers have struggled to increase their production rate immediately during the pandemic to meet high demands (Wu et al., 2020). Hence, scholars and practitioners should pay considerable attention to the underlying risks and vulnerabilities of a particular firm or an entire SC (Lopes de Sousa Jabbour et al., 2020).

A lack of research exists on properly addressing strategies to mitigate the demand disruption of essential items, such as facemasks. This gap includes the absence of an SC recovery disruption model that considers extraordinarily disrupted situations, such as the COVID-19 pandemic (P. Chowdhury et al., 2021). Therefore, it is timely and imperative to study and evaluate strategies for mitigating demand disruptions. Then, essential item manufacturers could quickly scale up their production during extraordinary disruptive situations. The smooth flow and supply of high-demand essential items are imperative during pandemics to ensure the highest protection level. The strategies might not apply to all types of essential items. However, they will help explore further strategies based on the product types and outbreak severity. The literature review revealed that there had been several studies undertaken using mathematical, structural equations, and other empirical models regarding SC disruption, as discussed in Table B1 in Appendix B. However, limited research has been undertaken using simulation modelling approaches to mitigate disruptions due to extraordinary pandemics. No significant studies using agent-based simulations for recovery planning and managing SC risks have been found in the current literature. The agent-based modelling method is useful for simulating and evaluating complex SC interactions without formally developing a mathematical model for risk recovery situations (Mizgier et al., 2012).

The present study investigated the following research questions considering the lack of research regarding strategies for mitigating essential items' high demand during a pandemic:

1. What are the likely effects of a catastrophic situation on the manufacturing business of essential items?
2. What risk recovery plans can SC stakeholders use to mitigate the ongoing demand for essential items?
3. After implementing these strategies, how can SC decision-makers assess procurement and manufacturing improvements to meet the demand?

SC's long-established and conventional qualities of readiness, responsiveness, technological capability, and resiliency are inadequate for helping essential medical item manufacturers to craft risk recovery strategies to alleviate ongoing disruptions (Hobbs, 2020; Paul et al., 2020a). Moving toward designing a reconfigurable, adaptive, and dynamic SC strategy for risk recovery could alleviate COVID-19's impact (Sharma et al., 2020). Consequently, facemask manufacturers can meet the ongoing demand to leverage their humanitarian and social responsibilities in creating more employment opportunities in the production and distribution sectors (Hobbs, 2020).

The present study's contribution is two-fold. First, we contribute to the literature by developing an agent-based model (ABM) using simulation software with several strategies and recovery plans. This is done to improve products' procurement and production to mitigate the skyrocketing demand for essential items, such as facemasks. Second, we evidence how a simulation-based methodology can analyse and anticipate the impacts of a pandemic situation on SCs using AnyLogic—a simulation modelling software program. This simulation modelling was instrumental in highlighting different strategies to bring resilience to SCs. They can then be implemented when there is a global shortage of essential items in the future.

3.2. Problem description

The demand for essential medical items is at its peak, including facemasks and ventilators, essential food items (e.g. pasta, canned foods, and canned fruits), and essential daily items (e.g. toilet paper and hand sanitiser) (Zhang, 2020; Chowdhury et al., 2020). Consumer demands have surpassed normal times due to the lockdown, which has been exacerbated by the shortage of goods from suppliers. This supply-demand fluctuation is occurring because of two reasons. The primary reason is the disruption of producing essential items due to supply shortages and demand increases from increasing pandemic needs. The second reason is the hoarding behaviour of people (Sim et al., 2020). People have been panic-purchasing and stockpiling essential items, skyrocketing the demand for such items. However, essential items have been scarce in the market during the pandemic situation caused by COVID-19.

Evaluating facemasks can be used as an example to understand the supply-demand and production capacity of essential items during a pandemic in Australia. The facemask demand in Australia increased after Victoria declared the mandatory use of facemasks, while other states encouraged their use to combat further COVID-19 cases (Stead, 2020). The compulsory use of facemasks resulted in an approximately 400% demand increase for these items (Dewey et al., 2020). This sudden demand increase left many retailers without stock. Social media often exaggerates the news of shortages. There has been an enormous customer boom at clinical suppliers through mid-July 2020 (Dewey et al., 2020). Following the NSW Government Health advice, wearing a facemask while using public transport has been strongly recommended (NSW Government, 2020). This recommendation has further increased the demand for facemasks. Manufacturers are attempting to increase their production of essential items to meet this increasing demand (H. liang Wu et al., 2020). However, the demand keeps growing as the pandemic worsens and consumers panic-buy essential items. This increased demand for essential items during a pandemic is related to a supply shortage of raw materials, inadequate production capacity, transportation disruption, and consumers' panic-purchasing tendencies. Consequently, health workers and the public cannot access essential items, such as facemasks, during a pandemic. Thus, the present study aimed to determine possible strategies for increasing the supply of facemasks to consumers.

3.3. Proposed strategies and model formulation

This section explains the proposed mitigation strategies and formulation of an SC recovery disruption simulation model for experimentation.

3.3.1. Proposed strategies and SC disruption recovery plans

During extraordinary pandemic situations, such as COVID-19, we propose the strategies listed below to increase raw material supply and essential item production to serve the increased consumer demand. The objective was to meet the demand for facemasks and mitigate SC's financial shock and lost service levels during a pandemic.

The present study considered and analysed the following two main strategies to increase the supply of raw materials and production capacity and ensure an adequate supply of facemasks to consumers.

Strategy 1: Emergency supply to increase the supply of raw materials

The first strategy aimed to increase the supply of raw materials for production facilities to produce more facemasks. The following sub-strategies were considered to increase the raw material supply.

A. Increase suppliers from different locations

We proposed increasing suppliers from different geographical locations, including at least one local supplier, to help manufacturers obtain the correct amount of raw materials for a quick disruption recovery (Sayed et al., 2020).

B. Maximise use of national medical stockpile and available supply

This strategy is a part of agile SCs (Tarafdar et al., 2017). The national medical stockpile aims to hold and purchase sufficient supplies to help meet the high demand for medical equipment (e.g. personal protective equipment) during a national emergency (Australian Government Department of Health, 2020). Therefore, the national medical stockpile could maximise their sourcing capacity and raw materials of facemasks to quickly mitigate the demand disruption (Australian Government Department of Health, 2020; Hsin Chang et al., 2019).

C. Redeploy existing inventory from other industries

This strategy is a part of flexible and adaptive SCs (Paul et al., 2020b; Poudel et al., 2020). Under this strategy, manufacturers must collaborate and share information, resources, and backup suppliers as part of their humanitarian SC to mitigate SC disruptions during a pandemic (Ivanov et al., 2020). This horizontal collaboration has been discussed previously in Barratt (2004), Pomponi et al. (2015), and Scholten et al. (2015).

Strategy 2: Increase the production capacity

The second strategy was to increase the production capacity using the following sub-strategies.

A. Maximise the capacity of existing manufacturers

This strategy is a part of the resiliency and transformability of SCs (Lopes de Sousa Jabbour et al., 2020). Manufacturers can hire more people and arrange more operational shifts to continue production 24/7, leveraging corporate social responsibilities by providing extended employment opportunities (Paul et al., 2020b).

B. Develop alternative specifications and designs

Various facemasks exist for health workers and the general population. We proposed that manufacturers collaborate to produce a single quality surgical facemask to suit all purposes at a minimum price to increase the production capacity and thus meet the maximum consumer demand during a pandemic (Hobbs, 2020; Paul et al., 2020b).

C. Unlock new capacity for manufacturers

Facemask manufacturers can purchase and deploy new automated machines to increase facemask production while maintaining long-term financial benefits (Cai et al., 2020). Many similar industries, such as garment factories, produce fabric- and cloth-related products could quickly decide to make facemasks to meet the increased demand. Few studies have investigated introducing new production lines in relevant manufacturers; however, some significant examples have been found in practice, as stated by ABC News (2020).

D. Public-private collaborative efforts to overcome shortages

Public-private collaborative efforts could be enhanced to overcome essential item shortages during disrupted situations (Cai et al., 2020). The government could promote subsidies for capital investment to essential item factories and other manufacturing facilities. They could further support raw materials procurement as emergency economic measures. Further, the business community could request the government to initiate a subsidy project (Ministry of Economy, Trade, and Industry, 2020).

The present study analysed four scenarios on production capacity increases, as shown in **Table 3.1**.

Table 3.1: Scenarios considered in the present study

Scenario	Recovery Period	Increase in Production Capacity
Scenario 1 (**S1**)	Long (18 months)	Low (+50%)
Scenario 2 (**S2**)	Short (6 months)	Low (+50%)
Scenario 3 (**S3**)	Long (18 months)	High (+100%)
Scenario 4 (**S4**)	Short (6 months)	High (+100%)

We proposed four recovery plans based on these strategies and scenarios.

Recovery plan 1 (RP1): In this recovery plan, we gradually increased the production capacity up to 50% with increased raw materials over a long period of up to 18 months under **S1**.

Recovery plan 2 (RP2): In this recovery plan, we gradually increased the production capacity up to 50% with increased raw materials over a short period of up to 6 months under **S2**.

Recovery plan 3 (RP3): In this recovery plan, we gradually increased the production capacity up to 100% with increased raw materials over a long period of up to 18 months under **S3**.

Recovery plan 4 (RP4): In this recovery plan, we gradually increased the production capacity up to 100% with increased raw materials over a short period of up to 6 months under **S4**.

We compared the SC performances for facemasks in normal and disrupted situations caused by the COVID-19 pandemic, respectively. The SC model involving facemasks was developed using an ABM simulation framework. The model formulation details are provided in the following sub-section.

3.3.2 Model formulation

This section proposes the ABM that simulates a typical SC for facemasks to compare and analyse the SC risk recovery scenarios (discussed in Section 3.3). **Figure 3.1** offers a conceptual overview of the proposed agent-based SC system.

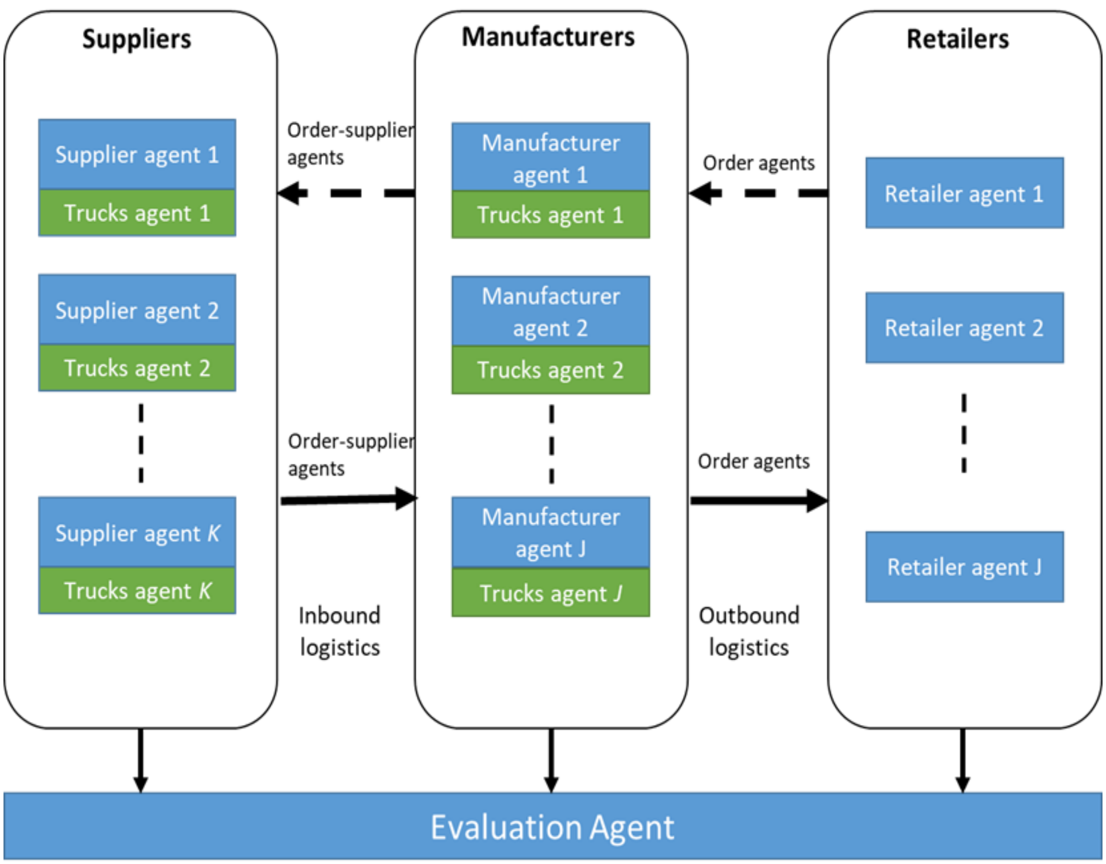

Figure 3.1: Overall conceptual overview of the proposed agent-based SC system

The proposed model agents represent SC entities in the real world. They simulate specific functions to fulfil retail orders by coordinating SC entities (Ivanov, 2017). We considered a typical SC network of facemasks, involving a set of suppliers, manufacturers, and retailers together with a set of supplier and manufacturer transport trucks to fulfil the incoming orders for the finished products and raw materials (Mizgier et al., 2012; Zhang et al., 2017). The pack size of the finished products is considered a carton, where each carton contains 100 facemasks.

The costs considered in the analysis framework include the following:

- manufacturing costs (MCs; including the sourced raw material costs from suppliers)
- transportation costs (TCs) for suppliers and manufacturers
- inventory costs (ICs) for manufacturers and retailers
- shortage costs (ShCs) at the manufacturing stage

Seven suppliers, three manufacturers, and 18 retailers were included in the current model. These agents collectively attempt to satisfy incoming product orders from retailers while meeting various performance objectives (e.g. lead time and total SC costs). **Appendix B** shows the model parameters (**Table B2**), the agent details (**Table B3**), and the cost metric equations evaluated by the agents for each period.

The list of parameters used in each agent (see **Table B4, Table B5,** and **Table B6 in Appendix B**) and the assumed changes in demand, production, and supply of facemasks (**Figure B1**) are also shown in **Appendix B**.

3.4. Scenario analysis and outcomes

3.4.1. Baseline scenario

In the simulation model, we compared the total SC of facemask production under normal and disrupted situations caused by the COVID-19 pandemic. The simulation was run for a maximum of two years for better prediction and analysis.

Normal baseline situation without the COVID-19 pandemic (BS0): There was no disruption to the SC in the normal situation. The ABM was simulated using all baseline parameters and without disruption (i.e. simulating 'business-as-usual'). The results from the simulation model indicated that no ShCs were incurred (**Figure 3.2**). Therefore, the existing SC for facemasks could effectively fulfil the market demand.

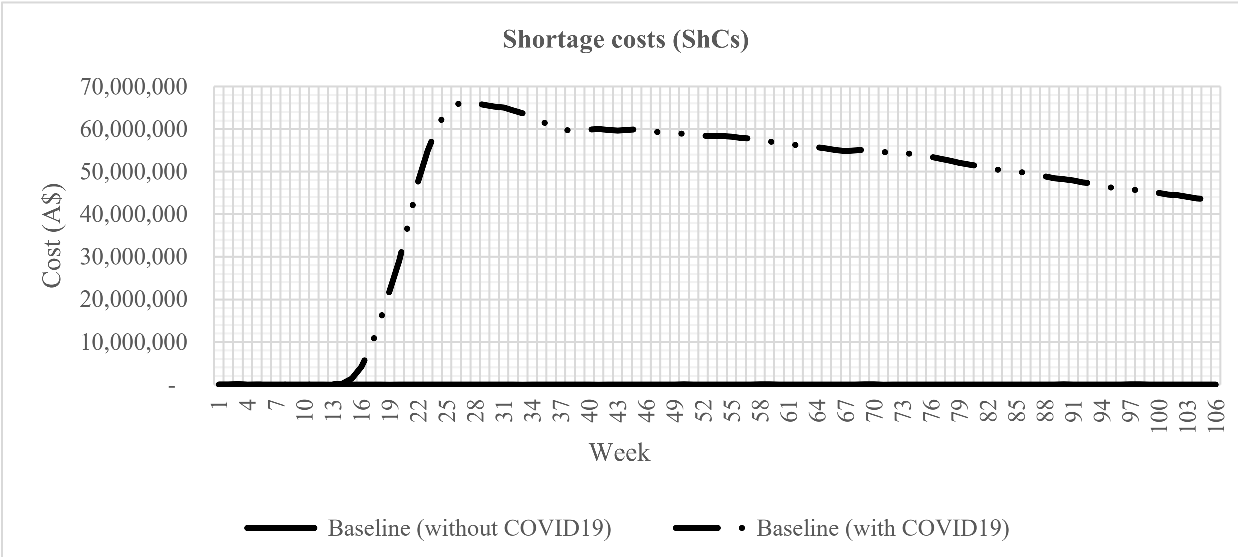

Figure 3.2: Shortage costs in normal and disrupted situations

Disrupted baseline situation with the COVID-19 pandemic (BS1): In the disruption situation, the supply and demand shock significantly impacted facemask production and supply. Our model assumed that demand, production, and supply capacity disruptions began after 10 weeks of the simulated run, as depicted in **Figure B1** in **Appendix B**. The demand for facemasks increased rapidly from week 11, with a 50% increase, and peaked at 18–20 weeks, with a 400% increase. This demand was later reduced and stabilised at a 15% increase in the average demand. Similarly, the production disruption began in week 11, with a 5% decrease in overall production capacity. We included a supplier capacity decrease under disruption, with the highest decrease occurring at 18–22 weeks. Also included was a production capacity decrease to simulate the impact on production levels due to lockdowns and physical distancing (see **Figure B1 in Appendix B)**.

We included changes in the SC model's demand, manufacturing capacity, and supplier capacity. The ShCs from the simulation are shown in **Figure 3.2**. If the manufacturing production capacity was not increased, supply and demand disruptions could lead to high ShCs. **Figure 3.2** shows that the ShCs started increasing from week 15 and peaked at week 28, with ShCs of A$66 million (approx.). Therefore, demand disruption during the pandemic significantly impacted the supply of essential items, such as facemasks. We simulated immediate recovery plans by increasing the production capacity to determine SC improvements during a disrupted situation. This was done to mitigate the demand disruption in the facemask SCs.

3.4.2. Impact of disruption on SCs

The performances of the SCs in a baseline scenario with the COVID-19 pandemic are shown in Figures 3.3 to 3.7. The following text details the disruption's impact on the SC in the baseline scenario.

Total supply chain costs (TSCCs): The TSCCs remained at approximately A$3 million per week with fluctuations up to week 13 in the disrupted situation. The TSCCs started increasing in week 13 and peaked in week 27 before improving slightly and remaining there until week 105. During the last week, the TSCCs were A$49 million (approx.) for BS1 in Figure 3.3.

Shortage costs (ShCs): The ShCs started increasing in week 15 and peaked in week 28. The ShCs stayed high until the last week, with increased ShCs of A$42 million (approx.), as depicted for BS1 in Figure 3.4.

Transportation costs (TCs): The TCs remained between A$0.15 and A$0.22 million (approx.), as seen for BS1 in Figure 3.5.

Manufacturing costs (MCs): The MCs remained between A$4 and A$5 million (approx.) in the disrupted situations depicted for BS1 in Figure 3.6.

Inventory costs (ICs): The ICs started increasing in week 36 and peaked during that week before decreasing until week 92. After week 92, the IC was normalised with A$0.2 million (approx.), as depicted for BS1 in Figure 3.7.

3.4.3. Immediate recovery plans and outcomes

We tested four recovery plans to improve facemask manufacturing firms' SC, including production capacity increases over short- and long-term periods. The recovery plans were as follows.

Recovery plan 1 (RP1): Under this plan, the production capacity gradually increased to 50% over a long period of 18 months. The model results are illustrated under Scenario 1 (**S1)** in **Figures 3.3** to **3.7**, describing the TSCCs (**TSCC1**), ShCs (**ShC1**), TCs (**TC1**), MCs (**MC1**), and ICs (**IC1**).

Recovery plan 2 (RP2): Under this plan, the production capacity gradually increased to 50% over a short period of 6 months. The model results are illustrated under Scenario 2 (**S2)** in **Figures 3.3** to **3.7**, describing TSCCs (**TSCC2**), ShCs (**ShC2**), TCs (**TC2**), MCs (**MC2**), and ICs (**IC2**).

Recovery plan 3 (RP3): Under this plan, the production capacity gradually increased to 100% over a long period of 18 months. The model results are illustrated under Scenario 3 (**S3)** in **Figures 3.3** to 3.7, describing TSCCs (**TSCC3**), ShCs (**ShC3**), TCs (**TC3**), MCs (**MC3**), and ICs (**IC3**).

Recovery plan 4 (RP4): Under this plan, the production capacity gradually increased to 100% over a short period of 6 months. The model results are illustrated under Scenario 4 (**S4)** in **Figures 3.3** to **3.7**, describing TSCCs (**TSCC4**), ShCs (**ShC4**), TCs (**TC4**), MCs (**MC4**), and ICs (**IC4**).

Comparative discussion of the outcomes

Total supply chain costs (Figure 3.3): In the disrupted situation, the TSCCs started increasing in week 13, peaked in week 28, and remained at high levels, as seen for **BS1** in **Figure 3.3.** We increased the capacity by 50% for **RP1** and **RP2** over the long- and short-term, respectively, to recover from the disruption. When **RP1** was implemented under **S1**, the **TSCC1** peaked in week 28 and remained high until week 67, when it became normalised. Meanwhile, when **RP2** was implemented under **S2**, the **TSCC2** peaked in week 30. It stayed higher than all other recovery plans up to week 92 before becoming normalised. **RP1** reduced the SC costs better than **RP2**. We also increased the capacity by 100% for **RP3** and **RP4** over the long- and short-term, respectively. When **RP3** was implemented under **S3**, the **TSCC3** peaked in week 27 and remained high until week 67. The **TSCC3** of **RP3** was lower than that of **RP1** and **RP2** but higher than that of **RP4**. Finally, when **RP4** was implemented under **S4**, **TSCC4** peaked in week 25. Following this, it started improving and became normalised at week 41. **RP4** produced better results because **TSCC4** was lower than the other recovery plans.

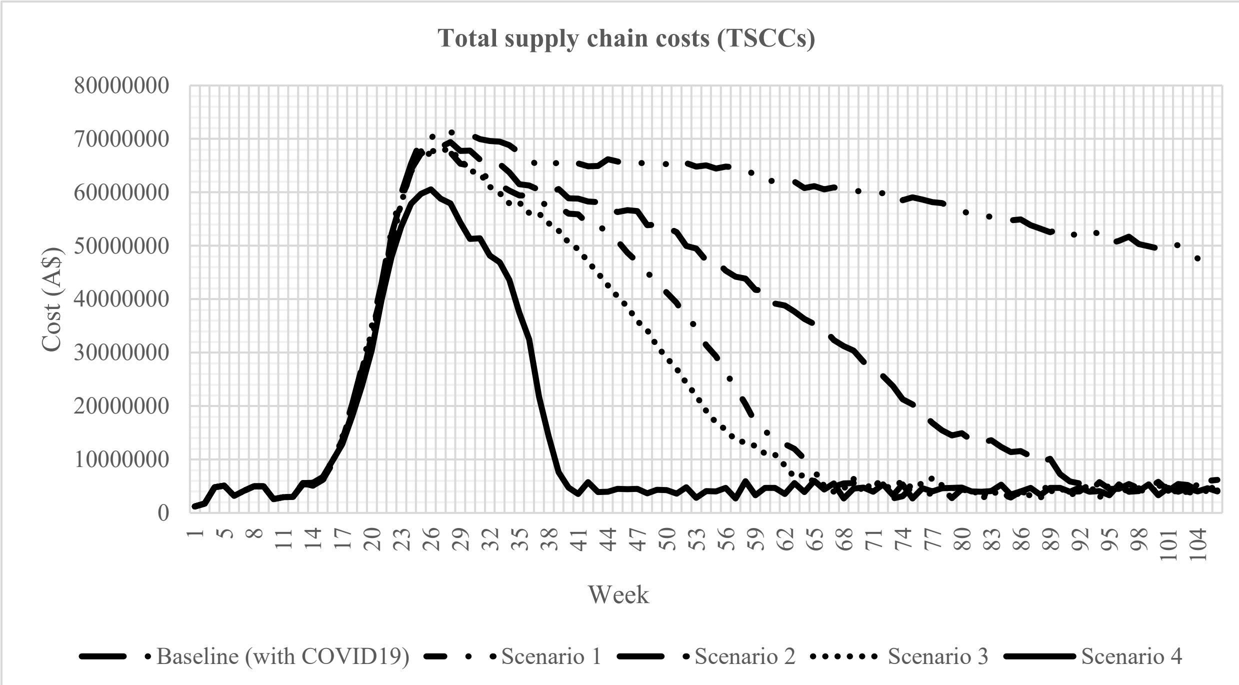

Figure 3.3: Total supply chain costs for the recovery plans under different scenarios

Shortage costs (Figure 3.4): The ShCs started increasing in week 15, peaked in week 28, and stayed very high in the disrupted situation, as seen for **BS1** in **Figure 3.4**. When **RP1** was implemented under **S1**, **ShC1** peaked in week 28 before starting improving and becoming normalised at week 67. However, when **RP2** was implemented under **S2**, **ShC2** peaked in week 28 and stayed high until week 92 before normalising. **ShC2** was higher than that of the other recovery plans. When **RP3** was implemented under **S3**, **ShC3** peaked in week 28 and stayed lower than that of **RP1** and **RP2** but higher than that of **RP4** until week 68 before becoming normalised. Finally, when **RP4** was implemented under **S4**, **ShC4** peaked in week 26 before improving and normalising from week 39. Thus, **RP4** lowered the ShCs better than the other recovery plans.

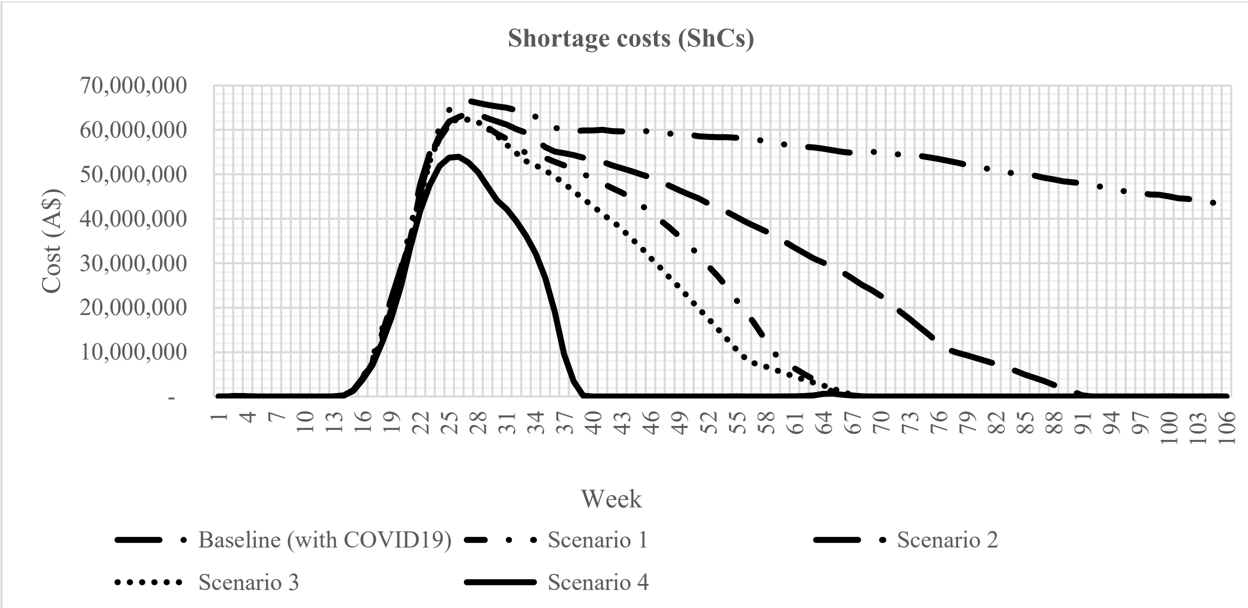

Figure 3.4: Shortage costs for the recovery plans under different scenarios

Transportation costs (Figure 3.5): TC1, **TC2**, and **TC3** remained almost the same during the implementation period of **RP1** under **S1**, **RP2** under **S2**, and **RP3** under **S3**. However, when **RP4** was implemented under **S4**, **TC4** was high between weeks 32 and 42 before normalising. Although the initial TCs for **RP4** were higher than the other recovery plans, **Figures 3.3** and **3.4** show that **TSCC4** and **ShC4** of **RP4** were lower than the other recovery plans, respectively.

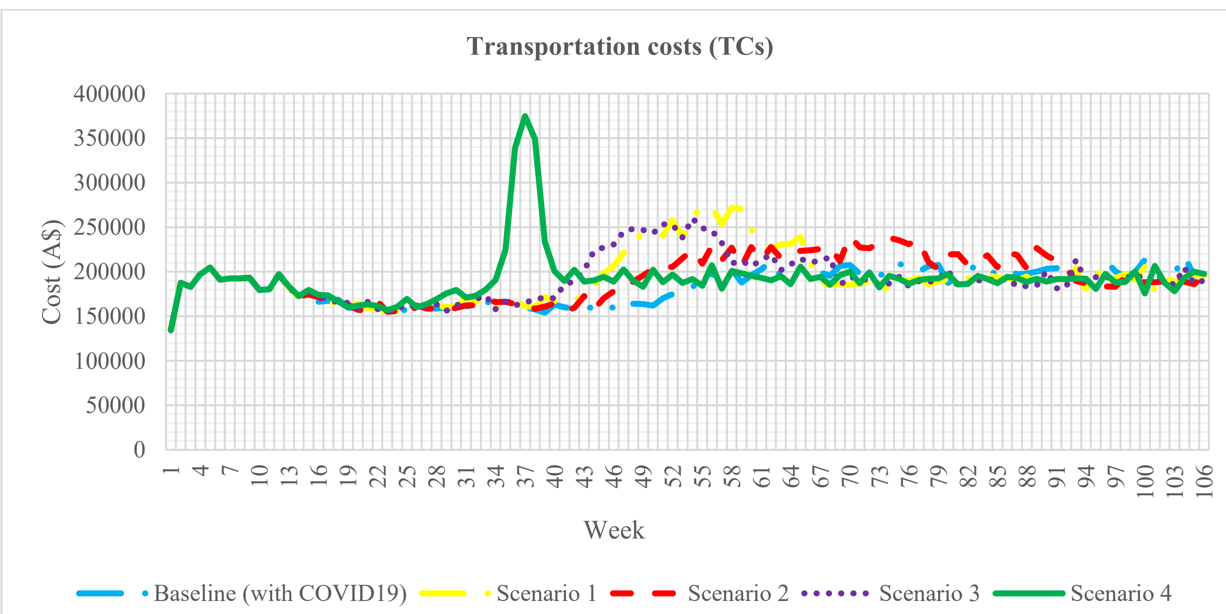

Figure 3.5: Transportation costs for the recovery plan under different scenarios

Manufacturing costs (Figure 3.6): MC1, **MC2**, and **MC3** remained almost the same during the implementation period of **RP1** under **S1**, **RP2** under **S2**, and **RP3** under **S3**. However, when **RP4** was implemented under **S4**, **MC4** became high between weeks 25 and 41 before normalising. Although the initial MCs for **RP4** were higher than that of the other recovery plans, **Figures 3.3** and **3.4** show that **TSCC4** and **ShC4** of **RP4** were lower than the other recovery plans, respectively.

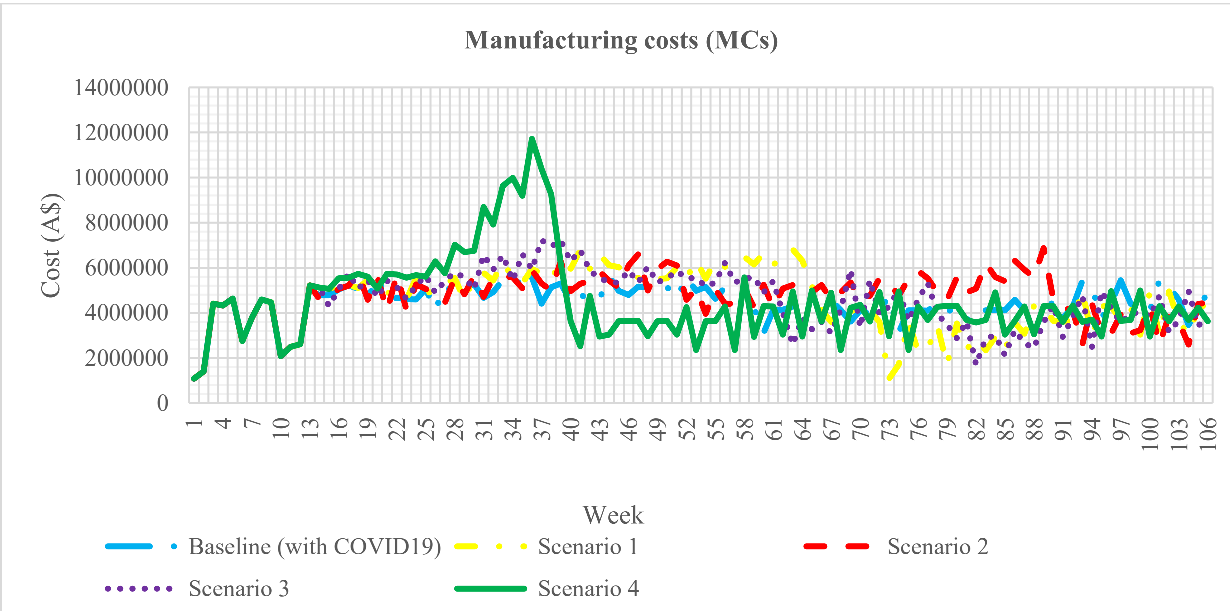

Figure 3.6: Manufacturing costs for the recovery plans under different scenarios.

Inventory costs (Figure 3.7): ICs started increasing in week 36, peaked in week 58, and stayed high during the disrupted situation, as seen for **BS1** in **Figure 3.7**. When **RP1** was implemented under **S1**, **IC1** peaked in week 45 and again in week 72 before starting to improve and normalising in week 87. When **RP2** was implemented under **S2**, **IC2** peaked in week 52 and stayed high up to week 78 before increasing and staying very high during the last week. **IC2** was higher than that of the other recovery plans. When **RP3** was implemented under **S3**, **IC3** peaked in week 42 before improving and again peaking in week 80. However, it stayed lower than **RP1** and **RP2** but higher than **RP4** up to week 92. Finally, when **RP4** was implemented under **S4**, **IC4** peaked in week 37 before improving and normalising in week 57. **RP4** lowered the ICs better than that of the other recovery plans.

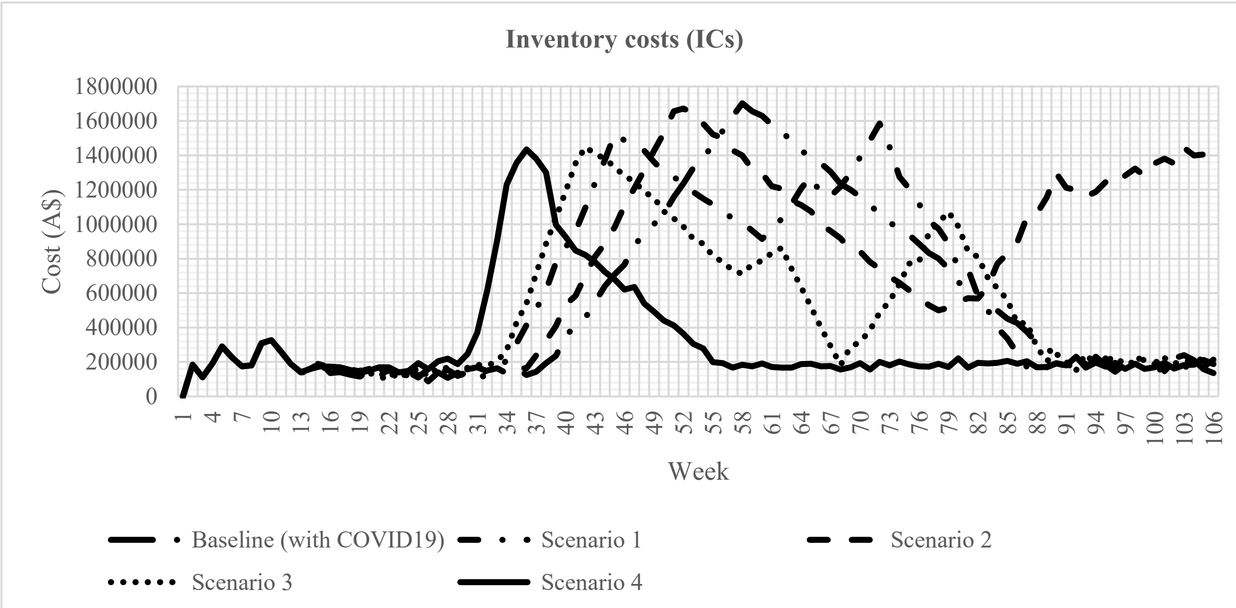

Figure 3.7: Inventory costs for the recovery plans under different scenarios

3.4.4. Delayed recovery plans and outcomes

We tested the immediate and delayed plans for **RP4** under **Scenario 4** (immediate and delayed implementation). Following this, we analysed the impact of the recovery plan implementation time on overall SC costs, as presented in **Figure 3.8**.

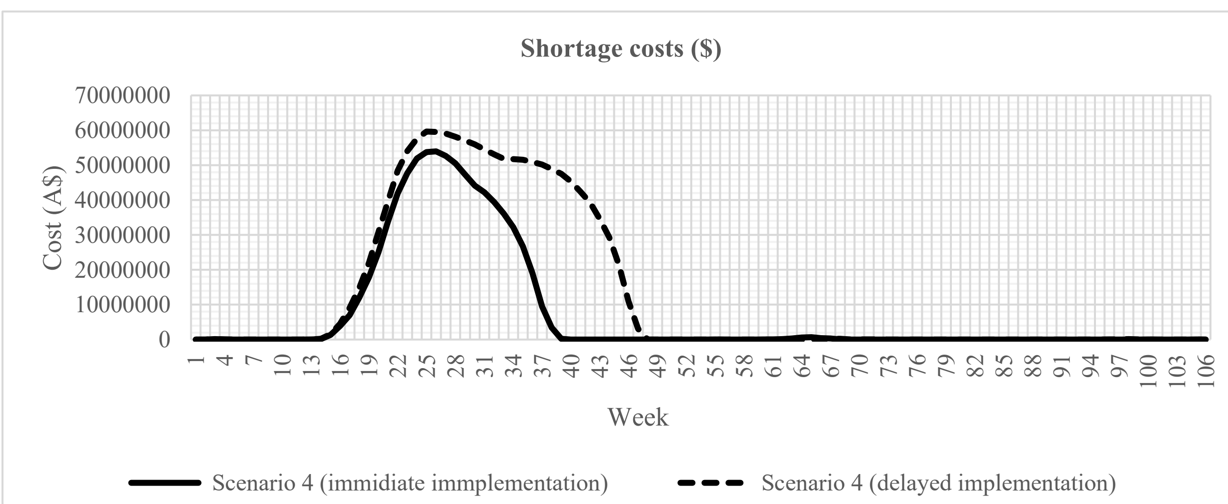

Figure 3.8: Shortage costs of immediate and delayed implementation for Scenario 4

In **RP4**, the production capacity gradually increased to 100% within 6 months. The ShCs remained normal up to week 14 for the immediate implementation of the recovery plan (**Figure 3.8**). From week 15, the ShCs started increasing and peaked in week 26, with increased ShCs of A$54 million (approx.). After week 26, the ShCs decreased but stayed high until week 39. After that, the ShCs started normalising until week 105 in **Scenario 4 (immediate implementation)** of **Figure 3.8**.

After delaying the implementation of **RP4** by 2 months, we noticed that the ShCs of **Scenario 4 (delayed implementation)** remained normal up to week 14 before starting to increase in week 15. The ShCs in the delayed implementation peaked in week 25, with increased ShCs of A$60 million (approx.), much higher than the immediate implementation in **Scenario 4 (immediate implementation)**. In the delayed implementation, the ShCs started decreasing in week 25 but stayed high up to week 48, much higher than the ShCs in the immediate implementation. After week 48, the ShCs in the delayed implementation started normalising until week 105.

Therefore, the immediate and delayed implementation analysis highlights that the ShCs in the delayed implementation of **RP4** were much higher than that of the ShCs in the immediate implementation of **RP4.** Therefore, the speedy congruent recovery plan implementation reduced the SC costs of manufacturing firms of essential items, such as facemasks.

3.4.5. Sensitivity analysis

A One-Factor-At-a-Time (OFAT) method was applied to observe the sensitivity of model outputs against the selected set of input parameters. We considered a variance of (±10%) of the base case values of demand, maximum inventory policy (S), and minimum inventory policy (s).

Variance in total supply chain costs (TSCCs): TSCCs are more sensitive to changes in demand than changes in other parameters, such as the maximum inventory policy (S) and minimum inventory policy (s). A 10% increase in the demand resulted in a 21.72% increase in the average TSCCs. The TSCCs increased due to increased shortage costs (ShCs). The existing SC capacity could not meet the sky-rocketing demand due to supply failures during the COVID-19 pandemic lockdown. The leftover variances in TSCCs are reported in **Table 3.2**.

Variance in shortage costs (ShCs): The sensitivity analysis indicates that the model is most sensitive to shortage costs (ShCs) with the demand changes. A decrease and an increase of 10% in demand lead to a 139.14% and 213.06% increase in average ShCs, respectively. The existing SC cannot increase the production capacity due to the supply failing to meet the huge demand. Therefore, the ShCs increased. The average ShCs remained high compared to the baseline condition with no disruption, even when the demand decreased by 10%. When the maximum inventory policy (S) increased, the average ShCs increased correspondingly as they did not have sufficient capacity to fill the required inventory level to meet increasing demands. Therefore, when the maximum inventory policy (S) decreased, the ShCs were slightly lower because of the policy relaxation. For the changes (±10%) in the minimum inventory policy (s), ShCs are usually higher than normal. This is because the insufficient production capacity does not allow the existing SC to maintain a minimum inventory level, thus increasing the ShCs. The ShCs variances are reported in **Table 3.2**. **Figures 3.9–3.11** offer details on the sensitivity analysis for ShCs with changes in the parameters.

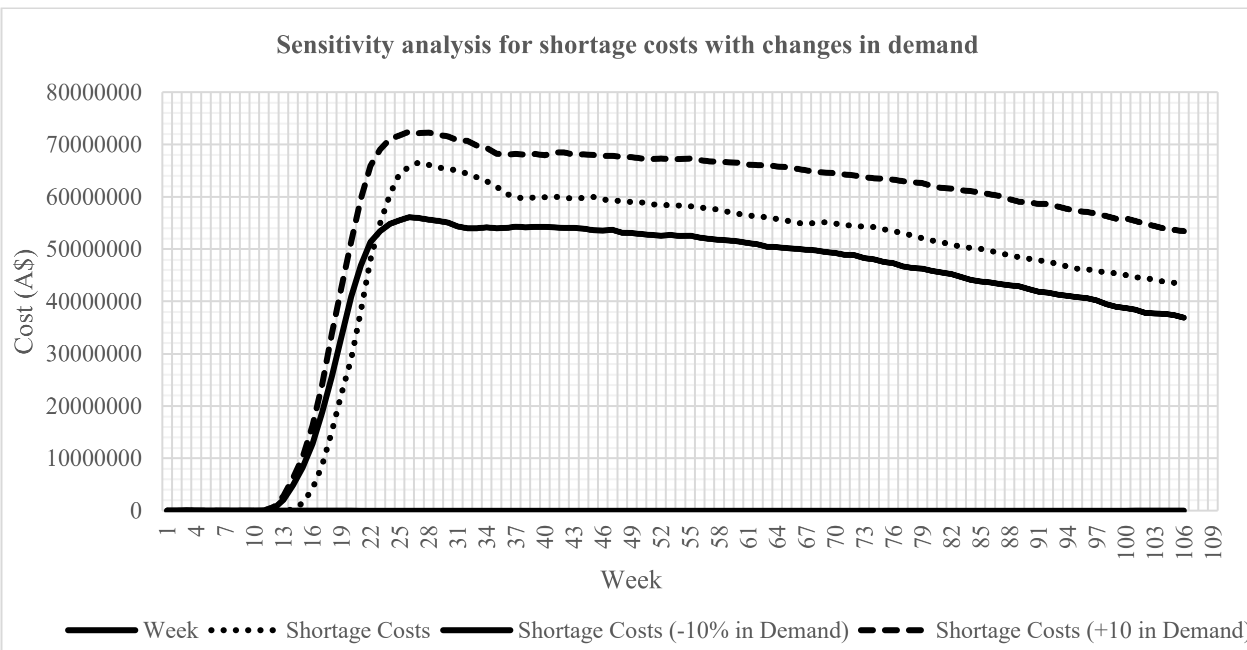

Figure 3.9: Sensitivity analysis for shortage costs with changes in demand

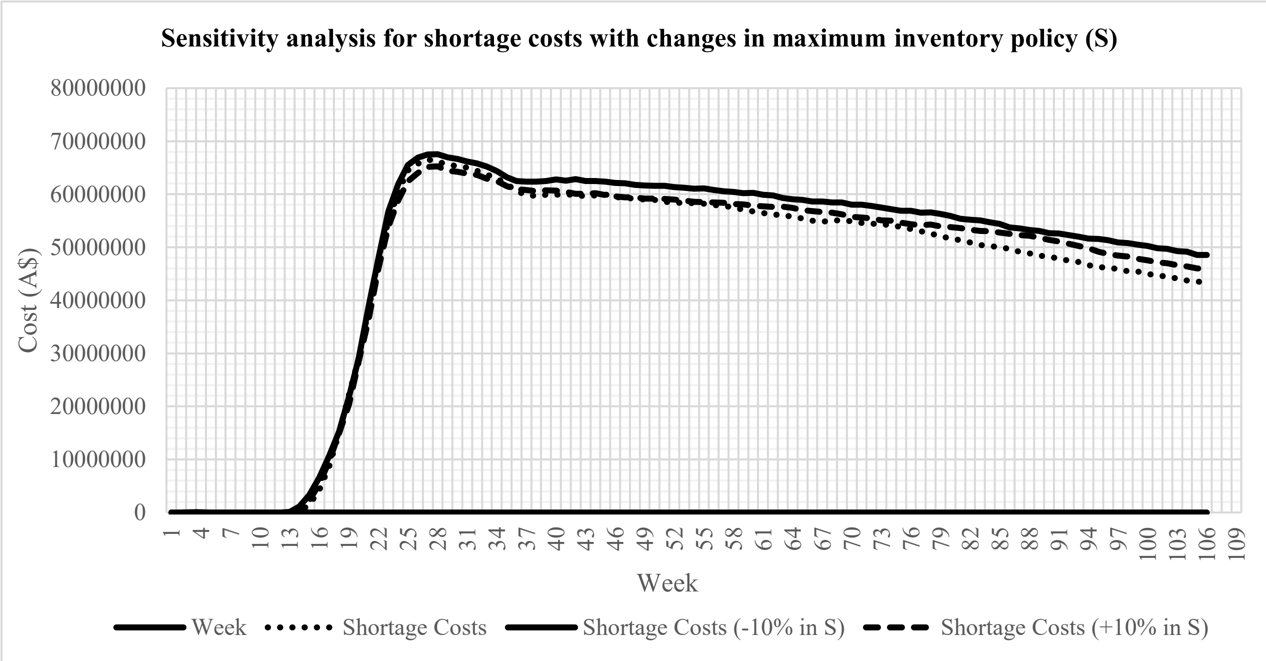

Figure 3.10: Sensitivity analysis for shortage costs with changes in the maximum inventory policy (S)

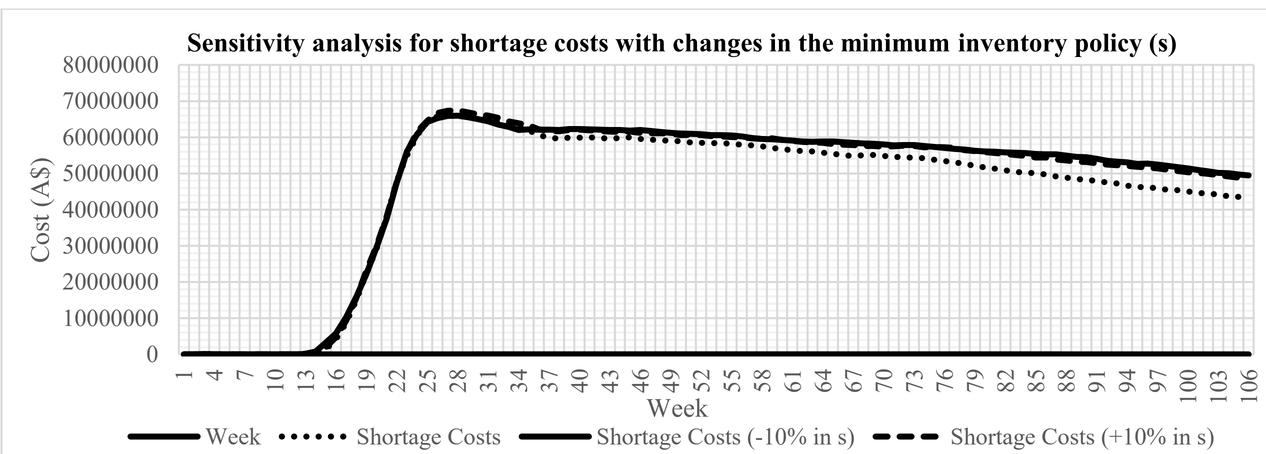

Figure 3.11: Sensitivity analysis for shortage costs with changes in the minimum inventory policy (s)

Variance in transportation costs (TCs), manufacturing costs (MCs), and inventory costs (ICs): The sensitivity analysis reveals that changes in parameters, such as the demand, maximum inventory policy, and minimum inventory policy, do not significantly vary transportation costs (TCs) and manufacturing costs (MCs) from their base values. Similarly, the inventory costs (ICs) are also less sensitive to the parameters' changes. The demand surged, and manufacturers failed to increase the production capacity due to a supply failure caused by the COVID-19 pandemic. Consequently, ShCs increased, but the other costs (e.g. TCs, MCs, and ICs) did not drastically increase due to the shutdown of manufacturing sites, slowed delivery, and supply failure during the lockdown. **Table 3.2** provides a synopsis of the sensitivity analysis.

Table 3.2: Synopsis of the sensitivity analysis

Parameters	**Rate of change**	**Average variance in total supply chain costs (TSCCs)**	**Average variance in shortage costs (ShCs)**	**Average variance in transportation costs (TCs)**	**Average variance in manufacturing costs (MCs)**	**Average variance in inventory costs (ICs)**
Demand	**-10%**	-2.57%	+139.14%	+1.21%	+0.38%	+5.84%
	+10%	+21.72%	+213.06%	-1.09%	+1.27%	+17.40%
Maximum inventory policy (S)	**-10%**	+5.05%	+19.08%	+0.08%	-1.20%	-12.17%
	+10%	+2.79%	+2.11%	-0.05%	+3.55%	+10.18%
Minimum inventory policy (s)	**-10%**	+5.02%	+16.43%	-0.09%	-0.12%	-6.78%
	+10%	+4.81%	+14.61%	+0.25%	+0.77%	+5.90%

During the COVID-19 pandemic, demand disruptions and supply failures significantly impacted SCs because of the lockdown situations. TSCCs increased because of the significant increase in ShCs due to the pandemic's demand surge and supply failure. Notably, robust recovery strategies, such as increasing production capacities with smooth and increased supply (discussed in Section 3.3), are necessary to tackle such extraordinary demand and supply disruptions in any global pandemic situation.

3.5. Results, analysis, and discussion

3.5.1. Impact of increasing emergency raw materials

The raw materials for facemask manufacturers can be increased by maximising the use of available supplies, emergency sourcing from the national stockpile, redeploying inventory from other industries by horizontal and vertical collaborations, and emergency and collective resource sharing among manufacturers. The increase in raw materials positively impacts production during pandemics, when there are huge supply and demand shocks. The production capacity increased to 50% over the long- and short-term in **RP1** and **RP2**, respectively, using increased raw materials. It further increased to 100% over the long- and short-term in **RP3** and **RP4**, respectively. **Figure**

3.3 and **Table 3.3** show a huge improvement in TSCCs when the production capacity increased quickly using the increased raw materials in demand disruption.

3.5.2. Impact of increasing production capacity

Facemask manufacturers can increase their production capacity by maximising their capacity. This can be achieved by increasing the number of shifts, hiring more staff, developing single-quality products for all-purpose use, increasing public-private collaboration, and implementing the proposed strategies for increasing emergency raw materials.

We chose four recovery plans to increase the production capacity to various degrees over different short- to long-term timeframes. A decreased cost represents an efficient plan, whereas an increased cost represents a less efficient plan. A recovery plan that decreases the SC costs is an efficient plan, whereas a recovery plan that increases the SC costs is a less efficient plan. The comparison of the efficiency of the recovery plans based on the extent to which they reduced the SC costs is shown in **Figures 3.3** to **3.7** and **Table 3.3.**

The order of the TSCCs of the four recovery plans is as follows:

TSCC4 (RP4) < TSCC3 (RP3) <TSCC1 (RP1) <TSCC2 (RP2)

The order of the ShCs of the four recovery plans is as follows:

ShC4 (RP4) < ShC3 (RP3) < ShC1 (RP1) < ShC2 (RP2)

The order of the ICs of the four recovery plans is as follows:

IC4 (RP4) < IC3 (RP3) < IC1(RP1) < IC2 (RP2)

Table 3.3: Ranking of the recovery plans based on costs (1 = Decreased cost to 4 = Increased cost)

Recovery Plans (RPs)	Total Supply Chain Costs (TSCCs)	Ranking	Shortage Costs (ShCs)	Ranking	Transportation Costs (TCs)	Ranking	Manufacturing Costs (MCs)	Ranking	Inventory Costs (ICs)	Ranking	Overall Ranking of RPs
RP1	TSCC1	3	ShC1	3	TC1	1	MC1	1	IC1	3	**3**
RP2	TSCC2	4	ShC2	4	TC2	1	MC2	1	IC2	4	**4**

RP3	TSCC3	2	ShC3	2	TC3	1	MC3	1	IC3	2	**2**
RP4	TSCC4	1	ShC4	1	TC4	2	MC4	2	IC4	1	**1**

For **TSCC4, ShC4,** and **IC4**, **RP4** was the most efficient of all plans as it reduced the SC costs most efficiently. **RP3** was ranked second. **TSCC3, ShC3,** and **IC3** of **RP3** were higher than **RP4**; however, **RP3** reduced the SC costs better than **RP1** and **RP2. RP1** was ranked third. **TSCC1, ShC1,** and **IC1** of **RP1** were higher than **RP3** and **RP4**; however, **RP1** reduced the SC costs better than **RP2. RP2** was ranked fourth because **TSCC2, ShC2**, and **IC2** were higher than the other proposed recovery plans.

TCs and MCs were almost the same for **RP1, RP2**, and **RP3.** However, the initial TCs and MCs were higher than the other recovery plans for **RP4.** Indeed, production capacity increased by 100% in a short period in the first 6 months in **RP4** to mitigate the skyrocketing demands. Later, the higher initial TCs and MCs of **RP4** became normalised very quickly, reducing the TSCCs, as depicted in **Figures 3.3** to **3.7** and **Table 3.3**.

3.5.3 Findings from the recovery plans

When there are huge supply and demand shocks in any disrupted situation, the SC resilience of essential item manufacturers is determined by efficiently increasing raw materials and the production capacity to meet the increasing demand. Our findings showed that resiliency, agility, and adaptability are vital for reducing SC risks in disruption situations. Managerial insights from the findings are discussed below.

Managerial insight 1:

When the proposed recovery plans were compared concerning the recovery period, **RP4** demonstrated the best short-term performance. As the production capacity increased to 100% over a short period, **RP4** decreased the TSCCs lower than the other recovery plans. Meanwhile, **RP2** was the least efficient of all the recovery plans. Although the production capacity of **RP2** increased over the short term, the capacity increased by 50% less than that of **RP4.**

The findings reveal that short-term quick responsive recovery plans work best if a higher production capacity percentage gradually increased in the short-term following the supply-demand shock in any disruption situation to minimise the financial shock.

Managerial insight 2:

When we compared **RP1's** and **RP3's** recovery periods, **RP3** performed better than **RP1** over the long term. In **RP3**, the production capacity gradually maximised to 100% over a long period. Therefore, the TSCCs of **RP3** were lower than those of **RP1**. Meanwhile, the long-term production capacity in **RP1** was 50% less than that of **RP3.** Therefore, the TSCCs of **RP1** were higher than those of **RP3**.

The findings reveal that the long-term recovery plans worked well when a higher production capacity percentage gradually increased in the long-term following the supply-demand shock in any disruption situation to minimise the financial shock.

Managerial insight 3:

RP4 had the highest production capacity increase as the capacity increased gradually to 100% over the short term. Thus, the TSCCs of **RP4** were lower than the other recovery plans. However, when we compared **RP4** with **RP3,** the TSCCs of **RP3** were higher than that of **RP4.** However, the production capacity increased gradually to 100%, similar to **RP4**, but in the long term.

Suppose the maximum raw material was available and managed per the supply-demand shock in a disruptive situation. In this case, the findings suggest we should use the production's maximum capacity quickly in the short term to maximise the benefits. Essential item manufacturers must upgrade their machines, equipment, technology, and workforce and escalate sourcing raw materials, as suggested by Paul et al. (2020b). This would increase production capacity over a short period during demand spikes, which should increase SC resiliency in any disruption situation.

Managerial insight 4:

RP1 had better production capacity than **RP2**. The production gradually increased to 50% in **RP1** over a long-term period, and the TSCCs of **RP1** were lower than that of **RP2**. Similarly, the production capacity gradually increased to 50% in **RP2** over a short-term period. Therefore, the TSCCs of **RP2** were higher than that of **RP1**.

Suppose the managed and available raw materials were lower than needed per the supply-demand shock in a disruptive situation. In this case, findings suggest utilising the production capacity for a long time to maximise the benefits is better. Essential item manufacturers must upgrade their forecast technology to predict the essential item demand during any disrupted situation to escalate the sourcing capacity (Rainisch et al., 2020). If they fail to manage the correct amount of raw materials per the predicted demand, they should utilise fewer raw materials to increase the production capacity over the long term. They could limit taking orders to sustain their goodwill in the market by fulfilling the demand for a longer time.

Managerial insight 5:

RP4 was the best recovery plan as the production capacity was maximised to 100% over a short period. Therefore, the TSCCs were lower than that of all other recovery plans.

From **RP4,** when the production capacity was maximised in any disruption over the short term, the TSCCs reduced quickly, but the initial TCs and MCs remained high. Nevertheless, this initial high investment in **RP4** reduced the TSCCs, improving the SCs. Thus, if essential item manufacturers can increase their production capacity to meet high demands during a disrupted situation, they should pay the initial high TCs and MCs for long-term benefit.

Managerial insight 6:

When comparing the responsiveness of recovery plans, the immediate and quick implementation of congruent recovery plans reduced essential item manufacturers' SC costs in any disruption (**Figure 3.8**). The delayed implementation of recovery plans increased the ShCs and TSCCs in any disruptive situation with a huge supply-demand shock. Essential item manufacturers should act quickly to increase their production capacity to meet high product demands in any disruption to reduce financial shock and make their SCs more agile, resilient, and responsive (Ivanov, 2020).

Managerial insight 7:

Essential item manufacturers must immediately determine product demand increase and synchronise this demand with production and supplier capacity. This would help mitigate the high demand and reduce the financial shocks to firms during an extraordinary disruption. These manufacturers must focus on demand-driven visible and adaptive SCs to reduce supply, demand, and financial shocks and increase resiliency (Jüttner et al., 2007).

Essential item manufacturers can mitigate supply, demand, and financial shocks by increasing raw materials for quick, responsive, and increased maximum production capacity.

3.6. Chapter summary

SC resiliency and risk mitigation practices are gaining popularity in various manufacturing industries globally. Global SCs face extraordinary disruptions caused by COVID-19. The worst sufferers are the manufacturers of essential items, such as facemasks. This study sought to determine the congruent strategies and recovery plans for essential item manufacturers to meet high demands and mitigate financial shocks to firms. We developed a typical model involving the SCs of facemask manufacturers using an ABM under normal and disrupted situations. We compared changes in demand, manufacturing, and supplier capacity. The results revealed that if the production capacity was not increased by increasing raw materials, the TSCCs increased, leading to financial shocks and demand increases. The study further suggested that '*increasing suppliers from different locations*', '*maximising the usage of national stockpile and available supply*', and '*redeploying existing inventory from other industries*' would '*increase the emergency raw materials*' for production during disrupted situations. Further, '*increasing production capacity*' by '*maximising the capacity of existing manufacturers*', '*deploying alternative specification and design*', (i.e. single quality facemasks for all purpose use), '*unlocking new capacity for manufacturers*', and '*public-private collaborative efforts*' would help meet high demands, reduce TSCCs, and mitigate firm financial shocks during disruptions.

The study's theoretical and empirical contributions and novelty are outlined below.

1. The study proposes a set of congruent strategies (composed of two main strategies and seven sub-strategies) to mitigate the skyrocketing demand for essential products (i.e. facemasks) during disruptions through a literature review and case study. The strategies can be a theoretical construct for future empirical studies for other essential item manufacturers.

2. The study contributes to the extant literature by identifying and proposing four recovery plans to help essential item manufacturers mitigate the supply-demand and financial shocks during disrupted situations.

3. The study contributes by predicting how pandemics impact SCs and demonstrating findings for essential item manufacturers to cope during disrupted situations by testing four recovery plans in an ABM using AnyLogic-simulation software.

The study's findings guide essential item manufacturers to tackle high demands in uncertain situations like pandemics. These manufacturers can follow the strategies or sub-strategies to increase raw materials and production capacities. Suppose manufacturers can procure and manage the right amount of raw materials per the actual need and demand. Then, they can use strategies to increase production capacities over a short period to maximise benefits and reduce financial shocks. The proposed strategies, sub-strategies, and recovery plans provide insights into Australian facemask manufacturers to tackle supply, demand, and financial shocks during disruptions. The study will motivate future researchers to predict disruption's impact on SCs and determine further strategies to tackle SC supply, demand, and financial shocks.

This study has limitations. From a theoretical perspective, disruption impacts on SCs were studied, and strategies and recovery plans were proposed based on the extant literature. A more scientific approach and empirical validation are required to determine disruption impacts and formulate strategies and recovery plans for Australian facemask manufacturers. New strategies might help facemask manufacturers tackle supply, demand, and financial shocks. They could be included in the study's proposed conceptual model to observe SCs' improvement during disrupted situations.

From a methodological perspective, the present study used arbitrary data based on secondary data. More recent primary data could determine the real simulation and observations. The model was tested with an ABM for an Australian case; other geographical-based investigations should be conducted and compared. The other proposed strategies in recovery plans should be considered and tested to observe improvements. For example, future investigations could evaluate how increasing manufacturing capacities by increasing production lines that surge set-up cost impacts long-term SC improvement. More mathematical analysis of other SC dynamics, such as the impact of disruptions on the sustainability performance of SCs and the recovery strategies to improve them in a multiple-stage SC structure by simulation models, could be conducted as future research. The methodology and strategies developed in this study could be applied to other manufacturers of high-demand essential items, such as canned food, toilet paper, and other personal protective equipment.

To the best of our knowledge, this study is one of the first to predict the impacts of extraordinary disruptions on SCs and determine strategies to mitigate supply, demand, and financial shocks for facemask manufacturers under disruptive situations. The findings and recovery plans set the stage for further research and practical implementations. More research is required to evaluate the present global extraordinary disruption caused by the COVID-19 pandemic.

Chapter 4

Dynamic Supply Chain Risk Management Plans for Mitigating the Impacts of the COVID-19 Pandemic

The COVID-19 pandemic prompted supply chain (SC) disruptions and heightened demand for crucial items like facemasks and ventilators. Lockdowns and border closures hindered raw material supply and manufacturing capacity expansion. Consequently, manufacturers faced challenges in inventory, transport, and delivery, resulting in higher shortage costs, elevated SC expenses, and reduced SC efficacy. Using an integrated agent-based model (ABM) and optimisation, this chapter examines COVID-19's multifaceted impacts on facemask SCs. It assesses four primary resilience strategies: enhancing manufacturing capacity, improving raw material supply, increasing transportation and distribution facilities, and maintaining dynamic inventory policy. Moreover, the model tested the proposed strategies under different scenarios by optimising the inventory policy and transportation strategies, leading to improved facemask production and delivery during extreme events. Our study found that increased production capacity through an optimal inventory and transportation strategy for an extended period reduced the multiple impacts of the pandemic on facemask SCs, resulting in diminished total SC costs and increased consumer access to finished products. Based on demand forecasts, maintaining dynamically optimal reordering points and order up to levels can help maximise raw material supply and inventory levels, thereby minimising risks. Using these findings, future risks related to outbreaks and pandemics can be more effectively planned.

4.1. Introduction

Global SCs have faced significant risks and uncertainties due to random and unpredictable disruptions during the last decade (Paul & Chowdhury, 2020a; Paul & Chowdhury, 2020b; Furstenau et al., 2022). SC disruptions largely depend on the type of industry and the impacted geographical locations (Rahman et al., 2020). The recent COVID-19 pandemic has drastically imposed 'unknown-unknown' risks and uncertainties in global SCs, the long-term impacts of which in post disruptive stage are yet to be ascertained (Ivanov, 2021b; Rahman et al., 2021). In contrast to the known-known, known-unknown, and unknown-known risks, the unknown-

unknown risks cannot be planned for similarly to the other three risk categories (Chowdhury et al., 2021). Currently, very little is known about the risks that might emerge post-COVID-19 pandemic because of other uncertainties, such as the Russia-Ukraine war, and previous studies focused only on those three groups (Njomane & Telukdarie, 2022). The COVID-19 pandemic can be considered a super disruption that has raised the importance of restructuring global SCs and business models to survive and sustain during and after such long-lasting disruptions (Ivanov, 2021c). Long-established efficient SCs cannot manage the simultaneous, dynamic, and multiple impacts of the disruptions (Cheramin et al., 2021). A paradigm shift is needed to transform the current efficient SC models into resilient SCs to make them viable and sustainable (Queiroz et al., 2020). This paradigm shift may raise the current level of SC costs to avoid bigger losses (Ivanov, 2021b).

During the COVID-19 pandemic, multiple region-based lockdowns and shutdowns hampered the operational process of SCs and businesses, hindering their revenue and goodwill (Ivanov & Dolgui, 2021). Most manufacturing companies, particularly those that manufacture essential items, faced extreme supply-demand fluctuation during the pandemic (Paul & Chowdhury, 2020a; Rahman et al., 2021). For example, the demand for essential healthcare items, such as facemasks and ventilators, increased when the rate of COVID-19-related infected cases increased (Coustasse et al., 2020). The manufacturers of facemasks and ventilators faced a stockout of raw materials and struggled to immediately ramp up their production capacity during the pandemic due to supply failure and shortage of production capacity (Mehrotra et al., 2020). Hence, significant attention should be paid to considering the underlying risks and vulnerabilities to adopt dynamic adaptation strategies to increase raw material supply and production rate. To date, most SC risk-related studies have focused on risk identification, assessment, and mitigation, with limited research focusing on risk recovery from the simultaneous, dynamic and multiple long-term impacts of disruptions (Chowdhury et al., 2021; Rahman et al., 2021). Most manufacturers of essential healthcare items struggled to predict the multiple impacts on SCs, and find the appropriate dynamic adaptation strategies to recover from the effects of the COVID-19 pandemic (Ivanov, 2021c). Hence, a dynamic SC model combined with adaptation strategies and a long-term plan that will ensure agility, resilience, and sustainability is needed to increase the viability of SCs (Govindan et al., 2020; Bender et al., 2022).

There is a lack of research in addressing the simultaneous and dynamic impacts of the COVID-19 pandemic on the SC networks of essential product manufacturers (i.e. facemasks and ventilators) and dynamic adaptative strategies and plans to manage these. Therefore, studying the impacts of simultaneous and dynamic disruptions in SC performances and evaluating the dynamic adaptive strategies to manage such long-term disruptions is crucial (Mitręga & Choi, 2021; Rahman et al., 2022). This evaluation framework would help essential product manufacturers adopt timely strategies to survive disruptions. A smooth flow of raw materials from suppliers, smooth operations in the manufacturing facility, available transportation and delivery systems, and a dynamic inventory policy are all needed to ensure essential product manufacturers' survivability during any pandemic or climate change-related meso- and micro-level disruption (Paul, Moktadir, et al., 2021; Ambrogio et al., 2022). These adaptation strategies may not aid all disruptions for all types of products, but they can be adopted by other manufacturers to survive any future disruptions. The previous literature indicates significant research on evaluating SC disruptions and mitigation strategies using mathematical modelling and optimisation methods, multicriteria decision-making methods, structural equation models, and other structural network analysis and optimisation methods (Chowdhury et al., 2021; Rahman et al., 2022). Please refer to Table C1 in Appendix C for the studies on risk management in SCs, Table C2 for adaptation strategies for SC risk management and Table C3 for modelling methods to manage SC disruptions. Nevertheless, few studies have attempted to predict the simultaneous and dynamic impacts of the COVID-19 pandemic in SC networks, evaluate dynamic adaptation strategies, and plan to manage such long-term disruptions using agent-based simulation and optimisation modelling approach (Rahman et al., 2021). Rahman et al. (2021) developed an ABM model in their research into a single short-term disruption, such as demand fluctuation, which did not optimise any parameters to maximise SC performance. No significant research has been conducted on the simultaneous and dynamic long-term impacts of the COVID-19 pandemic in SC networks of essential healthcare product manufacturers (i.e. facemasks and ventilators), and none has evaluated the dynamic adaptation strategies to improve the conditions for survivability. This study observes the impacts of long-term simultaneous disruptions in SCs and evaluates dynamic adaptation strategies to manage them over a period by developing an integrated ABM and optimisation method.

Due to the lack of research on the potential simultaneous, dynamic and multiple impacts of the COVID-19 pandemic on SCs, and dynamic and long-term plans to handle both the impacts, the present research investigates the following research questions:

1. What are the likely simultaneous, dynamic, and multiple impacts of the COVID-19 pandemic on the SC networks of manufacturers?
2. What optimal combination of dynamic adaptive strategies and long-term plans can be used to manage the simultaneous, dynamic, and multiple impacts and make the SCs viable during and post the disruption era?
3. What methods and techniques can be used as analytics tools to predict the impact of super disruptions and measure the effectiveness of the proposed adaptation strategies to manage multiple and long-term impacts in SC networks?

The long-established and conventional capabilities of SCs—agility, efficiency, and effectiveness—are not sufficient for essential healthcare manufacturers to craft adaptive strategies to recover from the long-term effects of SCs due to the super disruptions (Chowdhury et al., 2021; Bag et al., 2022; Hsu et al., 2022). Shifting toward adaptive, reconfigurable, resilient, and viable SCs could alleviate the impacts of the COVID-19 pandemic (Ivanov, 2021c; Sonar et al., 2022).

The present study's contribution is three-fold. First, we identify several dynamic adaptation strategies focusing on the essential healthcare product industry. The second contribution we make to the literature is an SC simulation model using an ABM to understand the simultaneous and dynamic impacts of the COVID-19 pandemic on facemask SCs, including multiple disruptions in supply, demand, manufacturing capacity, inventory management, transportation, and distribution. Rahman et al. (2021) used an ABM model to study a short-term disruption, that is, a demand fluctuation; however, they did not optimise any parameters to maximise SC performance. The last contribution is to conduct an optimisation experiment within an agent-based simulation model by optimising inventory policies and transportation planning to justify dynamic strategies and plans to manage disruption impacts in the SCs, production, and delivery to sustain them during and after a disruption. This data-driven model can be used to predict and reconfigure SCs when super disruptions, such as the COVID-19 pandemic, occur.

4.2. Problem Statement

The current SC disruptions caused by the COVID-19 pandemic can be classified under unidentified risks, known as unknown-unknown types of risks (Chowdhury et al., 2021; Ivanov & Dolgui, 2021; Bastas & Garza-Reyes, 2022). These types of risks are unpredictable in terms of their complexity, timing, and location of occurrence. They simultaneously occur as businesses are challenged to operate in a volatile, uncertain, complex, and ambiguous environment (Pettit et al., 2019; Vegter et al., 2020). The COVID-19 outbreak is an example of a large-scale unknown-unknown risk that has significantly affected national and international SC operations (Cai & Luo, 2020). During the outbreak, most manufacturers' production capacity reduced significantly due to restrictions to maintain social distancing and lockdowns, disruption of transportation and distribution systems, and disruption of the supply of essential products, which affected social and environmental sustainability practices and significantly reduced financial performance (Chowdhury et al., 2021; Ivanov, 2021c; Rahman et al., 2021). Most decision-makers design cost-efficient SCs and compromise resiliency, sustainability, and other risk management practices (Dolgui et al., 2018; Ivanov, 2021b; Wang & Yao, 2021). A cost-efficient SC is considered a lucrative option in the short term; however, such an SC may not survive in the longer term if decision-makers mostly focus on saving money and maximising profit (Dolgui & Ivanov, 2020; Ivanov & Dolgui, 2021; Wang & Yao, 2021; Xiaoping Xu & Choi, 2021).

Exploring the facemask SCs provides an example in evaluating the simultaneously occurring supply failure, production capacity degradation, restrictions in transportation, and demand spikes of essential healthcare items during the COVID-19 pandemic in Australia. The demand for facemasks increased daily as the coronavirus infection rate increased (Rahman et al., 2021; Wu et al., 2020). Since the beginning of the pandemic, several states in Australia have faced several lockdowns (Chowdhury et al., 2021; Rahman et al., 2021; Zhou, 2020). Melbourne, Victoria's capital, has had more than eight lockdowns to stop the spread of the virus (Chowdhury et al., 2021). In addition, Australia closed its borders for about 2 years to most countries during the pandemic and subsequently faced severe supply-side disruptions (Paul et al., 2021). Due to lockdowns and border closures, most facilities' manufacturing capacities decreased to stop the virus from spreading among workers. Transporters could not deliver items to the retailers promptly. Thus, Australian manufacturers of essential products faced simultaneous and dynamic disruptions across their SCs. When the situation improved slightly, other disruptions, such as demand spikes or supply failure, hit the recovery progress (Rahman et al., 2021). From July 2021, the COVID-19 Delta strain halted the SC recovery progress in Australia (Chowdhury et al., 2021). Health researchers and policymakers were unsure when the COVID-19 pandemic would end (Chowdhury et al., 2021; Sharma et al., 2020). In 2023, COVID-19 emerged severely in China that can increase the demand of facemask usage to stop the spread of the virus (Ivanov & Keskin, 2023). The Disease Control and Prevention (CDC) recommends wearing masks in public places and practicing other preventive measures such as frequent hand washing, social distancing, and staying home when unwell (Fernandes, 2020; Nayeri et al., 2022). The emergence of new variants of the coronavirus has the potential to increase the need for the use of facemask, which could lead to an increase in demand for them in the market in future. Hence, it is crucial to identify possible dynamic adaptation strategies and ensure long-term planning to manage the simultaneous and dynamic impacts of the COVID-19 pandemic on SCs and to regulate the flow of products in the market. This paper aims to develop an integrated ABM and optimisation model to predict the impacts of the COVID-19 pandemic on essential product SCs. This paper also proposes adaptation strategies to manage the extreme impacts on SCs. These adaptation strategies are tested in different scenarios via the proposed model to observe the effectiveness of improving SC performance.

4.3. Proposed Dynamic Adaptation Strategies and Model Formulation

This section discusses the proposed dynamic adaptation strategies and model formulation for solving the stated problem using an integrated ABM and optimisation model.

4.3.1. Proposed dynamic adaptation strategies

This research proposes the following four main dynamic adaptation strategies to manage the simultaneous and dynamic impacts of the COVID-19 pandemic in SCs:

Strategy 1: Enhancing manufacturing capacity

This strategy aims to streamline and ramp up manufacturing capacity to meet the demand surge for essential healthcare items during the COVID-19 pandemic.

Strategy 2: Improving raw material supply

This strategy aims to improve the supply flow of raw materials to manufacturers to scale up the production rate to meet the increasing demand for highly sought-after essential healthcare items during the COVID-19 pandemic.

Strategy 3: Increasing transportation and distribution facilities

This strategy aims to smoothen and improve the timely delivery of items to retailers and consumers during emergencies.

Strategy 4: Maintaining dynamic inventory policy

This strategy aims to maintain optimal inventory by means of '*s, S*' inventory policy in manufacturing facilities to continue extended production during extreme disruptions. These main strategies are all part of the scalability-adaptation strategy.

4.3.2. Proposed recovery plans

Based on the adaptation strategies, six scenarios have been considered, including long-, medium-, and short-term recovery plans for low, medium, and high levels of production capacity increases for adopting strategy 1 – 'enhancing manufacturing capacity'. Each scenario is optimised with decision variables—re-order point, order up to level, number of transports (trucks), raw material supply, production quantity, inventory level, and delivery quantity—to function dynamically to mitigate the simultaneous and dynamic impacts. Optimal re-order point and order up to level increase raw material supply and inventory level as the '*s, S*' inventory policy is considered in the model for adopting strategies 2 and 4 – 'improving raw material supply' and 'maintaining dynamic inventory policy', respectively. The optimal number of trucks at manufacturing facilities is also obtained to maximise the delivery capacity and minimise total SC costs for adopting strategy 3 – 'increasing transportation and distribution facilities'. Table 4.1 and Figures 4.1–4.3 summarise the scenarios considered for analysis in this study.

Table 4.1: Scenarios considered for analysis in this study

Scenarios	**Recovery period**		**Decision variables for single objective optimisation (Min-Max)**

		Increase in production capacity	ROP (s_j)	Order up to level (S_j)	Trucks (l)
Scenario 1	Long	High (+100%)	Min (+50%): 1500 – Max (+100%): 2000	Min (+50%): 4500 – Max (+100%): 6000	Min (+50%): 15 – Max (+100%): 20
Scenario 2	Long	Low (+50%)	Min (+25%): 1250 – Max (+50%): 1500	Min (+25%): 3750 – Max (+50%): 4500	Min (+25%): 13 – Max (+50%): 15
Scenario 3	Medium	High (+100%)	Min (+40%): 1400 – Max (+80%): 1800	Min (+40%): 4200 – Max (+80%): 5400	Min (+40%): 14 – Max (+80%): 18
Scenario 4	Medium	Low (+50%)	Min (+20%): 1200 – Max (+40%): 1400	Min (+20%): 3600 – Max (+40%): 4200	Min (+20%): 12 – Max (+40%): 14
Scenario 5	Short	High (+100%)	Min (+30%): 1300 – Max (+60%): 1600	Min (+30%): 3900 – Max (+60%): 4800	Min (+30%): 13 – Max (+60%): 16
Scenario 6	Short	Low (+50%)	Min (+15%): 1150 – Max (+30%): 1300	Min (+15%): 3450 – Max (+30%): 3900	Min (+15%): 11 – Max (+30%): 13

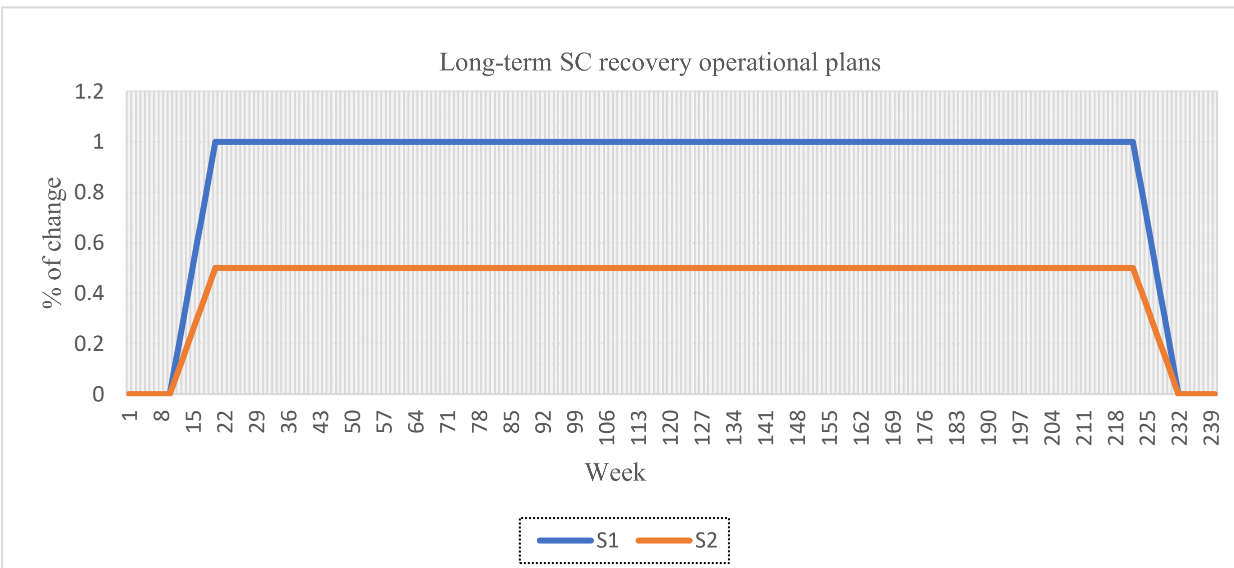

Figure 4.1: Long-term recovery plans for scenarios 1 (S1) and 2 (S2) for manufacturing capacity increase

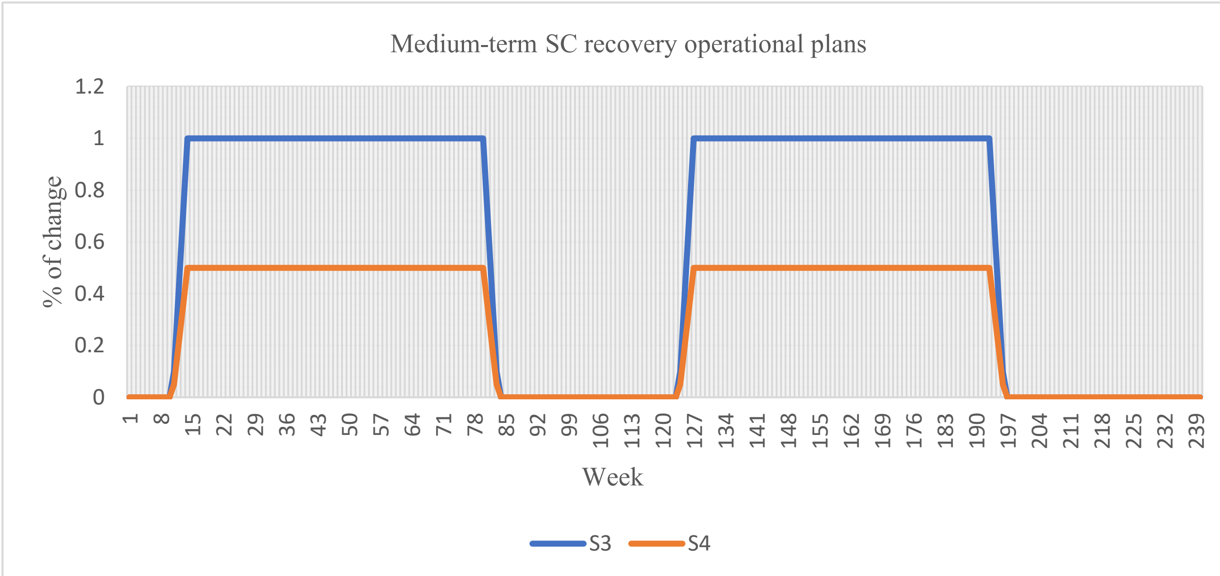

Figure 4.2: Medium-term recovery plans for scenarios 3 (S3) and 4 (S4) for manufacturing capacity increase

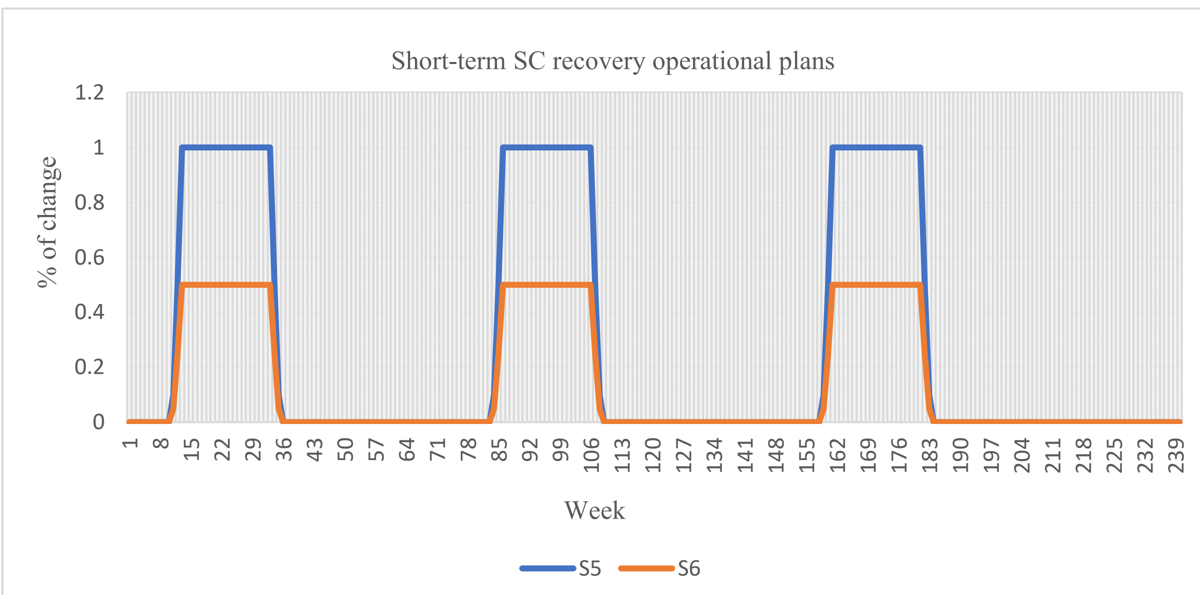

Figure 4.3: Short-term recovery plans for scenarios 5 (S5) and 6 (S6) for manufacturing capacity increase

4.3.3. An integrated ABM and optimisation model formulation

In this section, an ABM for simulating and optimising a typical SC for facemasks is proposed to compare and mitigate risks. Please refer to Figure 4.4 for proposed research methodology.

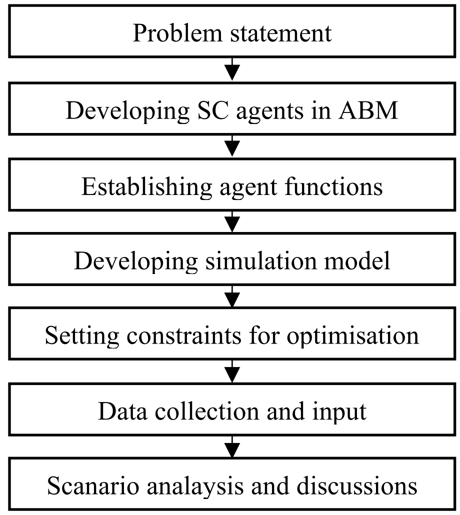

Figure 4.4: Proposed agent-based model overview

In the proposed model, a set of agents represents SC entities in the real world. By coordinating SC entities and determining the decision variables' optimised values for the best outcome, they simulate specific functions to fulfil retail orders (Ivanov, 2017). To fulfil incoming orders for the finished products and raw materials, the typical SC network of a facemask manufacturing company is considered, which would involve a set of suppliers, manufacturers, and retailers, and a set of transport trucks for suppliers and manufacturers (Mizgier et al., 2012; Zhang et al., 2017). The model used hypothetical data derived from secondary data. Please refer to Tables 4.2 and 4.3 for agent descriptions and model parameters, and Table C4 in Appendix C for manufacturing agents' parameters. SC performance is evaluated using the following measures:

Backorder level: Undelivered products to the retailer within a week by the manufacturer in time window $t = d_j^t$

Financial performance: The costs considered to evaluate financial performances in the analysis framework include,

a. total supply chain costs (TSCCs)
b. manufacturing costs (MCs, including the raw material costs from suppliers)
c. inventory costs (ICs) for manufacturers and retailers
d. transportation costs (TCs) for suppliers and manufacturers
e. shortage costs (ShCs) at the manufacturing stage
f. discount costs (DisCs) at the manufacturing stage. Table 4.4 lists the cost metric equations used by the agents.

Manufacturing performance: Based on the number of products manufactured by the j^{th} manufacturer in time window $t = p_j^t$

Table 4.2: Description of agents of the proposed model

Agent Name	**Functions**
Retailer agents	Orders (represented as order agents) are created continuously by retail agents to meet customer demand. When an order is created at a given time, it is assigned to the most preferred manufacturer.
Manufacturer agents	Once a manufacturing agent receives an order from a retailer agent, the agent tries to meet the order using its make-to-stock inventory of finished products (Q_j^t) and a set of available trucks. A request is sent to the suppliers if the inventory level drops below the reordering level (s_j), requesting a fixed amount of raw material and/or components (S_j) to replenish the stock of finished goods.
Supplier agents	This agent's role is to produce the components (in a make-to-order setting) and transport them to the respective manufacturer through trucks.
Order agents	Order agents are created stochastically by retail agents with predefined order size distributions and at predefined arrival times. They represent retail demand in the simulation model. For order fulfilment, order agents pass orders to relevant manufacturers.
Truck agent at manufacturers	Manufacturer trucks transport finished goods to retail agents through these agents.
Order supplier agent	These agents are part of the simulation model as an entity that represents the orders from manufacturers to suppliers for components and raw materials needed to manufacture finished products.
Truck agents at suppliers	Suppliers use these agents to ship components or raw materials to the manufacturers.
Evaluation agent	This agent communicates with all the other agents in the system to maintain track of the current SC's key performance indicators. They look at MCs, sourcing costs, TCs at the manufacturing and supplier stages, ICs at the supplier, manufacturer, and retail stages, ShCs, DisCs, and products/components produced/shipped/received at the various SC stages.

Table 4.3: Model parameters

Notations	**Descriptions**
$\boldsymbol{i}$	Retailers
$\boldsymbol{j}$	Manufacturers
$\boldsymbol{k}$	Suppliers
$\boldsymbol{l}$	Manufacturer trucks
$\boldsymbol{m}$	Supplier trucks
$\boldsymbol{D}$	Demand
$\boldsymbol{C_i}$	i^{th} Supplier's capacity
$\boldsymbol{IR_i}$	Holding costs for inventories for i^{th} retailer (each item, per day)
$\boldsymbol{\varphi_j}$	Fixed operating cost for j^{th} manufacturer
$\boldsymbol{\vartheta_j}$	Manufacturing cost per unit of j^{th} manufacturer
$\boldsymbol{IM_j}$	Inventory holding cost for j^{th} manufacturer (each item, per day)
$\boldsymbol{\psi_j}$	Fixed cost associated with managing transport services at j^{th} manufacturer

ω_j	Variable transportation cost at j^{th} manufacturer (per unit item per unit time)
η_j	Shortage cost for j^{th} manufacturer (per unit item)
λ_j	Discount cost for j^{th} manufacturer (per unit item)
ρ_k	Cost of manufacturing raw materials supplied by k^{th} supplier
θ_k	Fixed cost associated with managing transport services at k^{th} supplier
υ_k	Variable transportation cost k^{th} supplier (per unit item per unit time)
s_j	ROP at j^{th} manufacturer
S_j	Order up to level at j^{th} manufacturer
a_j	Per unit manufacturing time at j^{th} manufacturer
b_k	Per unit manufacturing time at k^{th} supplier
p_j^t	Manufactured item by the j^{th} manufacturer
α_{ijl}^t	Transport time by truck l to carry items x_{jk}^t from j^{th} manufacturer to i^{th} retailer in time window t
β_{jkm}^t	Transport time for supplier truck m to carry items y_{jk}^t from k^{th} supplier to j^{th} manufacturer in time window t
x_{ij}^t	Items transported from j^{th} manufacturer to i^{th} retailer in time window t
y_{jk}^t	Items transported from k^{th} supplier to j^{th} manufacturer in time window t
τ	Time window
Q_j^t	Inventory level on average at j^{th} manufacturer in time window t
R_i^t	Inventory level on average at i^{th} retailer in time window t
d_j^t	Undelivered items to retailer within a week at j^{th} manufacturer in time window t
w_j^t	Undelivered items to retailer within a specified time at j^{th} manufacturer in time window t (for the consideration of discount cost)
$\sum_j x_{jk}^t$	Items supplied to the i^{th} retailer
$\sum_j y_{jk}^t$	Raw materials supplied by the k^{th} supplier

4.3.4. Optimisation within the simulation model

The optimal value of the following decision variables by optimisation experiments is obtained using AnyLogic's (simulation software) in-built optimisation algorithm within the simulation model: 1. *Reordering point* (s_j), 2. *Order up to level* (S_j), and 3. *Number of trucks* (l) used in manufacturing units using the upper bound and lower bound of the decision variables mentioned in Table 4.1 for each of the six scenarios considered in this study. The objective function is to minimise the TSCCs, as presented in Equation (1).

Min (TSCCs in time window t) $= \sum_j \varphi_j.\tau + \sum_j \vartheta_j.p_j^t + \sum_j \sum_k \rho_k.y_{jk}^t + \sum_j IM_j.Q_j^t + \sum_i IR_i.R_i^t + \sum_j \psi_j.\tau + \sum_l \sum_i \sum_j \omega_j.x_{ij}^t.\alpha_{ijl}^t + \sum_k \theta_k.\tau + \sum_m \sum_j \sum_k \upsilon_k.y_{jk}^t.\beta_{jkm}^t + \sum_j d_j^t.\eta_j + \sum_j w_j^t.\lambda_j$ (1)

Subject to: $\sum_j y_{jk}^t = S_j$ (2)

$\sum_j y_{jk}^t \leq Q_j^t$ (3)

$$\sum_j x_{jk}^t \leq D \tag{4}$$

$$y_{jk}^t \leq C_i \; ; \forall_i \tag{5}$$

$$y_{jk}^t \geq s_j; \forall_i \tag{6}$$

Equation (1) is derived from the summation of manufacturing costs (MCs), inventory costs (ICs), transportation costs (TCs), shortage costs (ShCs), and discount costs (DisCs) mentioned in Table 4.4. Order constraint is mentioned in Equation (2), where total raw material supply ($\sum_j y_{jk}^t$) is equal to the order up to level (S_j) and must be less than the inventory capacity (Q_j^t) of the facility (inventory capacity constraint in Equation [3]). Demand constraint is mentioned in Equation 4, where the number of products ($\sum_j x_{jk}^t$) supplied to the retailers by the manufacturers must be less than or equal to the demand (D). Supplier's capacity constraint is mentioned in Equation (5), where raw material supply (y_{jk}^t) by the supplier must be less than the supplier's capacity (C_i). The constraint for the reordering point is mentioned in Equation (6).

The model minimises the backorder along with TSCCs by optimising s_j and S_j over time as this model has used '*s, S*' inventory policy to increase raw material supply and inventory level. Optimising s_j and S_j dynamically optimises raw material supply *(* $\sum_j y_{jk}^t$ *)*, production quantities *(*p_j^t*)*, inventory level *(*Q_j^t *)*, and delivery quantities *(*$\sum_j x_{jk}^t$*)* over time t to meet consumers' demand to reduce the simultaneous and dynamic impacts of the disruptions. The model assumes that one-unit raw material is required for one-unit finished good for formulation simplicity. The optimised number of trucks (l) carry the goods to the retailer. Therefore, the proposed optimisation model within the simulation maximises production capacity by increasing the optimal level of the following decision variables to meet the unmet demand and demand surge over time dynamically:

1. Raw material from the suppliers ($\sum_j y_{jk}^t$)

2. Amount to produce in the manufacturing units (p_j^t)

3. Amount available in the inventory (Q_j^t)

4. Number of products to deliver to the retailers ($\sum_j x_{jk}^t$).

Please see the optimal values obtained for s_j, S_j, and l from the optimisation experiments for the six considered scenarios in Table 4.6.

According to the current model, seven suppliers, three manufacturers, and 18 retailers are included in the study. To satisfy incoming orders from retailers, the agents collaborate to meet various performance objectives (such as lead times and total SC costs). Table C4 in Appendix C provides manufacturer details. Rahman et al. (2021) developed an ABM to simulate the SC of an essential product manufacturer. They included temporary, short-term fluctuations in demand and only used simulation capability. The significance of the present study lies in the fact that it extends the model and utilises optimisation experiments within the simulation in extended scenarios to find the optimal values of decision variables for managing the simultaneous and dynamic impacts of the COVID-19 pandemic over an extended period. We have built the ABM model and run the simulation and optimisation in AnyLogic (version 8.3.2) simulation software for this study.

Table 4.4: Cost metrics assessed by agents in each of the periods

SC costs	Equation
Manufacturing cost in time window t	$\sum_j \varphi_j.\tau + \sum_j \vartheta_j.p_j^t + \sum_j \sum_k \rho_k.y_{jk}^t$
Manufacturing inventory cost in time window t	$\sum_j IM_j.Q_j^t$
Retailer inventory cost in time window t	$\sum_i IR_i.R_i^t$
Transport cost at the manufacturing stage in time window t	$\sum_j \psi_j.\tau + \sum_l \sum_i \sum_j \omega_j.x_{ij}^t.\alpha_{ijl}^t$
Transport cost at the supplier stage in time window t	$\sum_k \theta_k.\tau + \sum_m \sum_j \sum_k \upsilon_k.y_{jk}^t.\beta_{jkm}^t$
Shortage cost at the manufacturing stage in time window t	$\sum_j d_j^t.\eta_j$
Discount cost at the manufacturing stage in time window t	$\sum_j w_j^t.\lambda_j$
Total supply chain cost in time window t	$\sum_j \varphi_j.\tau + \sum_j \vartheta_j.p_j^t + \sum_j \sum_k \rho_k.y_{jk}^t + \sum_j IM_j.Q_j^t +$ $\sum_i IR_i.R_i^t + \sum_j \psi_j.\tau + \sum_l \sum_i \sum_j \omega_j.x_{ij}^t.\alpha_{ijl}^t + \sum_k \theta_k.\tau +$ $\sum_m \sum_j \sum_k \upsilon_k.y_{jk}^t.\beta_{jkm}^t + \sum_j d_j^t.\eta_j + \sum_j w_j^t.\lambda_j$

4.4. Results, Scenario Analysis, and Discussions

4.4.1. Baseline scenario analysis

In the proposed ABM model, we evaluated the performances of facemask manufacturers' SC under the business-as-usual situation and disrupted situation caused by the COVID-19 pandemic. We ran the simulation and optimisation for a maximum of 5 years for better anticipation.

Business-as-usual situation (normal baseline situation): The SC of facemask manufacturers had no disruption. We simulated the ABM with all normal parameters in a business-as-usual or normal baseline situation. The simulated results (see Figure 4.6) indicate that the facemask manufacturer's SC was normal. There were no significant backorder-related (unmet demand) shortages and discount costs. The manufacturing units produced adequate finished goods within their capacity, maintained an optimal inventory, and arranged transportation for smooth delivery to retailers. The TSCCs were normal in the business-as-usual situation. Hence, the existing SCs for facemask manufacturers ran their production effectively and fulfilled demand smoothly.

COVID-19 pandemic-related disruptive situation (disrupted baseline situation)**:** In the disruptive situation caused by the COVID-19 pandemic, the facemask SCs faced mild (single disruption, such as a demand spike), moderate (parallel disruptions due to several lockdowns), and extreme (parallel and/or sequential disruptions due to lockdowns and border closure) simultaneous disruptions. Our model assumed that the demand, manufacturing capacity disruptions, and supply delay due to lockdown and shutdown began after a couple of weeks (i.e. 10 weeks) of the simulation run, as presented in Figure 4.5.

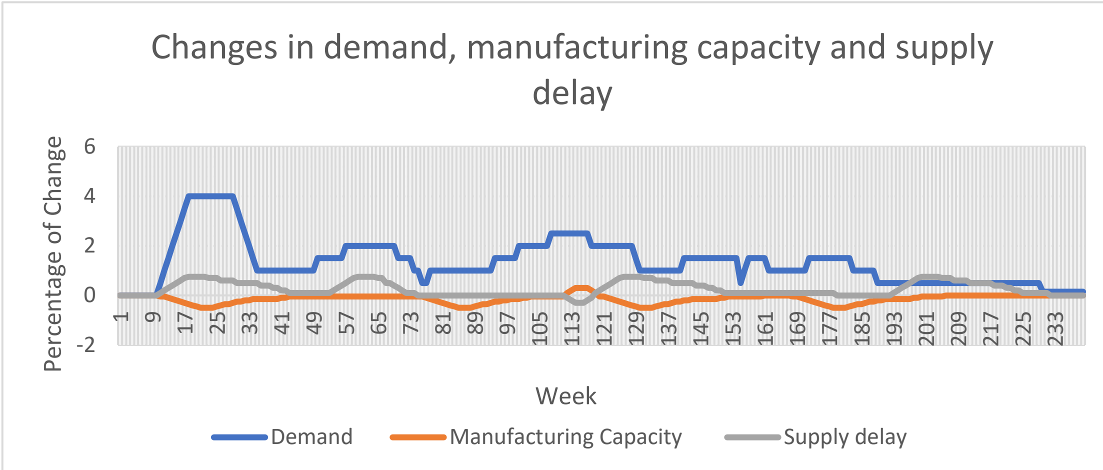

Figure 4.5: Changes in demand, manufacturing capacity, and supply delay

Demand initially peaked for several months and stayed very high, increasing by 15% to 400% during the 5 years in the simulation run. It is assumed that the increased demand for facemasks is 150% on average during the disruption in the simulation model. Essentially, one of the major issues of a sudden increase in demand, such as 400% in a certain period, was the irrational consumption of products during the pandemic due to panic-purchasing. Our model considered irrational consumption as a demand spike that gradually becomes rational over time. Similarly, manufacturing capacity disruption occurs in parallel and/or one after another, along with demand disruption. From Week 10, the manufacturing capacity is disrupted to varying extents due to location-based lockdowns. The manufacturing capacity decreased in the 5% to 100% range, with an average decrease of 15% at different times, mimicking the shutdown of manufacturing units during the pandemic. Similarly, the supply delay is assumed to be 10% to 75%, and an average delay of 25% at different times, mimicking the delay of raw material supply due to the temporary shutdown of local suppliers and borders being closed to overseas suppliers. Also, in the simulation, we assumed no strategy was adopted in this disruptive circumstance. To assess how simultaneous disruptions affect the performance of facemask SCs, we assumed a disruption scenario (refer to Figure 4.5) into our ABM framework. This scenario closely resembles the demand, manufacturing, and supply disruptions observed during the COVID-19 pandemic and its aftermath. By simulating these disruptions, we obtained valuable insights into their impact on the overall performance of the facemask SC.

4.4.2. Analysing impacts of simultaneous disruptions in SC performances

The simultaneous and dynamic impact of the pandemic on SCs when no strategy is adopted to manage the situation are presented in Figure 4.6 and Table 4.5, and described below.

Impact on backorder level: In the baseline disrupted scenario, facemask demand increased up to 400%, with an average increase of 150% during the 5 years in simulation. The manufacturing capacity decreased up to 100%, with an average decrease of 15% at different times. Similarly, the delayed supply was up to 75%, with an average delay of 25%. Manufacturers had to shut down their facilities temporarily and could not receive raw materials from suppliers due to strict lockdowns and the emergence of infected cases. As such, the manufacturing capacity decreased over time in the baseline scenario, and facemask SCs could not meet demand in time. Due to the high unmet demand in this situation for over 5 years, the backorder level increased significantly compared to the normal situation, as seen in Table 4.5. In the disrupted simulation, the absence of an adaptation strategy, specifically increasing production capacity, has led to a high backorder level. Therefore, the manufacturers need to implement the proposed strategies to boost production, penetrate the market, and reduce the impacts.

Table 4.5: SC performances in disruption compared to the normal situation

	SC performances in disruptions compared to the normal situation							
	Backorder level (Avg units/Week)	**Financial performances (Avg A$/Week)**						**Manufacturing performance (Avg units/Week)**
	Demand unmet	**TSCC**	**MC**	**IC**	**TC**	**ShC**	**DisC**	**Products manufactured**
Normal situation	921.16	1978582.28	1754319.50	120291.73	93139.61	3684.65	7146.78	12560.17
Disrupted situation	11109043.64	51793633.86	2396618.26	232554.43	69527.48	44436174.56	4658759.13	17589.21

Impact on SC's financial performances: As demand surged, production capacity decreased, and raw materials supply decreased, facemask SCs faced several backorders due to unmet demand, resulting in high ShCs (A$ 44.43M approximately). This high shortage cost due to high backorder level happened because no adaptation strategy was adopted in the simulation in disrupted situation. The estimated discount cost increased to approximately A$ 4.66M for delivery delay-related discounts. The TSCCs increased to approximately A$ 51.79M compared to the normal situation. The MCs increased only 37%, so the SC could barely ramp up its manufacturing capacity due to lockdowns in several locations during the simulation run. The manufacturing units could not receive raw materials from suppliers smoothly. When raw materials arrived, sudden shutdowns prevented production capacity from increasing, leading to a higher inventory level. This led facemask manufacturers' ICs to increase to 93%. Another important observation is that TCs decreased to 25%, compared to the normal situation. Due to lockdown and transportation restrictions, suppliers and manufacturers could not utilise their transports to send raw materials and finished goods to manufacturers and retailers. Thus, the facemask SC could not fulfil the huge demand that increased TSCCs and degraded overall SC performance (see Figure 4.6 and Table 4.5).

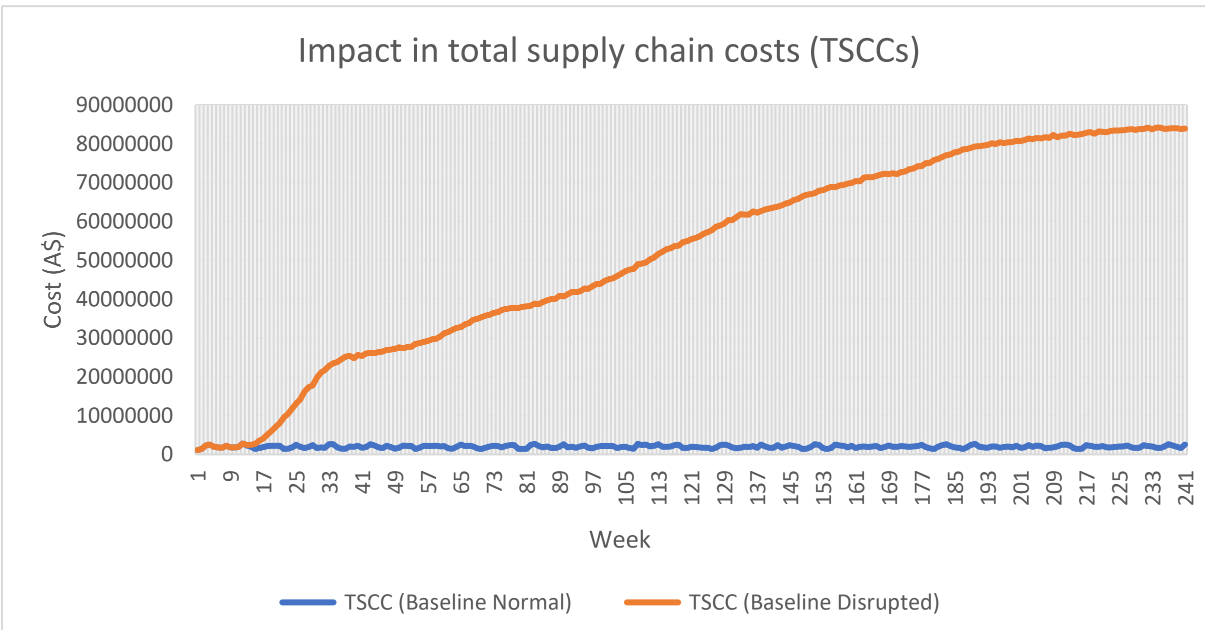

Figure 4.6: Multiple impacts of disruption in TSCCs

Impact on manufacturing performances: Table 4.5 shows that the number of products manufactured increased to only 40% in the disrupted situation, which is below the required number to meet the huge market demand during the pandemic. The manufacturing facilities could not ramp up production capacity due to raw material shortages, several shutdowns, and transportation restrictions during the pandemic. This resulted in a huge increase in unmet demand. Thus, ShCs, DisCs, and, eventually, TSCCs increased, and the SC performance degraded significantly. The disruption has had a huge impact on SCs because no strategy was adopted in the simulation of disrupted situation.

Therefore, this study found that high demand, decreased production capacity, and limited raw materials supply led to several backorders and high shortage costs for facemask SCs, resulting in increased total supply chain costs and degraded overall SC performance.

4.4.3. Recovery plan implementation, scenario analysis, and evaluation of SC performance

We implemented the proposed recovery plans based on adaptation strategies in six scenarios (see Section 4.3 for details) to improve the performance of the facemask SC. The recovery plans in the six scenarios are summarised as follows:

Scenario 1 (S1) increased the production capacity up to 100% for a long period of 50 months.
Scenario 2 (S2) increased the production capacity up to 50% for a long period of 50 months.
Scenario 3 (S3) increased the production capacity up to 100% for medium periods of 18 months.
Scenario 4 (S4) increased the production capacity up to 50% for medium periods of 18 months.
Scenario 5 (S5) increased the production capacity up to 100% for short periods of 6 months.
Scenario 6 (S6) increased the production capacity up to 50% for short-term periods of 6 months.

In each scenario, we ran the optimisation experiment with the parameters listed in Table 4.1 to optimise ROP (s_j), order up to level (S_j), and truck (l) to maximise manufacturing capacity to meet the maximum level of demand and minimise TSCCs. With an optimal ROP and order up to level, raw materials will be delivered to manufacturers from suppliers, which will maintain an optimal inventory. Meanwhile, optimal trucks will improve transportation and distribution. Table 4.6 shows the scenarios' optimal values of the decision variables.

Table: 4.6: Optimal value for decision variables by optimisation experiment

Scenarios	**Optimal value for decision variables**		
	ROP (s_j) (Units)	**Order up to level (S_j)** (Units)	**Trucks (l)** (Numbers)
Normal situation	1000	3000	10
Scenario 1	1567	6000	15
Scenario 2	1441	4457	14
Scenario 3	1457	4628	14
Scenario 4	1243	3757	13
Scenario 5	1314	4634	14
Scenario 6	1206	3484	11

Evaluation of backorder level: In the disrupted situation, backorder levels started to increase from Week 17 (refer to Figure 4.7 of the evaluation of TSCCs) and remained at very high levels. We increased the manufacturing capacity (Strategy 1) by 100% for a long time with optimal s_j (1567),

S_j (6000), and l (15) in S1. In S1, the backorder level decreased to 95% compared to the disrupted situation. S1 revealed the best result compared to the other scenarios. Notably, optimal ROP and order up to level to suppliers improved raw material supply from the supplier (Strategy 2) and maintained an optimal inventory (Strategy 4). The second-best scenario was S3. In S3, we increased the production capacity up to 100% for medium-term periods with an optimal value of s_j (1457), S_j (4628), and l (14). S3 decreased the backorder level to 84% compared to the disrupted situation. In S2, we increased production capacity up to 50% for a long time with optimal s_j (1441), S_j (4457), and l (14), while increasing production capacity up to 100% for short-term periods with optimal s_j (1314), S_j (4634), and l (14) in S5. In S2 and S5, the backorder level decreased to 82% and 81%, respectively. S4 and S6 are ranked fifth and sixth, respectively. Production capacity increased to 50% for medium-term periods in S4 with optimal s_j (1243), S_j (3757), and l (13); and for short-term periods in S6 with optimal s_j (1206), S_j (3484), and l (11). S1, S3, S2, and S5 showed better results as production capacities were increased and steps were taken to increase raw material supply (Strategy 2) and inventory level (Strategy 4) by increasing ROP and order up to level dynamically, and the optimal increased level of transportation (Strategy 3) was used for smooth delivery.

Evaluation of financial performances

Total supply chain costs (TSCCs): TSCCs increased from Week 17 in the disrupted situation (see Figure 4.7). When we increased production capacity, optimised raw material supply, inventory capacity, and transportation capacity in S1, the TSCCs decreased to 86%, which is lower than all other scenarios. In S1, SC manufacturers could meet huge demand due to adaptation strategies, which reduced the backorder level and associated ShCs and DisCs. Inventory holding costs were lowest in S1, as an optimal inventory level could be maintained due to optimal ROP and order up to level. MCs and TCs were not too high. S3, S2, and S5 are ranked second, third, and fourth, respectively, where TSCCs decreased to 74%, 71%, and 70%, respectively. Similar to S1, 100% production with optimal raw materials, inventory, and transportation for medium-term periods also showed good results. Suppose raw materials are scarce and there are obstacles in manufacturing units due to lockdowns and shutdowns. In that case, production can be increased by 50% for a very long time, or production can be increased by 100% for short-term periods to reduce TSCCs and maximise production capabilities to meet the huge demand. S4 and S6 are ranked fifth and sixth, respectively, where TSCCs are reduced to 53% and 31%, respectively. When there is a huge scarcity of resources (i.e. raw materials), 50% production capacity with optimal ROP and order up to level can be increased for medium-term periods rather than short-term periods for better SC performances.

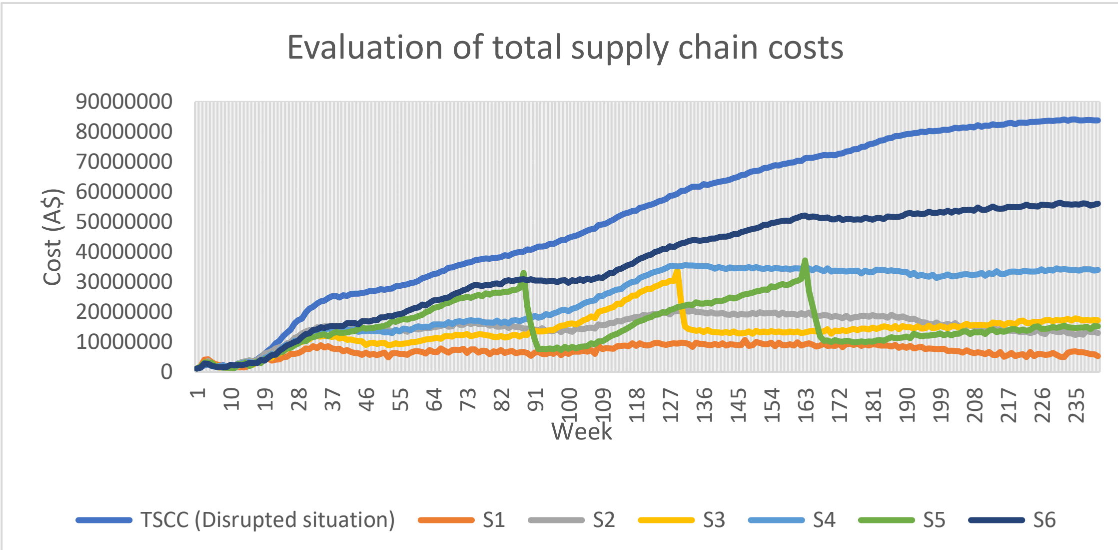

Figure 4.7: Evaluation of TSCCs from the scenarios

Manufacturing costs (MCs): It is noted from the previous section that S1, S3, S2, and S5 improved the SC better than the other strategies in other scenarios. S1, S3, S2, and S5 increased MCs to 12%, 13%, 12%, and 17%, respectively, compared to the disrupted situation. After implementing the adaptation strategies and recovery plans, the manufacturing capabilities increased in all four scenarios, which helped reduce backorder levels and TSCCs. Compared to long-term recovery plans, a 100% increase in production for a medium-term period in S3 and a short-term period in S5 spiked the production costs very quickly in weeks 89 (S5), 130 (S3), and 168 (S5). The MCs in S4 and S6 increased to 8% and 5%, respectively. These findings highlight that the lack of increased manufacturing capacity to meet higher demand and insufficient efforts to enhance raw material supply for optimal inventory levels were the factors behind the limited manufacturing capabilities observed in S4 and S6, as depicted in Figure 4.8.

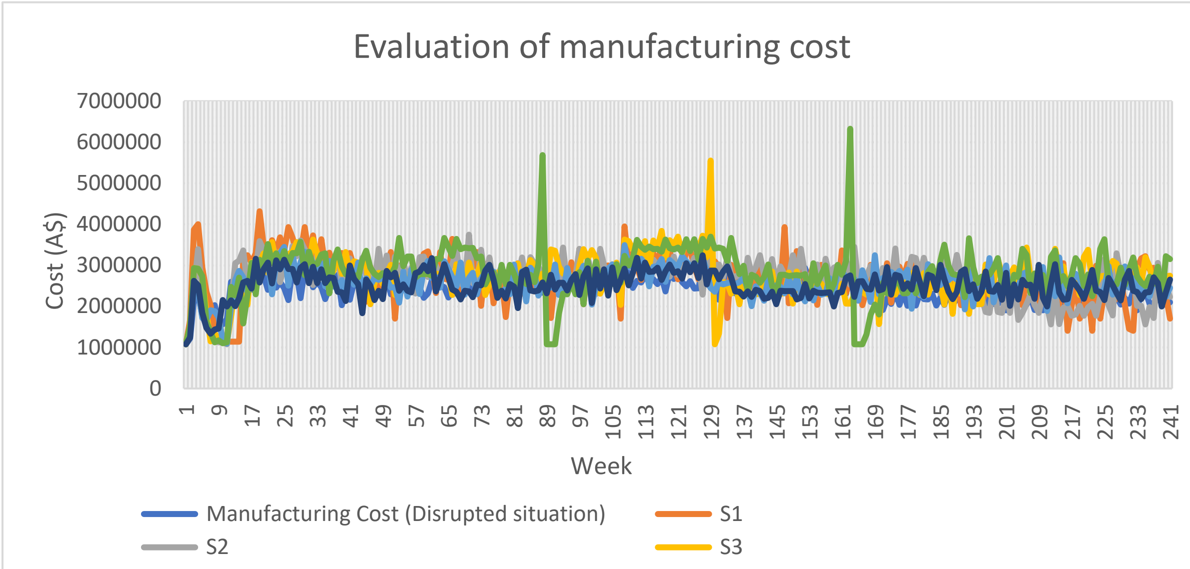

Figure 4.8: Evaluation of MCs from the scenarios

Inventory costs (ICs): In S1, the ICs only increased to 3% compared to the disrupted situation—the lowest among other scenarios. Although the order up to level was increased to 100% and ROP also increased to 57%, the manufacturing units in S1 could increase their production capacity to meet the extra demand. There were fewer backorders (see Table 4.6 for optimal values of ROP and order up to level, and Table 4.7 for improvement of SC performance). Companies could utilise their inventory properly, reducing ICs for manufacturers and retailers. In S3, S2, and S5, the ICs increased to 32%, 12%, and 53%, respectively. Similar to S1 and S2, the production capacity is increased for a long time to properly use inventory to meet the extra demand, reducing their IC compared to other scenarios. The TSCCs indeed decreased in other scenarios, such as S3 and S5, but it is also true that production capacity did not increase for a long time, leading to an increased inventory level and thus an increase in inventory costs (ICs) in weeks 90 (S5), 130 (S3), and 165 (S5). There should be a more dynamic inventory policy in recovery plans in medium- and short-term periods to avoid increased inventory holding costs. As production capacity was not increased significantly in S4 and S6, ICs slightly decreased (3% and 22%, respectively) compared to the other scenarios. Consequently, backorder levels and TSCCs increased in S4 and S6, as depicted in Figure 4.9.

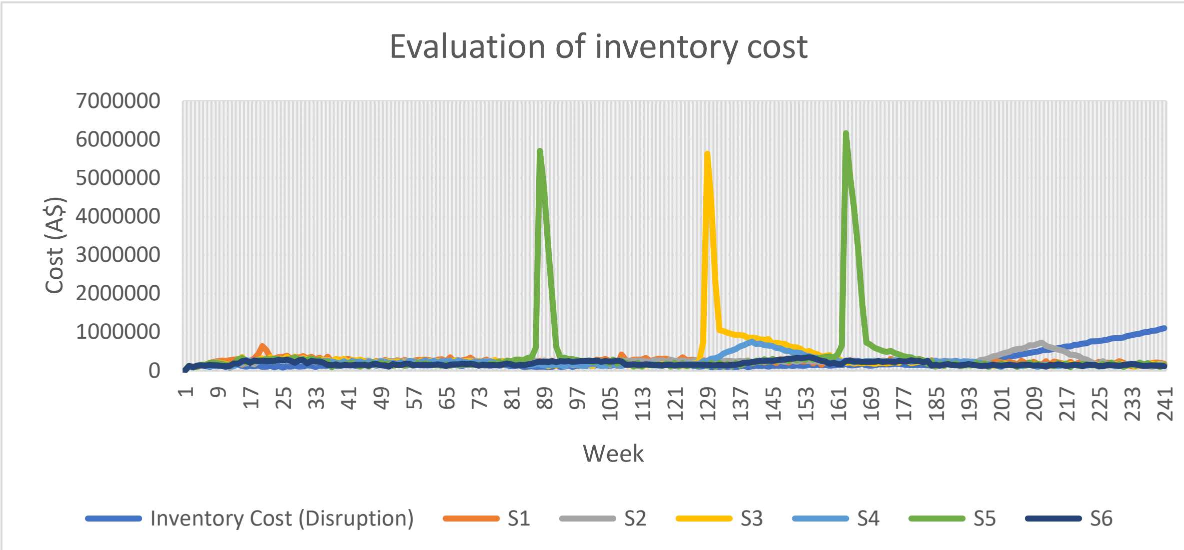

Figure 4.9: Evaluation of ICs from the scenarios

Transportation costs (TCs): Compared to the disrupted situation, the TCs for S1, S3, S2, and S5 increased to 35%, 30%, 36%, and 34%, respectively (see Figure 4.10). The main reason for this increase is that 50%, 40%, 40%, and 40% transportation capacities increased (Strategy 3) in S1, S3, S2, and S5, respectively (see Table 4.6 for the optimal value of transports), as the production capacities were boosted to manufacture and deliver more products to retailers to meet consumers' extra demand. Though there were small increases in the TCs in those scenarios, the extra transportation and delivery capacity helped manufacturers deliver the extra items produced to meet high demand, eventually helping them reduce TSCCs and increase SC performances. In weeks 89 (S5), 130 (S3), and 168 (S5), the TCs spiked extremely fast due to the 100% increase in production for the medium-term in S3 and for the short-term in S5. In these weeks, TCs spiked sharply, probably due to manufacturers acting quickly to increase trucks to meet increased retailer delivery. Conversely, TCs in S4 and S6 increased slower (22% and 12%, respectively) than in the other scenarios. The limited ability to increase raw material supply and production capacity had a detrimental impact on TSCCs, leading to decreased SC performance. Specifically, in S4 and S6, the number of trucks only saw marginal increases of 30% and 10%, respectively, further exacerbating the challenges.

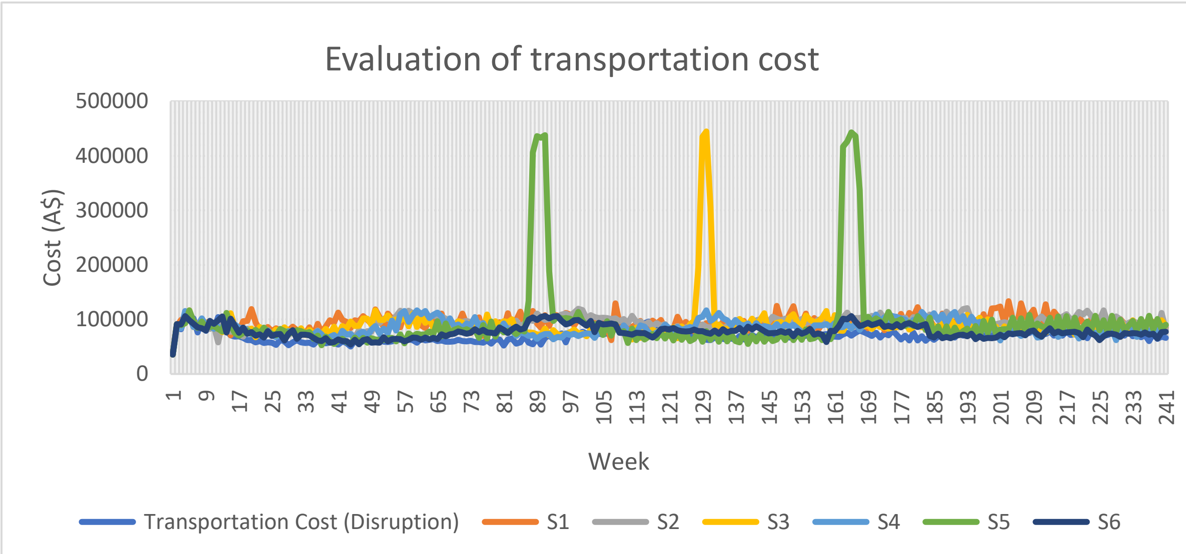

Figure 4.10: Evaluation of TCs from the scenarios

Shortage costs (ShCs): In the disrupted situation, ShCs increased from Week 17 and remained very high (see Figure 4.11). In S1, ShCs decreased to 95% compared to the disrupted situation. This is because there were significantly fewer backorders due to increased raw materials, production capacity, and delivery facilities. S1 reduced the backorders and TSCCs better than all the other scenarios (see Figure 4.7). S3 was second in improving SC; it decreased the ShCs to 84% compared to the disrupted situation. S2 and S5 follow, with ShCs decreasing to 82% and 81%, respectively. S4 and S6 are ranked fifth and sixth, respectively. S1, S3, S2, and S5 improved the SC as production capacities were increased. Steps were taken to increase the raw material supply and inventory level by increasing ROP and order up to level and the optimal level of transport used for smooth delivery. A 100% production with optimal raw materials, inventory, and transport could reduce ShCs in all recovery periods. However, a 50% production increase could reduce backorders if continued for a very long period. Conversely, a 50% production capacity increase with optimal ROP, order up to level, and delivery system in medium- and short-term periods cannot comparatively and significantly reduce ShCs.

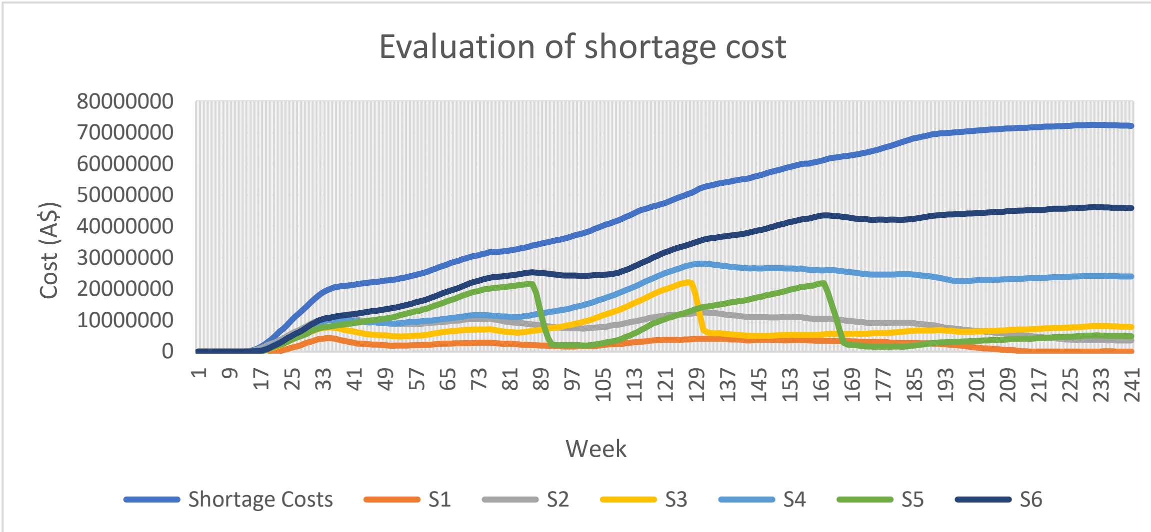

Figure 4.11: Evaluation of ShCs from the scenarios

Discount costs (DisCs): In the disrupted situation, DisCs for late delivery to retailers increased from Week 15 and remained at very high levels (see Figure 4.12). Unmet demand is included in the backorder level, delivered later with discounts to retailers to sustain goodwill and avoid lost sales. In S1, the DisCs decreased to 58% compared to the disrupted situation, as there was less unmet demand due to increased raw materials, production capacity, and delivery facilities. S1 reduced the DisCs and TSCCs better than all the other scenarios, as shown in Figures 4.7 and 4.12. S3 and S5 are ranked second and third, respectively, which decreased the DisCs to 24% and 21%, respectively, compared to the disrupted situation. Next, S2, S4, and S6 decreased DisCs to 16%, 17% and 17%, respectively. S1, S3, and S5 decreased DisCs as production capacity increased to 100% with optimal ROP, order up to level, and the number of transports in long-, medium- and short-term periods. However, 50% production, raw materials, and transportation increased across periods but barely reduced DisCs comparatively. An important observation across all scenarios is the presence of high DisCs, highlighting the significant occurrence of unmet demands or backorders and emphasising the initiative to restore customer goodwill.

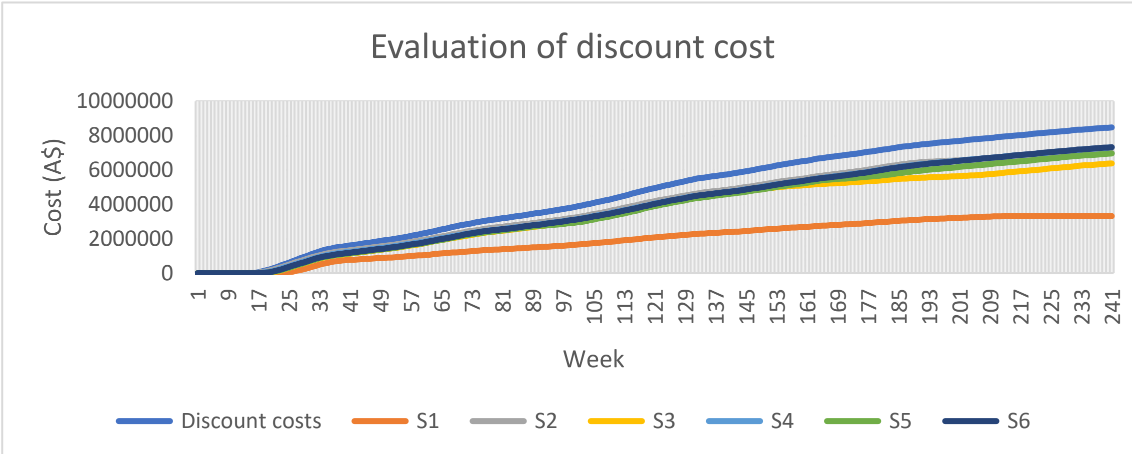

Figure 4.12: Evaluation of DisCs from the scenarios

Evaluation of manufacturing performances: The products manufactured in the manufacturing units significantly improved after adopting the strategies in the scenarios in Table 4.7. Specifically, the production rate increased to 66%, 64%, 59%, and 62% in S1, S2, S3, and S5, respectively. Notably, a 100% production increase (Strategy 1) with optimal raw materials (Strategy 2), inventory policy (Strategy 4), and transports (Strategy 3) in the long term increased production performances compared to other strategies. It is also imperative to increase the production capacity with optimal inventory policy up to 100% for medium- and short-terms for better manufacturing performances. Conversely, manufacturing performances did not improve in S4 and S6. They only increased the number of products manufactured by 43% and 22%, respectively. Finally, a 50% production increase with fewer raw materials in medium- and short-term periods could not improve manufacturing and overall SC performances.

Table 4.7: SC performances' improvement analysis compared to the disrupted situation

Variation in scenarios	SC performances' improvement analysis compared to the disrupted situation							
	Backorder level	Financial performances						Manufacturing performance
	Demand unmet	TSCCs	MCs	ICs	TCs	ShCs	DisCs	Products manufactured
S1	-95%	-86%	+12%	+3%	+35%	-95%	-58%	+66%
S2	-82%	-71%	+12%	+12%	+36%	-82%	-16%	+64%
S3	-84%	-74%	+13%	+32%	+30%	-84%	-24%	+59%
S4	-61%	-53%	+8%	-3%	+22%	-61%	-17%	+43%
S5	-81%	-70%	+17%	+53%	+34%	-81%	-21%	+62%
S6	-35%	-31%	+5%	-22%	+12%	-35%	-17%	+22%

4.4.4. Sensitivity analysis

We used a one-variable-at-a-time method, which is the variation (±20%) of several parameters of the base case values of demand, *ROP* (s_j), *order up to level* (S_j), and *trucks (l)* at a time to evaluate the validity and sensitivity of the model.

Variation in backorder level: Backorder levels are more sensitive to demand changes than other parameters, such as s_j, S_j, and l. A 20% decrease in demand decreased the backorder level to 23%, and a 20% increase in demand increased it to 24%. Manufacturers of essential products need to increase raw materials from suppliers and production capacity during disruptions to avoid huge backorders. The other changes in the backorder level are reported in Table 4.8.

Variation in financial performances: The analysis highlighted that the model is most sensitive to demand changes as it significantly varies TSCCs, ShCs, and DisCs. TSCCs, ShCs, and DisCs decreased to 22%, 23%, and 21% for a 20% demand decrease and increased to 22%, 24%, and 15% for a 20% demand increase. When demand increases and manufacturing units cannot ramp up production capacity due to supply shortages and the COVID-19 lockdown, the TSCCs, ShCs, and DisCs increase. Considering the same capacity, the manufacturing units could fulfil more demand when the demand decreased, decreasing their TSCCs, ShCs, and DisCs. Without ramping up production capacity or raw material supply, changes in ROP, order up to level, or number of transports cannot significantly alter costs or performance. MCs and TCs were not significantly altered for changes in parameters. Conversely, ICs changed significantly with changes in each parameter. As such, manufacturers need to minimise TSCCs, ShCs, DisCs, and ICs by optimising ROP, order up to level, and transports to increase SC performances to meet consumers' demands. This will help manufacturers increase production capacity, maintain an optimal inventory, and avoid backorders.

Variation in manufacturing performances: Manufacturing performances were not significantly affected by changes in parameters such as demand, ROP, order up to level, and number of transports, as manufacturing performance (number of products produced weekly) is more related to production capacity. During disruptions, manufacturing performance significantly decreases. Adopting strategies such as increasing raw material supply and inventory level to increase production capacity can significantly enhance manufacturing performances. Table 4.8 summarises the changes in manufacturing performances. The sensitivity analysis reveals that the model outputs are robust and can provide insights into the dynamics of SC performances. By varying the parameters, it is evident that the model is validated and robust.

Table 4.8: Synopsys of sensitivity analysis

Parameters	**Rate of change**	**Variation in backorder level**	**Variation in financial performances**						**Variation in the number of products produced**
		Unmet demand	**TSCCs**	**MCs**	**ICs**	**TCs**	**ShCs**	**DiCs**	**Number of products manufactured**
Demand	**-20%**	-23%	-22%	-3%	-30%	+4%	-23%	-21%	-8%
	+20%	+24%	+22%	+2%	-36%	-3%	+24%	+15%	0%
ROP *(s_j)*	**-20%**	+1%	0%	-6%	-35%	-1%	+1%	-4%	-6%
	+20%	+1%	+1%	+1%	+24%	0%	+1%	-2%	0%
Order up to level *(S_j)*	**-20%**	+1%	0%	-11%	-19%	0%	+1%	0%	-5%
	+20%	+2%	+2%	+7%	+24%	0%	+2%	-3%	0%
Trucks *(l)*	**-20%**	+1%	+1%	-2%	+26%	-1%	+1%	-2%	-1%
	+20%	+1%	+1%	-2%	+18%	0%	+1%	-1%	0%

4.5. Managerial Implications

The findings of this chapter show that dynamic adaptation strategies and long-term plans to increase optimal raw material supply and production capacity, arrange optimal transports, and maintain an optimal inventory increase the resilience of essential products' SC and significantly reduce the simultaneous impacts of long-term disruptions. This study has several managerial implications, as discussed below.

Managerial insight 1: When we evaluated the recovery plans associated with production capacity increases (Strategy 1), the recovery plan in scenario 1 (S1) performed best. We increased 100% production capacity with optimal ROP, order up to level, and transports for a very long time in S1 during the disruption, which significantly improved the SCs and recovery from simultaneous and dynamic impacts. A 100% production increase with optimal ROP, order up to level, and transports for medium-term periods (Scenario 3) is also a beneficial recovery plan (see Table 4.7).

Thus, during large-scale disruptions, adopting dynamic strategies and plans for long- or medium-term periods helps manage simultaneous and multiple SC disruptions and makes essential products such as facemasks available. This works best if sufficient resources (i.e. raw materials, production capacity, and transportation) are available through adaptation strategies during disruptions.

Managerial insight 2: Regarding improving SCs, the recovery plans in scenario 2 (S2) and scenario 5 (S5) are ranked next. In S2, 50% production capacity is increased with optimal ROP and order up to level to increase raw materials from suppliers (Strategy 2), inventory level (Strategy 4), and the number of transports (Strategy 3) for a long-term period. Furthermore, 100% production capacity is increased in S5 with optimal ROP, order up to level, inventory level, and the number of transports for short-term periods. Both strategies improved the facemask SCs.

The recovery plans in S2 and S5 reveal that when the possibility of having sufficient resources or capacity is low, it is imperative that decision-makers either increase 50% of their raw material supply, production capacity, and delivery capacity by optimal ROP and order up to level for long-term periods or increase the capacities to 100% for short-term periods to reduce TSCCs and improve SC resilience. Decision-makers must evaluate the situation and their capabilities to implement timely adaptive strategies to make their SCs resilient.

Managerial insight 3: Although 50% production capacity and raw material increases for a long-term period improved the SCs, a 50% increase in raw material supply, production capacity, and transports by optimal ROP and order up to level for medium- and short-term periods did not significantly improve the SCs. This can be seen in the recovery plans in S4 and S6 in Table 4.7.

When there is a very low possibility of increasing raw material and production capacity within limited resources, it is imperative to continue increasing production capacity (i.e. 50%) with optimal raw material order and transports for a long-term period rather than medium- and short-term periods.

In summary, by adopting strategy 1 – ‘enhancing manufacturing capacity’, manufacturers can ramp up emergency production capacity by decentralising their manufacturing capacity (Rahman et al., 2022), sub-contracting facilities (Vecchi et al., 2020), and keeping backup factory (Nayeri et al., 2022). The decision-makers can adopt human-robot collaboration in their manufacturing facilities to boost production capacity during the COVID-19 pandemic (Choi et al., 2021). The decision-makers need to understand the importance of nearshoring their manufacturing facilities to nearby places or countries to avoid the impact of extreme situations like lockdowns caused by the COVID-19 pandemic (Fernández-Miguel et al., 2022). They can even re-purpose their production to boost the production of emergency products such as facemasks and ventilators (Ivanov, 2021c). The decision-makers can also diversify their product ranges to boost production and penetrate the market (Rahman et al., 2022).

Managerial insight 4**:** The production increase in manufacturing units needs a dynamic inventory policy (Strategy 4) for smooth raw material supply and cost-effective inventory levels. In S1, a production capacity increase of 100% for a very long-term provided the best result. This needed a 100% increase to get up to level and a 57% increase in ROP, which we obtained by running optimisation experiments.

In summary, in the case of a significant increase in production capacity for a long-term period, increasing order up to a level more than ROP is crucial for better raw material supply and inventory. Similarly, optimisation experiments obtained the optimal ROP and order up to level in all the scenarios (see Table 4.6). Decision-makers need to implement their optimisation capability to determine the optimal level of ROP and order up to the level to maintain an optimal inventory that would not increase their inventory holding costs even after the disruption ends (Paul et al., 2017). Therefore, by adopting strategy 4 – 'maintaining dynamic inventory policy', decision-makers of the manufacturing facilities can keep strategic stock, risk inventory, and redundancy to maintain optimal inventory in their facilities. Virtual stockpile pooling systems can be used among their retailers to maintain the inventory smoothly (Rahman et al., 2022).

Managerial insight 5: In all the scenarios reported in Table 4.6, the number of transports (trucks) for smooth delivery was obtained by optimisation experiments. The experiment revealed that 50%, 40%, 40%, 30%, 40%, and 10% increases in the number of transports (Strategy 3) helped manufacturers in S1–S6 to deliver products to retailers smoothly, which reduced TSCCs and improved SCs.

When the raw material and production capacities are increased to improve SC resilience, it is imperative to identify the optimal level of transportation number for smooth delivery to consumers and retailers to reduce further TSCCs and improve SCs. Otherwise, prompt failure to deliver to the consumers would increase backorder levels (Mehrotra et al., 2020). Therefore, by adopting strategy 3 – ‘increasing transportation and distribution facilities’, the decision-makers can collaborate with other transporters to improve delivery support during the COVID-19 pandemic if more goods are needed to be delivered (Wang & Yao, 2021). They can also adopt multimodal and multi-route shipments for smooth delivery (Kumar et al., 2014). Decision-makers of manufacturers can establish more collaborative distribution centres for enhanced delivery of products to customers in times of emergency (Rahman et al., 2022). Utilising omnichannel and e-commerce can be of great use during the pandemic for smooth ordering and delivery (Zhang et al., 2021).

Managerial insight 6: As ‘*s, S*’ inventory is assumed in the current integrated ABM and optimisation model, it is noted that increasing optimal ROP and order up to level in all the scenarios can significantly increase raw material supply (Strategy 2) to manufacturers so they can produce adequate finished goods (see Table 4.7). For 100% production increase in long-, medium-, and short-term periods in S1, S3, and S5, the ROP increased to 57%, 46%, and 31%, and order up to level increased to 100%, 54%, and 54%, respectively. However, 50% production increases in long-, medium-, and short-term periods in S2, S4, and S6 saw ROP increases of 44%, 24%, and 21%, and order up to level increases of 49%, 25%, and 16%, respectively (see Table 4.6 for optimal values of ROP, and order up to level). Dynamic ROP and order up to level in the scenario by optimisation in our model significantly improved the SC’s raw material supply.

Therefore, manufacturing facilities’ managers need to be strategic and quickly determine the dynamically optimal ROP and order up to level increase to increase raw material supply to produce finished goods. Incorrect and static ROP and order up to level may decrease or increase raw material supply, hamper production, or cause more inventory holding costs (Ivanov, 2017). Therefore, by adopting strategy 2 – ‘improving raw material supply’, decision-makers of manufacturers can arrange alternative or backup sourcing for getting raw material smoothly. Having multiple suppliers can also help get raw materials in an emergency and reduce the risk of supply failure (Rehman & Ali, 2021). During pandemics like the COVID-19 outbreak, local sourcing of raw materials can be beneficial as it can help to ensure a seamless supply of raw materials even when global SCs are disrupted (Remko, 2020). When extreme disruption occurs, such as during the COVID-19 pandemic, manufacturers can arrange emergency sourcing from other similar industries to get raw materials in time (Rahman et al., 2021).

Managerial insight 7: The current model is more sensitive to consumer demand (see Table 4.8). Essential product manufacturers' managers need to determine the demand fluctuation earlier and increase their production capacity using adaptation strategies as soon as possible to meet the demand. Based on the demand, managers must dynamically determine the frequency of ordering to suppliers to avoid further backorder-related ShCs. This can significantly improve the SCs.

Managerial insight 8: The findings of this study reveal that long-term adaptive recovery strategy and dynamic plans can significantly reduce the simultaneous impacts of the COVID-19 pandemic. Short-term recovery plans barely improve SC performances and can leave some after-disruption effects called disruption tails (Ivanov, 2019). Decision-makers must adopt long-term recovery plans to reduce the impacts of extreme disruptions.

However, the proposed strategies and recovery plans are well suited to manage extreme disruptions, such as the COVID-19 pandemic, and the model shows dynamism in formulating the strategy based on demand. It is imperative to revise the recovery plans when the disruption gradually ends; otherwise, SC may face further disruptions. Decision-makers of essential healthcare product manufacturers can consider this study's findings and adopt timely adaptation strategies to manage the impacts of large-scale disruptions to make their SCs much more resilient and viable.

4.6. Chapter Summary

Researchers and practitioners have recently focused on resilient and viable SC practices, particularly in light of the COVID-19 pandemic's impact. SCs across industries require survival and adaptation guidelines to maintain sustainability and robustness. Decision-makers must promptly choose adaptation strategies such as re-purposing, scaling up, substituting, and intertwining SCs to face disruptions effectively. Essential healthcare product manufacturers, like facemask producers, faced severe challenges during the pandemic, exemplified by Australia's prolonged lockdown and closed borders. This study of this chapter developed an integrated ABM and optimisation SC model to evaluate proposed strategies such as 'enhancing manufacturing capacity', 'improving raw material supply', 'increasing transportation and distribution facilities', and 'maintaining dynamic inventory policy' for mitigating the pandemic's impact on essential product SCs. The results showed that without adaptable measures to increase production capacity, ensure raw material supply, and maintain optimal inventory, SC's performance suffered from high shortage costs, highlighting the need for proactive measures during disruptions.

This study makes three significant contributions. Firstly, it proposes dynamic adaptive strategies to enhance the resilience of healthcare product SCs. Secondly, it extensively examines the COVID-19 pandemic's simultaneous and dynamic impacts on SCs, aiding in understanding vulnerabilities and developing adaptive strategies. Finally, it conducts an SC optimisation using an agent-based modelling method to justify proposed strategies and recovery plans, aiming to minimise total supply chain costs and improve performance and resilience. Overall, the study provides valuable insights for managing pandemic impacts on essential healthcare SCs.

Furthermore, this study proposes several recommendations for essential product manufacturers to enhance their production capacity during crises like the COVID-19 pandemic. These include increasing production through ramping up production, subcontracting facilities, utilising backup facilities, and diversifying products in the long term. In preparation for future disruptions, decentralising manufacturing capacity, leveraging human-robot collaboration, and considering reshoring and nearshoring can be effective strategies to scale up production capacity. Manufacturers can also adopt adaptation strategies such as alternative or switching to backup suppliers, having multiple suppliers, and localising sourcing to mitigate supply disruptions. Optimising strategic stock management, implementing minimum inventory policies, and making dynamic adjustments in the inventory can improve inventory levels in the face of disruptions. Decision-makers should identify optimal transportation options, foster collaboration with other transporters, and employ multimodal and multi-route shipment methods to ensure swift delivery during lockdowns. Retailers can utilise omni-channels to facilitate smooth delivery during lockdown periods. Given the prolonged nature of the COVID-19 pandemic, long-term dynamic planning is essential for optimal outcomes. The study emphasises the need for manufacturers to utilise data analytics tools to dynamically determine optimal raw material quantities, inventory levels, and the number of transportations, as demonstrated by the ABM and optimisation methodology employed in the research, to effectively mitigate the simultaneous impacts of the large-scale SC disruption caused by the pandemic. The proposed adaptation strategies and recovery plans, facilitated through a simulation and optimisation model, provide valuable insights for facemask manufacturers to manage concurrent SC disruptions effectively.

However, this study is not without limitations. Theoretically, a few adaptation strategies were considered for the simulation and parameters for optimisation to understand the multiple impacts on SCs focusing on the healthcare product industry. In future studies, it would be beneficial to consider other industry-specific (such as the semiconductor industry) strategies, as different industries may have distinct features and difficulties that necessitate tailored strategies. The present study used hypothetical data based on secondary data to predict impacts and improve SCs. During the COVID-19 pandemic, primary data collection was challenging as industries had to spend time collecting it. A future empirical study can compare the results based on primary data. Future studies could explore strategies to minimise instability in SCs during disruptions caused by war and other global events. Another important avenue in making SCs more resilient could be evaluating SCs' sustainability performances after implementing the resilient strategies. Future research must also identify and manage capability types, such as people, skills, systems, and processes, alongside adaptation strategies to manage large-scale SC disruptions. The present study is the first to predict the simultaneous and dynamic impacts of the COVID-19 pandemic and assess adaptation strategies to manage them. This chapter sets a benchmark and provides practical implications for future research.

Chapter 5

A Viable Supply Chain Model for Managing Panic-Buying Related Challenges: Lessons Learned from the COVID-19 Pandemic

The COVID-19 pandemic exposed the vulnerabilities of global supply chains (SCs) and highlighted the need for more resilient and viable SCs. In particular, panic-buying has been a major challenge for SCs as it can create sudden surges in demand that are difficult to anticipate and manage. However, the literature lacks viable SC models and strategies to address panic-buying-related challenges. As such, this research aims to identify and model viable recovery strategies to increase SC's agility, resilience, and survivability and reduce panic-buying's impact during a large-scale disruption in critical SCs. This chapter contributes by developing an integrated agent-based modelling (ABM) and optimisation method to simulate the behaviour of SCs under different scenarios and evaluating the effectiveness of four proposed strategies and three recovery plans. The findings reveal that increasing production at decentralised manufacturing facilities can be achieved by increasing order frequency to multiple suppliers and partnering with third-party transporters, which can mitigate the effects of panic-buying. This results in higher output and availability of essential goods, significantly managing panic-buying-related challenges. Lastly, this chapter recommends practical solutions for businesses to enhance their SCs' responsiveness to sudden demand surges from panic-buying.

5.1. Introduction

Global business relies on SCs as a vein of the economy (Ivanov & Dolgui, 2021). SCs are susceptible to risks and disruptions that can cause severe short-term and long-term damage to businesses. There are two main types of threats and disruptions to SCs: micro and macro (Macdonald et al., 2018). A micro disruption in an SC could result from short-term machine breakdowns, slight changes in lead times, or an employee's absence on a given day. On the other hand, macro disruption may be caused by a catastrophe, such as an earthquake, pandemic, climate change, or even geopolitical instability (Golan et al., 2020). Large-scale disruptions in SCs constitute macro disruptions (Shekarian & Mellat Parast, 2021). SCs may face environmental, economic, and operational risks and uncertainties associated with human thinking and decision-making in a large-scale disruption (Ivanov, 2020a). Businesses and SC operations have been disrupted on a large scale and for a long time due to COVID-19 and the Russia-Ukraine war. The COVID-19 pandemic has disrupted global business for over 2 years, and the emergence of the Russia-Ukraine war is exacerbating this uncertainty multi-fold. Global SCs have been disrupted dramatically due to these two consecutive recent events with devastating consequences (Lohmer et al., 2020). Experts predict global economic turmoil due to supply disruptions and reduced production. Global SCs are not yet prepared to manage such economic recessions (Rahman et al., 2022a). Thus, it is crucial to understand and study the different levels of the impact of such large-scale disruptions in SCs and how to manage future SCs sustainably.

There is a growing concern among researchers and practitioners about coping with large-scale disruptions and their consequences on SCs, and scholars are developing resilient, sustainable, and viable SC models and strategies (Ivanov, 2021c). SCs have been challenged in terms of survival, resilience, and sustainability. Moreover, global SC disruptions from COVID-19 have affected the entire process, from sourcing to delivery. There is a great deal of concern about the supply and demand of products during the pandemic (Ivanov, 2021a). The demand for high-demand and low-demand products has been changing since the emergence of COVID-19. As a result of the pandemic, fashion, apparel, and automobile products became low-demand products, while food, medicines, facemasks, and personal protective equipment became high-demand products (Chowdhury et al., 2021). As a result of multiple disruptions in supply, demand, production, inventory, transportation, and distribution support systems, manufacturers could not meet additional customers' demand for products such as food, facemask, and personal protective equipment (Dohale et al., 2021). During the pandemic, panic-buying tendencies worsened for some product segments, such as toilet paper in Australia (Paul & Chowdhury, 2020b; Rahman et al., 2021). Panic-buying often leads to hoarding, where individuals stockpile products to such an extent that it creates a shortage for others who genuinely need them. This hoarding behaviour can cause prices to rise, making the products less affordable for the common people (Rahman et al., 2022a). Panic-buying can exacerbate existing inequalities as those with more financial resources may be better able to stockpile products. In comparison, those with fewer resources may be left without access to essential products. The fear and uncertainty that drives panic-buying can cause significant psychological stress for individuals, particularly those already vulnerable (Paul &

Chowdhury, 2020a). Nevertheless, there has been a lack of evidence of strategies to manage SC disruptions in practice and literature (Taghikhah et al., 2021); hence, manufacturers struggled to manage disruptions related to panic-buying during the pandemic, which motivated this study to investigate how to address panic-buying related challenges in SCs.

SCs are currently ineffective at managing panic-buying-related challenges in SCs (Taghikhah et al., 2019) and related challenges that arise from large-scale disruptions, such as the COVID-19 pandemic, and geopolitical instability, such as the Russia-Ukraine conflict (Dolgui & Ivanov, 2020). To the best of the authors' knowledge, the literature lacks a viable strategy and SC model for managing panic-buying-related challenges in SCs during large-scale disruptions with a focus on the impact of consumer panic-buying in toilet paper SCs. Considering this void in the extant literature, this study examines the following research questions:

i) What challenges do manufacturers of high-demand products face during large-scale disruptions triggered by consumer panic-buying behaviours impacting SCs?
ii) Which strategies, tools, and methods can address the impacts of panic-buying-related challenges in SCs during large-scale disruptions?

Businesses need a viable supply chain (VSC) to restore their operations in a volatile and uncertain situation (Wang & Yao, 2021). SC viability (SCV) is gaining traction in operations and SC management. An SCV is its capacity to sustain itself and endure in a changing environment by redesigning its structures and repurposing its performance with long-term effects (Dolgui & Ivanov, 2021). According to Ivanov (2020), a 'Viable Supply Chain (VSC) is a dynamically adaptable and structurally changeable value-adding network able to (i) react agilely to positive changes, (ii) be resilient to absorb negative events and recover after the disruptions, and (iii) survive at the times of long-term, global disruptions by adjusting capacities utilisation and their allocations to demands in response to internal and external changes in line with the sustainable developments to secure the provision of society and markets with goods and services in long-term perspective'. In other words, developing a VSC model based on profitability, resilience, and survivability offers a holistic view of SC interactions with their ecosystems, extending sustainability and resilience to survivability (Ivanov, 2021b; Karmaker et al., 2021). Three cycles comprise a VSC model: agile, resilient, and survival. Table 5.1 presents the structural view of a

VSC model. SCs commonly adopt the first structure, as mentioned in Table 5.1 (leagile) in times of economic stability and normal circumstances. A second structural design (see Table 5.1) concerns disruptions and maintaining resilience during singular, locally-occurring events such as natural disasters, strikes, and fires. A third structure (survival in Table 5.1) is designed to withstand extreme disruptions such as the COVID-19 pandemic in SCs. A good example of one such SC structure during the pandemic is the repurposing of the manufacturing operations of an automobile company for facemasks production (Belhadi et al., 2021). As the literature lacks a VSC model to manage panic-buying-related challenges in SCs during large-scale disruptions, it is imperative to develop one.

Table 5.1: Structural view of a VSC model (adapted from Ivanov, 2020)

SC structure	Leagile	Resilient	Survivable
Strategies	Lean Agile Responsive Product variety	Risk inventory Capacity buffers Backup suppliers	Production changeover Localisation Redesign of supplier Base and logistics
Outcome	**Adaptation and recovery in a VSC**		

SC risk management strategies for managing large-scale disruptions have been extensively researched in the literature (Rahman et al., 2022a). In addition, mitigation strategies and various SC models have been proposed to deal with the impacts of the COVID-19 pandemic (Paul & Chowdhury, 2020b). Any large-scale disruption, such as the COVID-19 pandemic, causes supply disruptions and demand fluctuations (Ivanov, 2020a). Owing to the fear of lockdown, scarcity of critical products such as toilet paper, and exaggerated news from the media about a shortage of products, people try to stock up on necessary products during such disruptions, which can be called panic-buying (Nicola et al., 2020). Super shops and retailers run out of toilet paper when demand fluctuates during large-scale disruptions, and people panic-buy those items. There is a severe impact on a business's ongoing operations, profitability, and goodwill when customers panic-buy on a massive scale (Choi, 2021). Please see Table D1 for the summary of previous studies on SC disruption management strategies and methods. Given this backdrop and specific context, there are three research gaps. These include 1) a lack of literature identifying panic-buying-related challenges in SCs and strategies to manage their impacts during large-scale disruptions such as the COVID-19 pandemic. 2) In many studies, researchers have emphasised the strategies to manage demand fluctuations in SCs but have ignored the impacts of sudden demand fluctuations such as panic-buying. 3) In literature, many mathematical programming-based models deal with demand fluctuations, but there is a scarcity of simulation-based models, such as the ABM model, to manage the challenges of sudden demand disruption or panic-buying related challenges in SCs. Therefore, understanding panic-buying related challenges is necessary to formulate strategies to manage them during large-scale disruptions. Consequently, this study addresses the above concerns, contributing to the recent literature in the following ways:

i) Identifying strategies from literature and developing a VSC model for a toilet paper manufacturer.
ii) Identifying how panic-buying creates challenges in SCs during any large-scale disruption.
iii) Using an integrated ABM and optimisation model to examine proposed strategies in the VSC model to observe how they improve the SCs by reducing panic-buying impacts.

Panic-buying is a phenomenon that occurs when consumers stockpile goods, leading to shortages and price hikes, which further exacerbates the problem. This study develops VSC models, including integrated simulation and optimisation models and strategies, to manage these macro disruptions, particularly panic-buying-related challenges in SCs during large-scale disruptions, and contributes significantly to the literature. Firstly, a VSC model is developed, and strategies from the literature are proposed to manage panic-buying-related challenges in SCs in a large-scale disruption. These strategies have been developed based on a thorough literature review, and their effectiveness has been evaluated using simulation studies. Secondly, this study found the simulation-based model to be an appropriate tool to manage panic-buying-related challenges, a tool that does not exist in extant literature to solve such problems. Consequently, this research develops the VSC model and strategies through a novel integrated ABM and optimisation to address the implications of managing panic-buying-related challenges by implementing different operational recovery plans and comparing their strengths and weaknesses. ABM is considered one of the best methods as it integrates the SC into a network of independent tiers, where various SC actors employ different procedures for decision-making. The proposed model's effectiveness in dealing with challenges related to managing panic-buying is enhanced by integrating ABM and optimisation techniques, representing this study's significant contribution. To the best of the authors' knowledge, this is the first study that presents an integrated agent-based modelling and optimisation framework that effectively identifies the impact of panic-buying in SCs during large-scale disruptions and proposes resilience strategies and recovery plans to manage the resulting impacts. As a consequence of the ABM modelling in employing different procedures for decision-making, this study posed several managerial implications that practitioners can use in their organisations to improve their SC's viability to deal with panic-buying-related challenges in the future.

5.2. Problem statement

Global SCs experience multiple disruptions due to combinatory supply, demand, and financial shocks during large-scale disruptions like the COVID-19 pandemic. The supply of raw materials was severely disrupted due to border closures, restrictions in intermodal shipping, and social distancing during the lockdowns (Ivanov, 2021a). This interruption in the supply of raw materials created havoc in local and overseas manufacturing facilities globally. In addition, manufacturers had to reduce their operations because of the emergence of COVID-19 virus-related infections (Ivanov, 2021c). Distributions and transportation support systems were severely impacted. Manufacturing firms' economic performances also deteriorated because of high shortage costs which hampered their goodwill. Amid these multiple disruptions in SCs, people started panic-buying daily necessities such as food, facemask, and toilet paper (Rahman et al., 2021). The bullwhip effect occurs in SCs when demand fluctuations magnify from the customer to the supplier (Dolgui & Ivanov, 2020). Panic-buying refers to an abrupt and unforeseen surge in demand. The impact of panic-buying on SCs differs from the bullwhip effect in several aspects. Firstly, panic-buying involves a sudden and unexpected spike in demand, whereas the bullwhip effect entails a gradual amplification of demand fluctuations. Secondly, panic-buying is often driven by fear, while the bullwhip effect typically arises from more rational factors like forecasting errors and lead times. Lastly, panic-buying can have a more significant influence on SCs, resulting in shortages, price hikes, and disruptions, compared to the comparatively lesser impact of the bullwhip effect (Rahman et al., 2022b). Paul and Chowdhury (2020) developed a mathematical model to manage the supply-demand disruption of toilet paper SC during the COVID-19 pandemic but did not consider the panic-buying-related challenges within the proposed model. This study considers the example of a toilet paper SC of a manufacturing company in Australia to observe the impacts of panic-buying-related challenges in SCs and how strategies can mitigate them. During the COVID-19 pandemic, the border was closed for around 2 years in Australia. During the lockdown, toilet paper was one of the necessary products that customers stocked due to the fear of lockdown and stockout (Paul & Chowdhury, 2020b). Retailers and super shops ran out of toilet paper due to this heavy panic-buying tendency and customers' hoarding behaviour. Nevertheless, manufacturers could not take the necessary steps to manage the impacts of panic-buying in their SCs and normalise their operations to ensure a good flow of products to the markets to meet customers' extra demand (Ivanov, 2021c). It is a fact that the literature does not identify adaptive strategies to manage panic-buying-related challenges in SCs, which manufacturers of toilet paper in Australia could follow. Therefore, a VSC model is necessary to mitigate panic-buying-related challenges during large-scale disruptions.

5.3. Model formulation, viable strategies, and recovery plans

This study developed an ABM of a typical toilet paper SC, its sourcing, manufacture, dynamic inventory policy, and distribution system. The framework of the proposed model is depicted in Figure 5.1. This ABM model comprises several agents, including (1) retail agent, (2) supplier agent, (3) manufacturer agent, (4) order agent, (5) truck agent at the manufacturing and supplier ends, and (6) evaluation agents that represent SC entities in the proposed model. By coordinating SC entities and achieving the optimal value of decision variables inside the simulation-optimisation operations of the proposed model, the model simulates particular functions to satisfy retailer demand (i.e. customer demand). The modelled toilet paper SC has several strategies to ensure a VSC structure. These include (1) several local manufacturing plants (three local manufacturers in three different locations close to customer zones), (2) main and alternative multiple local suppliers (four main suppliers with three alternative suppliers), (3) dynamic inventory policy, and (4) trucks (collaborative transporters) at the supply and manufacturing ends. They supply their finished products (toilet paper) to 18 retailers from where the customers in the respective zones get their demanded products. We used hypothetical data derived from secondary sources to evaluate the model in this study. Please refer to Table D5–D7 in Appendix D for the data details. Table 5.2 shows the synopsis of the proposed strategies for a viable toilet paper SC to manage disruptions in the model. Table 5.3 lists the operational recovery plans used in this study to deal with large-scale SC disruptions and panic-buying-related challenges after the disruptions have occurred.

The model uses the optimum order quantity approach for inventory replenishment. Retail agents in the model continuously place orders to satisfy customer demand in their respective zones. These orders are sent to the most feasible manufacturer, which utilises a make-to-stock strategy. Following that, the manufacturing agent makes an effort to fulfil the order utilising a set of accessible trucks and its make-to-stock inventory of finished goods, denoted as Q_j^t. If the inventory level drops below the reordering level, which is the reordering point denoted as s_j, a request is sent to the suppliers for a specified quantity of raw materials and/or components, which is order up to level denoted as S_j, to replenish the raw material stock used for production. When panic-buying occurs in the market, the increased order quantity is communicated to manufacturers, who subsequently increase their orders with suppliers to produce additional products to meet the surge in demand. Trucks deliver the raw materials that supplier agents produce (in a make-to-order environment) to the appropriate manufacturer. Truck agents from manufacturers deliver finished goods to retail agents. Order supplier agents operate as the manufacturers' representatives when placing orders with suppliers for the parts and raw materials needed to produce final products. Suppliers utilise truck agents to transport parts or raw materials to factories. The evaluation agent interfaces with the other agents in the system to keep track of the important performance indicators for the current SC. This assessment agent takes into account production/manufacturing costs (MCs, including sourcing and raw material costs from suppliers), transportation costs (TCs), inventory costs (ICs), shortage costs (ShCs), discount costs (DisCs), and products/components produced/shipped/received at various SC stages. This study evaluates the performances of SCs by TSCCs, where TSCCs = MCs + ICs + TCs + ShCs + DisCs. Table D2 in the Appendix presents the descriptions of the model's agents, Table D3 presents the model's parameters, and Table D4 lists the cost metrics applied to this model. The assumed changes in demand, manufacturing capability, and supply postponement caused by disruption are depicted in Figure D1 in Appendix D.

The ABM model's simulation-optimisation procedure seeks to reduce the toilet paper SC's TSCCs while improving resilience, such as capacity expansion and responsiveness. When implementing strategies and recovery plans (see Tables 5.2 and 5.3) to maximise the supply of raw materials from suppliers, the number of finished products produced in manufacturing facilities, the inventory level, and the availability of products for retailers, the model optimises the reordering level (s_j), order size (S_j), and the number of trucks (l), while minimising TSCCs to minimise the impacts of large-scale disruptions and panic-buying-related challenges in SCs as much as possible. The goal of the objective function is to minimise the TSCCs, as shown in Equation 1.

Min (TSCCs in time window t) $= \sum_j \varphi_j.\tau + \sum_j \vartheta_j.p_j^t + \sum_j \sum_k \rho_k.y_{jk}^t + \sum_j IM_j.Q_j^t + \sum_i IR_i.R_i^t + \sum_j \psi_j.\tau + \sum_l \sum_i \sum_j \omega_j.x_{ij}^t.\alpha_{ijl}^t + \sum_k \theta_k.\tau + \sum_m \sum_j \sum_k \upsilon_k.y_{jk}^t.\beta_{jkm}^t + \sum_j d_j^t.\eta_j + \sum_j w_j^t.\lambda_j$ (1)

Subject to: $\sum_j y_{jk}^t = S_j$ (2)

$\sum_j y_{jk}^t \le Q_j^t$ (3)

$\sum_j x_{jk}^t \le D$ (4)

$y_{jk}^t \le C_i \,;\ \forall_i$ (5)

$y_{jk}^t \ge s_j;\ \forall_i$ (6)

Where,

MCs in the time window $t = \sum_j \varphi_j.\tau + \sum_j \vartheta_j.p_j^t + \sum_j \sum_k \rho_k.y_{jk}^t$

Manufacturing ICs in the time window $t = \sum_j IM_j.Q_j^t$

Retailer ICs in the time window $t = \sum_i IR_i.R_i^t$

TCs at the manufacturing stage in the time window $t = \sum_j \psi_j.\tau + \sum_l \sum_i \sum_j \omega_j.x_{ij}^t.\alpha_{ijl}^t$

TCs at the supplier stage in the time window $t = \sum_k \theta_k.\tau + \sum_m \sum_j \sum_k \upsilon_k.y_{jk}^t.\beta_{jkm}^t$

ShCs at the manufacturing stage in the time window $t = \sum_j d_j^t.\eta_j$

DisC at the manufacturing stage in the time window $t = \sum_j w_j^t.\lambda_j$

Equation (1) is obtained by adding the costs associated with manufacturing (MCs), storing inventory (ICs), transporting (TCs), shortages (ShCs), and discounts (DisCs), which are also specified in Table D4 in Appendix D (Rahman et al., 2021). The order constraint is outlined in equation (2), where the total amount of raw material supplied ($\sum_j y_{jk}^t$) must be equal to the order threshold (S_j) and must not exceed the storage capacity (Q_j^t) of the facility (as specified by the inventory capacity constraint in equation [3]). The demand constraint is described in equation 4, where the quantity of products ($\sum_j x_{jk}^t$) supplied to retailers by manufacturers must be less than or equal to the demand (D). The constraint for the supplier's capacity is outlined in equation (5), where the raw material supplied (y_{jk}^t) by the supplier must not exceed the supplier's capacity (C_i). The constraint for the reordering point is detailed in equation (6). The proposed model was developed using AnyLogic software.

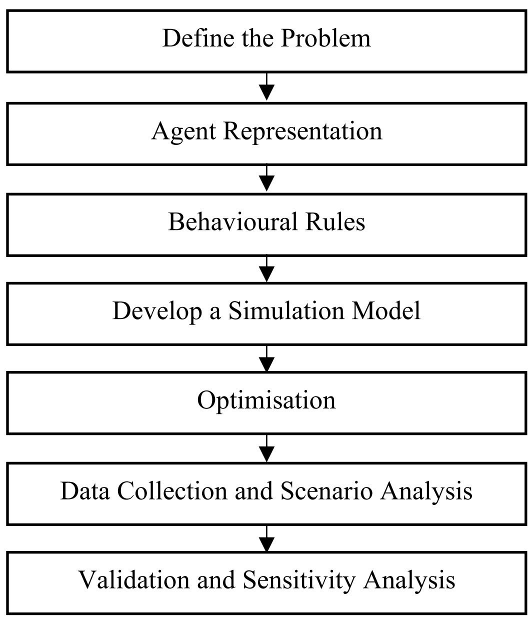

Figure 5.1: Framework of the proposed ABM model.

Table 5.2: Synopsis of the proposed strategies for a VSC to manage disruptions

Levels of SCs	**Proposed resilient strategies**	**Main features**	**Structural view of VSC**	**Simplified meaning**	**References**
Supplier	Multiple main and alternative local suppliers	Flexible; Low lead time	Leagile → Resilient → Survival	Even if some factories are unable to obtain smooth raw materials owing to different disruptions, having alternative sources enables them to do so.	Sazvar et al. (2021b)

Stock/inventory	Optimal order quantity	Integrated warehouse		The foundation of a robust SC is an optimal inventory policy. SCs are resilient and sustainable due to efficient and effective inventory management.	Gholami-Zanjani et al. (2021)
Production	Multiple local production facilities	Having capacity cushion		If SCs run multiple production facilities, they are more robust. When there is a significant interruption, such as the COVID-19 pandemic, multiple manufacturing sites help to preserve productivity.	Ivanov & Rozhkov (2020)
Transportation	Coalition with other transporters	Responsiveness		In addition to having their own transportation, producers can deliver goods quickly and on time by working in agreements with other transporters.	Wang & Yao (2021)

Table 5.3: Recovery plans considered in different scenarios

Scenarios	**Increased operational inputs**	**Increase in production capacity**	**Optimisation of raw materials supply, inventory, and trucks: lower and upper limits**		
			ROP	**Order-size**	**Trucks**
Scenario 1 (S1)	High	Max: +80.00% Avg: +71.00%	Min: 1400 Max: 1800	Min: 4200 Max: 5400	Min: 14 Max: 18
Scenario 2 (S2)	Medium	Max: +40.00% Avg: 35.50%	Min: 1200 Max: 1400	Min: 3600 Max: 4200	Min: 12 Max: 14
Scenario 3 (S3)	Low	Max: +20.00% Avg: +17.80%	Min: 1100 Max: 1200	Min: 3300 Max: 3600	Min: 11 Max: 12

5.4. Result analysis and discussion

This section analyses the dynamics of SCs in different scenarios, presents the results, and discusses the findings. It discusses the impact of different responsiveness in SCs and sensitivity analysis to ensure calibration and validation tests regarding our proposed ABM model.

5.4.1. Baseline scenario analysis

Our model considers two baseline scenarios: a normal baseline scenario and a disrupted baseline scenario. For better anticipation of the dynamics of SCs, we simulate it for 5 years.

SCs usually operate in the normal baseline scenario (please refer to Tables D5–D7 in the Appendix for the parameters) without disruptions in raw material supply, demand fluctuations, manufacturing facilities, transportation, or financial management. As the simulation was conducted under the normal baseline scenario, there were no significant high TSCCs due to the higher percentage of customer demand fulfilment. In the normal baseline scenario, only a small number of backorders occurred due to occasional fluctuations in demand. All other SC costs, such as manufacturing, inventory, transportation, shortage, and discount costs, were also normal and did not see any abrupt changes (see Table 5.4). In contrast, we mimicked the impact of significant disruptions, such as the COVID-19 pandemic, in the baseline disrupted scenario. When there was fear of lockdown coupled with the COVID-19 pandemic, toilet paper demand increased by 400% (Rahman et al., 2021), with an average weekly increase of 38.5%. Customers' panic-buying and hoarding behaviour contributed to this spike in demand. As a result of a significant delay from suppliers, manufacturing capacity decreased to 50%, with an average decrease of 7.6%. The supply of raw materials was delayed by up to 55%, with an average delay of 8.4% during the pandemic. These changes in demand, manufacturing capacity, and supply delays increased TSCCs significantly when the simulation was run under disrupted conditions. Figure 5.2 illustrates SCs in normal baseline and disrupted scenarios. Figure D1 in Appendix D shows the changes in demand, manufacturing capacity, and supply delay during disruption.

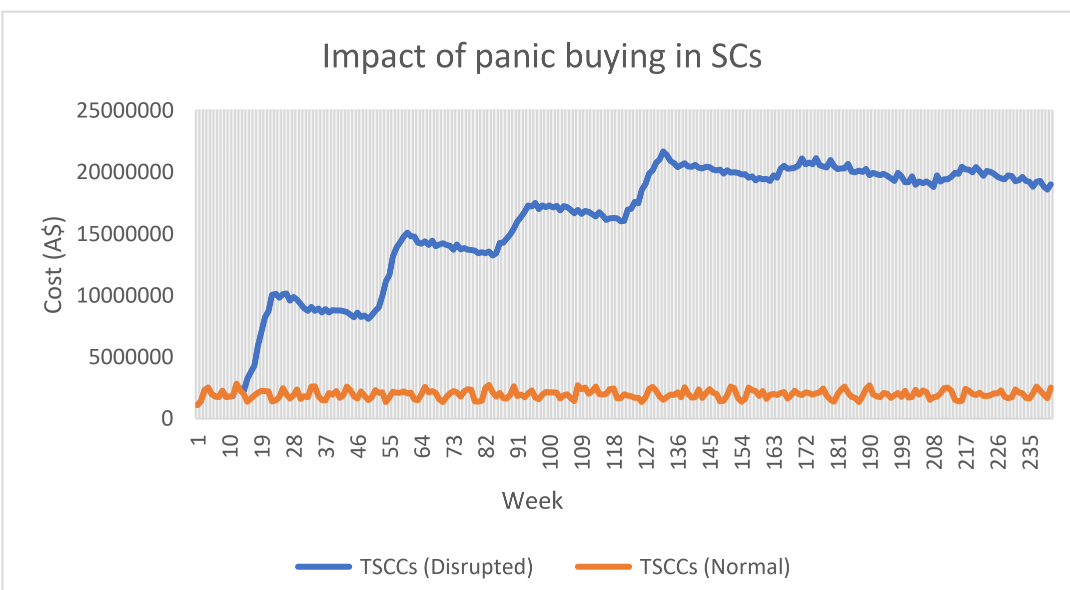

Figure 5.2: TSCCs in normal baseline and disrupted scenarios.

5.4.2. Impact of panic-buying in SCs during large-scale disruption

This study examines the impact of panic-buying-related challenges in the toilet paper SC during large-scale disruptions, such as the COVID-19 pandemic. When no strategies were implemented and demand spiked, people panic-purchased toilet paper, manufacturing facilities degraded due to lockdowns, suppliers significantly delayed delivery times (please refer to Figure D1 in the Appendix), and TSCCs increased by 691.86%. The reduced manufacturing capacity resulted in manufacturing facilities' inability to meet customers' extended demand, significantly increasing their backorder-related shortage costs. Delivery times increased as production slowed down and was limited, resulting in higher discount costs. Manufacturing facilities had to limit production due to a shortage of workers, thus increasing unused inventory levels. Also, manufacturing facilities' work-in-process inventory levels increased because of the delay in receiving raw materials, thus raising their inventory costs. A lack of proper strategies led to limited manufacturing, which resulted in lower manufacturing costs. During baseline disrupted conditions, there were few transportation activities when no strategies were implemented since manufacturing facilities could not increase production, thus reducing transportation costs. During a large-scale disruption such as COVID-19, panic-buying-induced demand spikes and other multiple disruptions can be detrimental to the performance of SCs. The impact of panic-buying-induced demand spikes during the COVID-19 pandemic can be seen in Table 5.4.

Table 5.4: Impacts of panic-buying in SCs during large-scale disruptions

	Impacts of large-scale disruptions in SCs							
	Backorder level (Units - Avg/week)	**Economic performances (A$ - Avg/week)**						**Manufacturing performance (Units - Avg/week)**
	Demand unmet	**TSCCs**	**MCs**	**ICs**	**TCs**	**ShCs**	**DisCs**	**Output**
Normal scenario	921.16	1,978,582.28	1,754,319.50	120,291.73	93,139.61	3,684.65	7,146.78	Avg: 12560.17, Max: 27000.00
Disrupted scenario	2,712,703.96	15,667,549.49	2,208,016.60	169,570.41	88,183.80	10,850,815.85	2,350,962.83	Avg: 15385.89, Max: 27000.00
Changes (%)	+294387.23%	+691.86%	+25.86%	+40.97%	-5.32%	+294387.23%	+32795.39%	22.50% (Avg), 0.00% (Max)

5.4.3. VSC strategies, recovery plans implementation, results, and outcomes

We implemented the proposed operational recovery plans with the viable strategies (please see Tables 5.2 and 5.3) in our proposed model to test the improvement in SCs. The proposed recovery plans (please see Table 5.3) are as follows:

Recovery plan 1 (RP1): In scenario 1, RP1 increased production capacity up to 80%, with an average of 71.00%, and optimal ROP, order-size, and trucks.

Recovery plan 2 (RP2): In scenario 2, RP2 increased production capacity up to 40%, with an average of 35.50% and optimal ROP, order-size, and trucks.

Recovery plan 3 (RP3): In scenario 3, RP3 increased production capacity up to 20%, with an average of 17.80%, and optimal ROP, order-size, and trucks. Please refer to Table 5.5 for the optimal ROP, order-size, and trucks over time.

Table 5.5: Optimal value for decision variables

Scenarios	**Optimal value for decision variables**		
	ROP (s_j)	**Order-size (S_j)**	**Trucks (l)**
Normal scenario	1000	3000	10
Scenario 1 (S1)	1461	4625	14
Scenario 2 (S2)	1329	3836	12
Scenario 3 (S3)	1163	3391	11

Comparative analysis of the outcomes

Evaluation of manufacturing performances and backorder levels: In scenario 1, when manufacturing capacity was increased to 80%, with an average of 71%, backorder levels decreased to 99.49%. In scenario 1, recovery plan 1 reduced backorder levels the best. Recovery plans 2 and 3 also reduced backorder levels to 97.20% and 87.57%, respectively. In scenario 1, the optimal ROP, order size, and truck contributed to the timely delivery of raw materials to manufacturing facilities and finished goods to retailers. With the implementation of recovery plans, decentralised manufacturing facilities produced more products, ensuring a sufficient supply of finished goods (toilet paper) to the market and reducing the impact of panic-buying and other multiple impacts on SCs significantly (see Table 5.6). Increasing production capacity and managing raw materials from local suppliers improved the SCs' agility, resilience, and survivability.

Evaluation of TSCCs: After reducing backorder levels, recovery plan 1 in scenario 1 significantly reduced TSCCs to 83.61%. This is due to the SC's agility in meeting the extended customer demand. As a result of strategic decisions and dynamic capabilities to forecast the demand and increase raw material supply and production capacity using capacity cushions, the manufacturing companies were able to meet the extended demand, which reduced their backorder-related shortage costs. In scenarios 2 and 3, recovery plans 2 and 3 reduced TSCCs to 78.38% and 65.88%, respectively. The more agile and dynamic the SCs become in increasing capacity with optimal ROP, order size to suppliers, and optimal trucks, the better they could reduce TSCCs by meeting more demand and reducing shortage costs (see Figure 5.3).

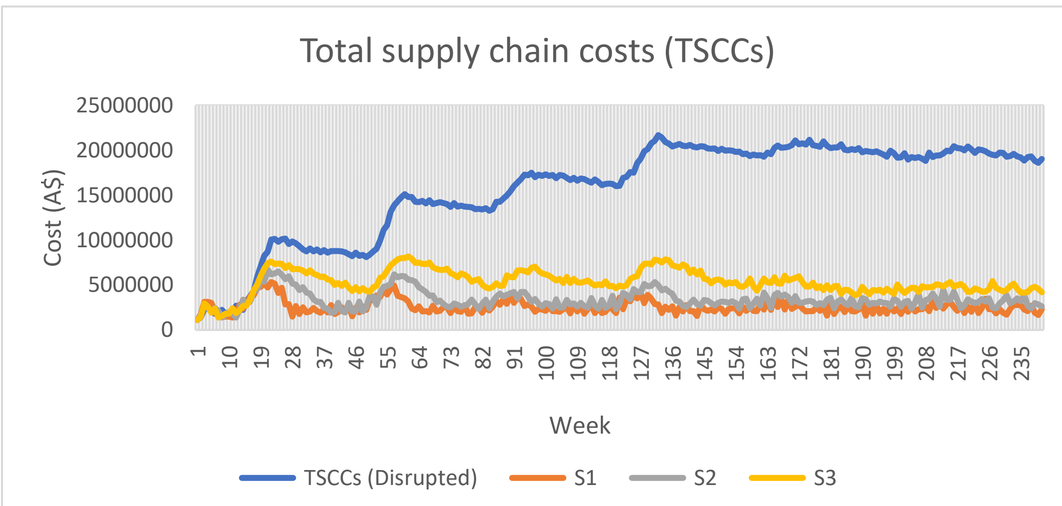

Figure 5.3: Evaluation of TSCCs from different scenarios.

Evaluation of manufacturing costs (MCs): In scenarios 1, 2, and 3, recovery plans 1, 2, and 3 reduced manufacturing costs to 8.72%, 8.74%, and 8.57%, respectively. The manufacturing cost increased during disruptions due to delays in raw material delivery and low production volumes. When manufacturing facilities could not get raw materials during the disrupted scenario, they had to occasionally increase production in low volume and push goods back onto the market as soon as the condition improved. In response to extended demand, manufacturing facilities adapted recovery plans by increasing the capacity to produce large volumes at once with an optimal ROP, order size, and truck capacity, thereby reducing manufacturing costs dramatically (see Figure 5.4). Costs are always reduced by economies of scale in production (Bui et al., 2021).

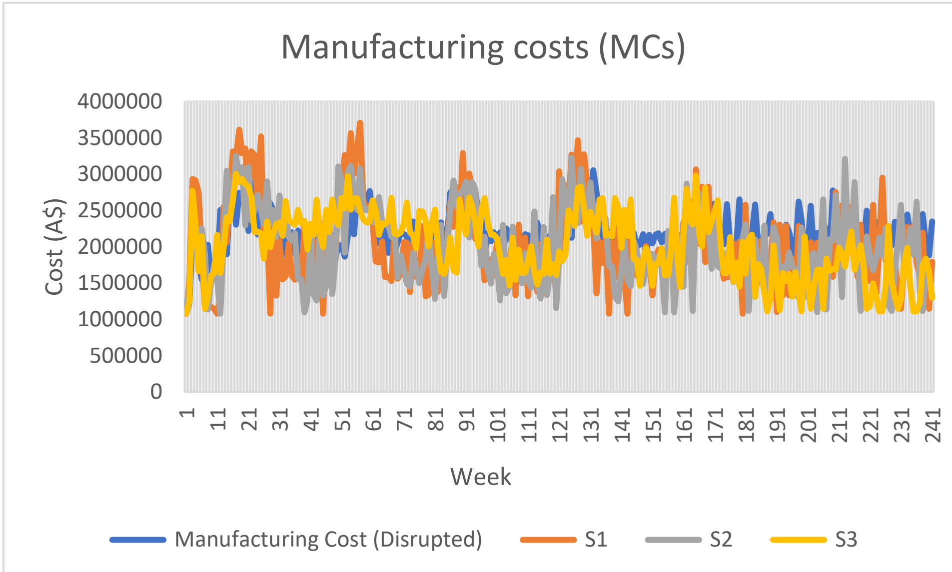

Figure 5.4: Evaluation of MCs from different scenarios.

Evaluation of inventory costs (ICs): In scenarios 1 and 2, recovery plans 1 and 2 increased production capacity to 80% and 40%, respectively. Inventory costs remained normal in both scenarios without much change (0.24% increase in scenario 1 and 1.81% decrease in scenario 2). In scenario 3, recovery plan 3 increased inventory costs by 39.61% due to imbalanced inventory policies and reduced toilet paper manufacturing to meet customers' extended demands. As can be seen in Figure 5.5, there is no extra inventory in scenarios 1 and 2. However, there is additional inventory in scenario 3.

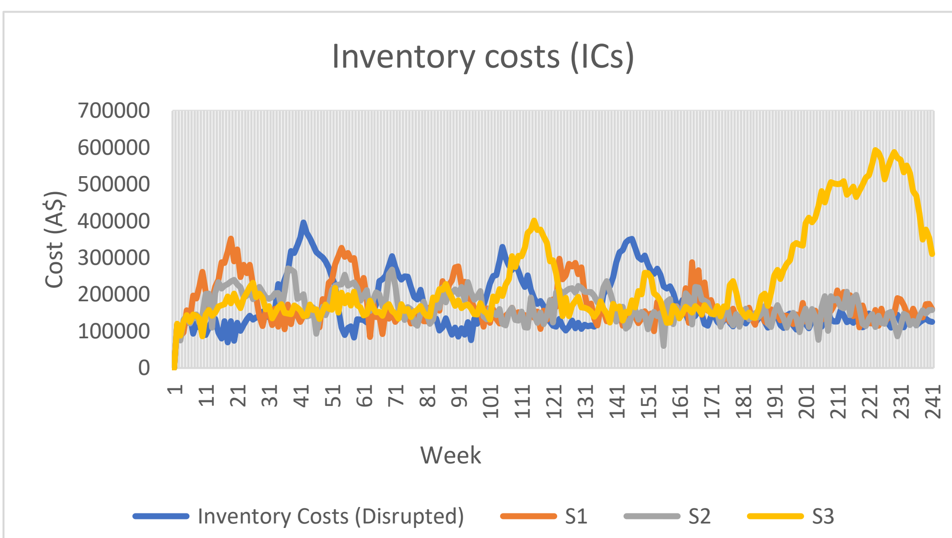

Figure 5.5: Evaluation of ICs from different scenarios.

Evaluation of transportation costs (TCs): In all scenarios, transportation costs are increased to 4.99%, 6.32%, and 7.29%, respectively, for delivering extra finished goods to retailers so that they can meet extended demand. This is displayed in Figure 5.6. For scenarios 1 and 2, there was an initial spike in transportation costs in weeks 26 and 36 due to recovery plans of increased production capacity to produce and deliver additional products to retailers, which eventually decreased with time. Despite initial higher transport costs to deliver additional toilet paper to retailers, this ultimately resulted in reduced shortage costs and TSCCs, reducing panic-buying and large-scale disruptions and increasing SC's resilience.

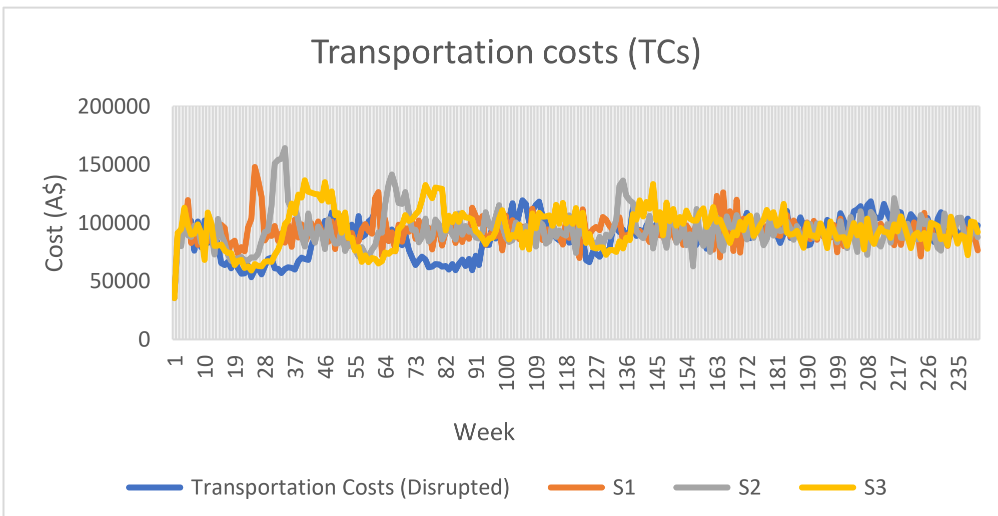

Figure 5.6: Evaluation of TCs from different scenarios.

Evaluation of shortage costs (ShCs): Recovery plan 1 in scenario 1 significantly reduced shortage costs to 99.49% after reducing backorder levels. This is due to the SC's agility in meeting customer demand. By forecasting demand and increasing raw material supply and production capacity using capacity cushions, they could meet the extended demand, resulting in lower backorder-related shortage costs. Recovery plans 2 and 3 reduced shortage costs to 97.20% and 87.57%, respectively. The more agile SCs can become in increasing capacity with optimal order size to suppliers, optimal trucking size, and optimal ROP, the better they can reduce shortage SC costs by meeting more demand and reducing backorder levels (see Figure 5.7).

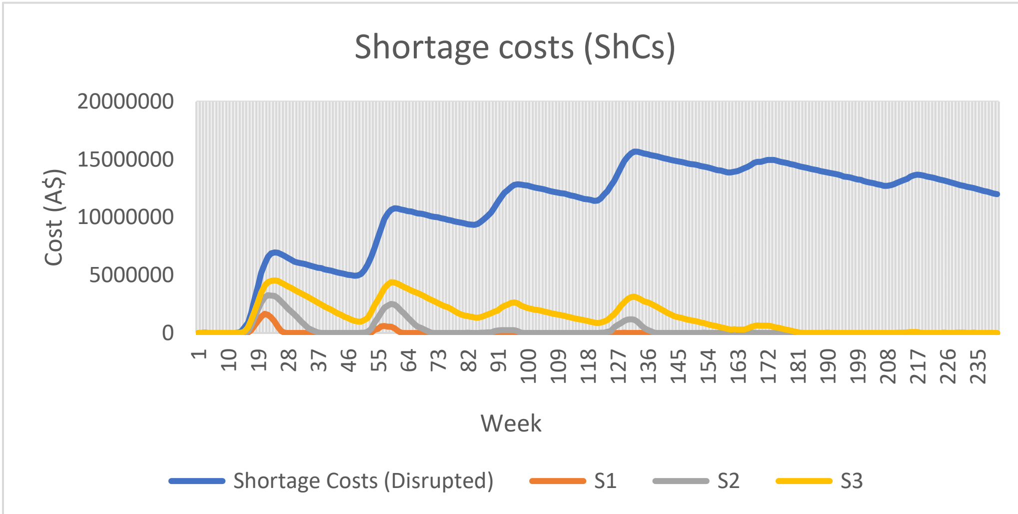

Figure 5.7: Evaluation of ShCs from different scenarios.

Evaluation of discount costs (DisCs): In scenario 1, recovery plan 1 reduced discount costs to 89.98%. Among the three recovery plans, plan 1 performed the best. Recovery plan 1 increases the manufacturing capacity so that the toilet paper SC can produce in bulk volume and deliver same to the market in time to meet extra customer demand, which helped them avoid higher discount costs. Recovery plans 2 and 3 have lower production rates than recovery plan 1, so their discount costs are higher (see Figure 5.8). The more agile and resilient SCs are, the greater their chance of surviving disruptions. To avoid discount costs during panic-buying, manufacturers should increase their production rate. For a performance evaluation of toilet paper SCs after implementing recovery plans with viable strategies, please refer to Table 5.6.

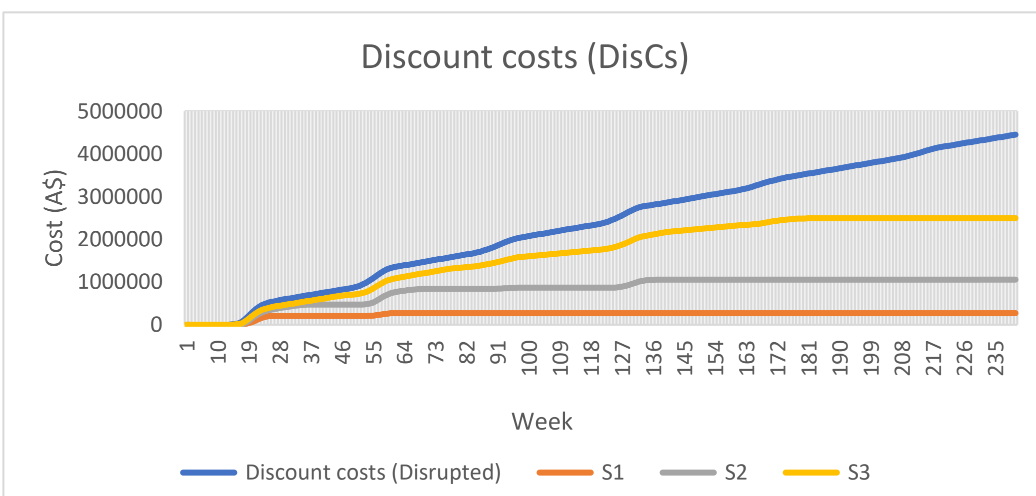

Figure 5.8: Evaluation of DisCs from different scenarios.

Table 5.6: Impacts of implementation of resilience strategies on SC performances

Variation in scenarios	SC performances' improvement analysis compared to the disrupted scenario							
	Backorder level (Avg/Week)	Economic performances (Avg/Week)						Manufacturing performance
	Demand unmet	TSCCs	MCs	ICs	TCs	ShCs	DisCs	Output
S1	-99.49%	-83.61%	-8.72%	+0.24%	+4.99%	-99.49%	-89.98%	Avg: +13.01%, Max: +105.56%
S2	-97.20%	-78.38%	-8.74%	-1.81%	+6.32%	-97.20%	-65.60%	Avg: +13.38%, Max: +27.87%
S3	-87.57%	-65.88%	-8.57%	+39.61%	+7.29%	-87.57%	-29.94%	Avg: +13.86%, Max: +13.03%

5.4.4. Impact of different responsiveness on the performances of SCs

We observed differences in performance in SCs due to the different responsiveness of implementing strategies and recovery plans. For example, we immediately implemented recovery plan 1 (increasing production capacity up to 80%) with a delay of 3 months. The results show that if the recovery plan is implemented with a delay of 3 months, the TSCC increases to 11.80%. Suppose manufacturers delay increasing their production capacity during large-scale disruptions such as COVID-19 when people start panic-buying critical products. In that case, it may result in higher SC costs due to higher shortage costs (see Figure 5.9).

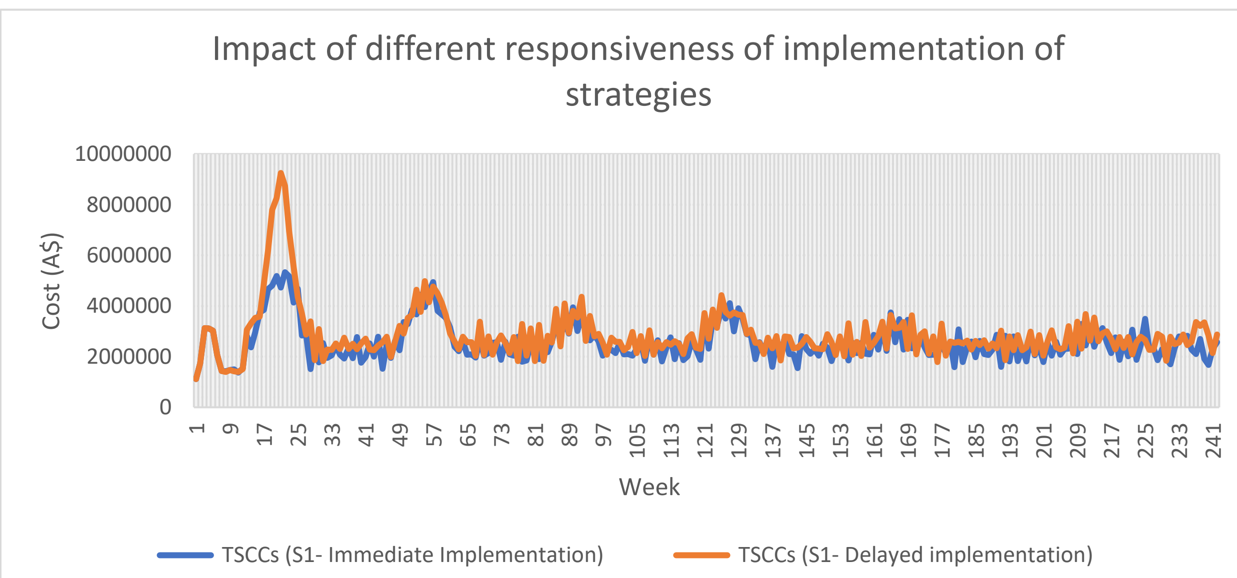

Figure 5.9: Impact of different responsiveness on implementation of strategies in TSCCs.

5.4.5. Model validation and sensitivity analysis

This study aimed to improve the SC management of a company that manufactures toilet paper to minimise the effect of panic-buying. An ABM model was developed using AnyLogic software to simulate the entire SC of a toilet paper manufacturer, including interactions among suppliers, manufacturers, transporters, and retailers. After applying hypothetical data, various scenarios were tested to evaluate SC performance under diverse conditions. Confidence intervals were calculated to compare the results of the strategies against the baseline disrupted scenarios. The outcomes of the strategies were within the range of the confidence intervals, indicating that they were effective (please see Table D8 in the Appendix). For example, TSCCs were reduced to 83.61%, and the confidence interval (CI) is calculated to be [-83.71%, -83.49%] at 95% CI for the case of strategy 1. We additionally conducted a one-sample t-Test (please see Table D9 in the Appendix), and the P-value indicates that the result is statistically significant for the case of strategy 1. In this case, the null hypothesis is that no significant difference exists between the results obtained from the disrupted scenario and the implemented strategies. The alternative hypothesis is that there is a significant difference between the two. The P-value obtained from the T-test is less than the significance level (usually set at 0.05), which indicates that the null hypothesis can be rejected, and the alternative hypothesis can be accepted. This means that the results obtained from the simulation are statistically significant and can be used to improve the SC of the toilet paper manufacturing company.

The preliminary outcomes of the research were presented at an international conference (Rahman et al., 2022b), demonstrating the model's effectiveness in improving the SC's efficiency and resilience. The attendees were impressed with the precision of the results. This research confirmed the usefulness of ABM in optimising complex systems and highlighted the significance of rigorous validation and analysis in ensuring the dependability of results.

Furthermore, the proposed model's robustness was evaluated using the 'one-factor-at-a-time' (OFAT) sensitivity analyses (see Table D10 in the Appendix) to ensure the robustness and validity of the proposed model. Compared to disrupted scenarios, we applied ±15% change in demand, manufacturing capacity, and inventory policies in SCs.

The sensitivity analysis shows that the model is most sensitive to demand and manufacturing capacity changes. As manufacturing capacity is not increased, a 15% increase in demand increased backorder levels, TSCCs, shortage costs, and discount costs. In contrast, a 15% decrease in demand reduced these costs. Increased manufacturing capacity also decreased backorder levels, TSCCs, shortage costs, and discount costs when demand remained the same. Increasing ROP by 15% decreased TSCCs, while decreasing ROP by 15% increased TSCCs. However, a 15% decrease in order size reduced TSCCs more than a 15% increase in order size. Thus, it can be concluded that instead of increasing order sizes, increasing the frequency of ordering to suppliers can increase raw material supplies to manufacturers in case of a sudden surge in demand due to panic-buying. This would enable them to produce more products to meet customer demand. In this case, a higher frequency of orders to suppliers can also reduce work-in-process inventory in the warehouses, reducing inventory costs. Increasing raw material supplies and manufacturing capacity increased transportation costs, reducing SC costs. Finally, we made changes of ±15% to all parameters simultaneously. When we increased demand, manufacturing capacity, ROP, and order size by 15%, the backorder level rose to 17.36%, resulting in higher costs across the entire SC, including manufacturing, inventory, shortage, and discount costs. However, as we increased manufacturing capacity, ROP, and order size in this case, we observed decreased transportation costs because the economic scale was maintained, reducing costs in this aspect. Conversely, when we decreased the combined parameters, the opposite effect occurred. The results of the parameter changes show a consistent pattern throughout the parameter changes. Therefore, the study's findings and analyses can be concluded to be fairly robust due to the model's robustness.

5.5. Managerial implications

This study has four managerial implications for the SCs of essential products such as toilet paper when facing panic-buying-related challenges during large-scale disruptions. This study will enable toilet paper manufacturers to determine whether panic-buying can negatively impact their SCs to develop viable strategies and recovery plans. These findings will allow managers to identify how large-scale disruptions, such as the COVID-19 pandemic, can induce panic-buying and how they can design their VSC models to manage challenges, reduce SC costs, and increase performances for SC agility, resilience, and survivability.

Firstly, the study reveals that panic-buying contributes to demand spikes for critical items such as toilet paper during large-scale disruptions such as the COVID-19 pandemic (Ivanov, 2021c; Nicola et al., 2020). This is exacerbated by the shortage of raw materials from downstream suppliers, the degeneration of production, and the disruption of transportation and distribution systems during the pandemic. Paul and Chowdhury (2020a) and Ivanov (2021a) demonstrate that increasing the production of critical items can successfully respond to the spike in demand. As such, following market demand dynamically, especially when purchasing capacity of customers cannot be managed during panic-buying, this study's findings indicate that manufacturing and supplying toilet paper to the shops can alleviate panic-buying quickly as SC agility is increased. Additionally, this study reveals that unfulfilled demand caused by panic-buying can lead to high shortage costs in SCs. According to the study, decentralised local manufacturers can increase the production and supply of finished goods to the markets by utilising their capacity cushion. Simultaneously, they can reduce shortages, discounts, and TSCCs. In summary, increasing the supply of finished goods to the market is the key to managing panic-buying in SCs. Therefore, firms can maintain their goodwill in the market, leading to better survivability and profitability, making SCs dynamic and viable.

Secondly, an optimal inventory in manufacturing facilities is necessary for smooth production. The study reveals that increasing the frequency of orders with optimal order size to multiple and alternative suppliers, especially local suppliers with low lead times and flexibility, is a significant factor in increasing raw material supplies to manufacturing facilities. SCs are more resilient when they have multiple and alternative local suppliers (Shekarian & Mellat Parast, 2021). When there are large-scale disruptions, there may initially be an increase in inventory costs to meet increased consumer demand, but this ultimately reduces the total cost of SCs by increasing production and offering finished goods to market, thereby reducing backorder levels. Having an integrated warehouse in manufacturing facilities can ensure that the manufacturing facilities have the inventory they need (Gholami-Zanjani et al., 2021). Decision-makers should continuously review inventory policies to ensure optimal inventory levels, increase production, manage panic-buying-related challenges, and ensure a VSC.

Thirdly, for manufacturers to deliver additional products to retailers, a smooth transportation and distribution system is essential (Rahman et al., 2022a; Zhen et al., 2016). There may be transportation restrictions due to government regulations to flatten the curve of virus emergence, as evidenced by the COVID-19 pandemic. Furthermore, manufacturers may need extra transportation to deliver their additional products to retailers (Ivanov, 2020a). Considering the increased demand and finished goods to be shipped to retailers, they can deliver the products smoothly if decision-makers find the optimal number of trucks needed. The decision-makers can use their transportation or collaborate with third-party logistics companies to deliver the extra products to retailers in time (Li & Chan, 2012). Furthermore, the study reveals that when there is high customer demand, transportation costs may spike initially, but eventually, they normalise and reduce TSCCs, leading to VSCs that can cope with panic-buying-related challenges.

Lastly, decision-makers can use this study's revealed viable strategies and operational recovery plans to manage panic-buying-related challenges in SCs during large-scale disruptions. Hence, they should dynamically design strategies as soon as they anticipate panic-buying in the market to cope successfully with panic-buying-related challenges. This study shows that delays in implementing strategies for dealing with panic-buying-related challenges may increase overall SC costs.

The study emphasises the value of using local suppliers, integrating manufacturing and warehouses, and collaborating with additional transporters to enhance SCs and reduce the impact of panic-buying-related challenges. These strategies have unique issues and challenges, but they are necessary to increase the effectiveness and resilience of SCs. The lack of local suppliers or their capability is one of the major challenges. This might lead to a shortage of resources for labour- and resource-intensive production and storage integration. This might result in resource rivalry amongst transporters, making SC optimisation more difficult. The fact that this can potentially necessitate additional financial commitments from businesses must be considered when formulating a strategic plan for SC optimisation. Early planning based on panic-buying signals may be used to get around these issues and ensure that firms have the resources they need to flourish.

These strategies emphasise the value of localising SCs and lowering reliance on a single supplier or transportation system from a conceptual standpoint, which helps to reduce the risks of interconnected SCs, such as interruptions brought on by calamities or geopolitical unrest. From a methodological standpoint, the emphasis on strategic planning and early planning emphasises the value of data-driven decision-making and risk management in SC disruption management. From a social perspective, utilising local suppliers and combining production and storage may benefit neighbourhood communities and economies by fostering employment growth and economic development. Practically, these strategies might increase the effectiveness, resilience, and sustainability of SCs, which would be advantageous to both businesses and consumers. However, its execution necessitates dedication to continuous development and adaptation, and a thorough evaluation of the difficulties and limitations inherent in each strategy.

Industrial managers can develop a simulation model of their SC using ABM to address issues like panic-buying. They might collaborate with their research and development (R&D) teams or academic experts to acquire information, develop the model, and test various scenarios. For instance, they may create an ABM-based simulation model that considers inventory levels, SC disruptions, and customer behaviour to control panic-buying. An advantage of adopting an ABM-based simulation model is that it offers a mechanism to test various scenarios, enabling industrial managers to find the most effective strategies and apply them more consistently without the risk and expense of making changes in the real world.

5.6. Chapter summary

This chapter aimed to identify challenges associated with panic-buying in critical SCs, such as toilet paper SCs to assist practitioners in formulating VSC strategies and recovery plans to mitigate the impact that panic-buying can have on SCs. This study provided a combination of four VSC strategies- ‘multiple main and alternative local suppliers’, ‘optimal order quantity’, ‘multiple local production facilities’, and ‘coalition with other transporters’, and three operational and reactive recovery plans to help manufacturers manage sudden spikes in demand during large-scale disruptions. These findings can help decision-makers set priorities in gathering resources and raw materials from suppliers to increase the supply of essential items, such as food, facemask, and toilet paper, in the market to reduce panic-buying during large-scale disruptions.

COVID-19 and other significant disruptions can cause sudden spikes in panic-buying, making it difficult for manufacturers to plan recovery strategies. To address this, an integrated ABM and optimisation model was developed in this study to analyse the impact of panic-buying on SCs and business performance. The study implemented viable strategies and recovery plans to manage these challenges and observe improvements. This simulation study contributes to the literature by examining a new and recent topic using an integrated ABM and optimisation model. To manage panic-buying during disruptions like COVID-19, this study found that increasing supply and production of critical items, increasing ordering frequency from local suppliers, and collaborating with logistics companies can help businesses meet extra customer demand and reduce total costs. Decision-makers can use these findings to design recovery strategies for increased agility, resilience, and survivability. Delays in implementing these strategies can increase SC costs.

The study's use of a simulation model at a specific moment limits its results as it represents a conceptual model. Further empirical research is recommended as recovery strategies may change with emerging disruptions. Companies experiencing changes in market demand due to the pandemic may benefit from the study's findings. Future studies can examine impacts and difficulties in other industries and expand into a comprehensive empirical study to develop and evaluate recovery strategies, including food, pharmaceuticals, and apparel SCs. Primary data can help identify and assess recovery plans and strategies for these industries.

Chapter 6

Evaluating Resilience and Sustainable Performance in Managing Large-scale Supply Chain Disruptions

The COVID-19 pandemic has exposed the fragility of supply chains (SCs) when faced with material/component supply shortages, production and delivery disruptions, and social restrictions. To ensure the uninterrupted and continuous operation of SCs, firms must carefully anticipate the impacts of disruptions and devise strategies for recovery accordingly. This chapter examines the relationships between resilience and sustainability strategies by identifying and modelling recovery strategies in the multinational healthcare enterprise. An integrated agent-based modelling (ABM) and optimisation approach is used to identify the major impacts of the COVID-19 pandemic on SCs. It examined four resilience strategies and three recovery plans to monitor the improvement and interactions between resilience and sustainability when the SC is subjected to large-scale disruptions. The findings revealed that increased resilience in healthcare SCs improved economic and social sustainability while decreasing environmental performance. Decision-makers can use this study to develop strategic policies considering resilience and sustainability post-COVID-19.

6.1. Introduction

Global trade and the global economy are severely impacted by disruptions in some or all stages of SCs (Moosavi & Hosseini, 2021). For SCs to survive in a multinational enterprise (MNE) setting, balancing resilience and sustainability is critical (Hsu et al., 2021). Global SCs have faced unprecedented disruptions in volatile, uncertain, complex, and ambiguous environments in the past decade (Ivanov, 2021b). As a result of the COVID-19 pandemic, the world has experienced unprecedented disruption for the first time in decades. In addition, several other recent world incidents have also impacted global SCs and, therefore, global trade. For example, the recent Russia-Ukraine war triggered a global supply shortage of essential products such as oil (Rahman et al., 2022). A significant supply deficit, price increases, and unpredictable demand for essential and luxurious products have occurred (Nicomedes & Avila, 2020). Current SCs could not withstand these sudden threats due to a lack of resilience, leaving them incapacitated to implement strategies. In contrast, after surviving for a considerable amount of time, global SCs are now looking for sustainable practices to achieve sustainable development goals (Paul et al., 2021).

These large-scale disruptions in global SCs have also imposed multiple impacts in the recent past, with consequences resulting from these unpredictable incidents, including the loss of goodwill for several companies across the globe. For example, essential product manufacturers could not fulfil the extended demands of their customers (Paul et al., 2021). Due to a shortage of raw materials supplies, manufacturing facility disruptions, inventory mismanagement, and transportation and distribution management disruptions, companies incurred large-shortage costs when they did not meet consumers' extended demand (Rahman et al., 2021a). Due to multiple disruptions and a lack of strategies to deal with them, the time to recover from disruptions was delayed (Moosavi & Hosseini, 2021). Global businesses are recovering very fast as the world gets used to COVID-19. Furthermore, political instability among countries has been a key cause of the interruption of product supply (Salama & McGarvey, 2021). Global businesses are attempting to accelerate their activities, highlighting the importance of developing a resilient and sustainable SC that can survive future challenges in a sustainable manner (Paul et al., 2021).

Resilience and sustainability are two factors that preserve SC networks and the environment (Hsu et al., 2021). SCs require resilience and long-term plans to endure large-scale disruptions. During the COVID-19 pandemic, most essential product firms encountered significant supply shortages, forcing them to reduce production. Furthermore, the advent of the coronavirus and the ensuing lockdown prompted production operations to slow down due to labour shortage (Zhu et al., 2020). The disruption in supply had a significant impact on inventory management (Gholami-Zanjani et al., 2021). As a result, transportation and distribution support systems were severely impacted in 75% of the world's companies (Bals & Tate, 2018). As the world increasingly adapts to COVID-19, borders have stabilised more, and manufacturers are expanding production and increasing carbon dioxide (CO_2), fossil fuels, and other waste emissions into the environment (Chowdhury et al., 2021). During the COVID-19 pandemic, essential items such as facemasks, food, and hand sanitisers were in great demand (Rahman et al., 2021a). Manufacturers had to expand production in a number of methods to meet rising customer demand, which has contributed significantly to waste generation and CO_2 emissions into the environment. It is critical to understand how measures to enhance SC resilience performance affect SC sustainability performances, such as economic, social, and environmental performances (Rahman et al., 2021a).

It is clear from the literature that researchers have made concerted efforts to develop strategies to mitigate SC disruptions. Resilience and sustainability strategies to manage the economic, environmental, and social performances of SCs exist individually in the literature (Lopes de Sousa Jabbour et al., 2020). Table E1 in Appendix E lists the summary of existing literature on resilience and sustainable strategies to manage SC disruptions. Enhancing SC resilience is essential in the case of a large-scale SC disruption, such as the COVID-19 pandemic. It is also essential to ensure that the sustainability performances are balanced. It would be extremely difficult to fulfil the aim of sustainable development goals without balancing resilience (i.e. capacity expansion) and sustainability performances catering for the economic, environmental, and social performances of SCs (Chowdhury et al., 2021). During the COVID-19 pandemic, vital supplies such as facemasks, food, and personal protective equipment were in great demand (Rahman et al., 2021a). On the one hand, manufacturers struggled to expand their production rate because of simultaneous and dynamic influences; on the other hand, they created the path for increased CO_2 emissions and other waste generation to the environment when they raised their production rate (Darom et al., 2018). The literature does not recognise the interaction between resilience and sustainability in managing large-scale SC disruptions like the COVID-19 pandemic. The literature also falls short of developing a mathematical, empirical, or simulation-based model to foresee the interaction between resilience and sustainability in SCs when coping with large-scale disruption. This is the fundamental purpose of this research.

This study uses the production of facemasks in an MNE context to investigate the effects of large-scale disruptions in SCs, the dynamics of resilience strategies in enhancing and balancing SCs, and the interaction between resilience and sustainable performances, which is lacking in the literature.

Given the identified research gaps related to the interaction between resilience and sustainability in managing large-scale disruptions, this study intends to address the following research questions:

a. What are the consequences of large-scale disruption in SCs in MNEs?
b. What tools, methodologies, and resilience strategies can be used to manage large-scale disruptions and the sustainability of SCs?

c. Is there a dichotomy between resilience and sustainability in managing large-scale SC disruptions?
d. How do resilience and sustainability interact in SCs when recovery strategies are implemented to manage large-scale SC disruptions?

Researchers and practitioners increasingly emphasise building a resilient and sustainable SC that can withstand unpredictable, uncertain, and extreme disruptions (Hsu et al., 2021). Globally, existing SCs are struggling to deal with extreme disturbances and equipping themselves to apply measures to handle SC disruptions. Motivated by this backdrop from industry and academia, this research aims to develop an ABM to investigate the interaction (dichotomy) between resilience and sustainability in managing the recovery of large-scale SC disruptions. This study makes three major contributions. First, this paper develops a resilient SC model of a typical facemask production and delivery in ABM in Anylogic software (version 8.3.2) to handle large-scale SC disruptions. Second, this study introduces an ABM simulation-optimisation model to predict the consequences of large-scale disruptions in SCs. Finally, this study employs various resilience strategies to look at how SCs handle large-scale disruptions and improve and balance their resilience and sustainability performances. It also examines the interaction between resilience and sustainable performances, leading to several managerial, theoretical, and future research opportunities.

6.2. Problem statement

This study used the example of an Australian-based multinational company that manufactures facemasks, personal protective equipment, and other respiratory-related devices. The company meets Australia's demand requirements and exports these vital medical items to other countries. The company has three manufacturing facilities in three distinct locations and states within the consumer zone and contracts with seven suppliers nationwide. This firm has its own transportation system and contracts with other transporters for delivery. The manufacturing factories have a large inventory capacity and their own distribution centre. This company receives orders from around 18 retailers and supplies them with facemasks. We chose this company's facemask SC and its production and delivery system as examples in our model to examine the dynamics of disruptive impacts and mitigation strategies.

The demand for facemasks in Australia increased by 400% during the lockdown and other times to flatten the viral curve during the COVID-19 pandemic (Rahman et al., 2021a). The government enforced tight rules requiring individuals to wear facemasks in indoor settings and public venues. Retailers experienced facemask stockouts due to high demand and consumers' panic-buying habits. Facemask manufacturers struggled to fulfil the growing demand. COVID-19 has significantly impacted both global SCs and Australian manufacturer SCs. Owing to the pandemic, Australia closed its borders for nearly 2 years, resulting in severe lockdown and shutdown within the country (Xunpeng Shi, 2021). Manufacturers and suppliers could not get raw materials from other countries in quarantine zones. Manufacturers had to shut down production partially for short- and long-term and laid off workers to flatten the viral emergence curve (Shaban et al., 2020). Companies could not take precautions to ensure employee health and safety because of the high transmission rate of COVID-19. Employees infected with COVID-19 had to isolate themselves for at least 5–14 days until they completely recovered, causing a labour scarcity in the manufacturing facilities and degrading production capacity (Antony et al., 2020). A similar problem extended to the transportation and distribution support system, impacting seamless delivery to retailers and customers. As a result, manufacturers of essential products, such as facemasks, struggled to meet the extended demand of consumers (Paul et al., 2021). Adopting strategies to raise companies' capacity to meet the additional demand affected the sustainability performances of SCs, such as economic, environmental, and social performances, which is also a study area to consider as it is currently absent in the literature. Rahman et al. (2021) developed an ABM that forecasted the effects of a single demand disruption in SCs and strategies for managing them without optimisation, and how they affect the sustainability performance of SCs. This is the primary issue that we will address in our research by developing an ABM-based simulation-optimisation model. The main aims of this study are as follows:

- To develop an ABM-based simulation-optimisation model for a typical facemask production and delivery support system to understand how large-scale disruptions, such as the COVID-19 pandemic, have had major repercussions on the SCs of essential manufacturers.
- To determine strategies and recovery plans for a resilient SC to handle multiple impacts in SCs and ensure sustainability requirements.
- To incorporate the strategies and recovery plans into the model and see how the performance of the SCs improves as the dichotomy between resilience and sustainability is analysed. The

main objective is to examine how resilience (capacity expansion and responsiveness) and sustainability (economic, environmental, and social performances of SCs) interact in managing large-scale SC disruptions.

6.3. Model formulation and proposed framework

In this section, an ABM-based simulation-optimisation model of a facemask SC and its production and delivery system for a multinational firm is built, and the proposed framework is elaborated.

6.3.1. Model formulation

Several SC agents are similar to real-world SCs, such as retailer, manufacturing, supplier, order, and truck agents at the manufacturing and supplier ends, and evaluation agents represent SC entities in the proposed ABM model. The model simulates certain functions to fulfil retailer demand (i.e. customer demand) by coordinating SC entities and attaining the optimal value of decision variables inside the simulation-optimisation model. The modelled facemask SC has three manufacturing facilities, seven suppliers, 18 retailers, and trucks at the supply and manufacturing ends. To test the model, we utilised hypothetical data based on secondary data derived from Rahman et al. (2021a) and Lee et al. (2021).

Our approach uses the (s, S) inventory model. Retail agents continually make orders to meet customer demand, which are sent to the most convenient manufacturer (R. Das & Hanaoka, 2014). The manufacturing agent subsequently attempts to satisfy the order using a set of available trucks and its make-to-stock inventory of finished products (Q_j^t). If the inventory level falls below the reordering level *(sj)*, a request is issued to the suppliers for a predetermined amount of raw material and/or components *(Sj)* to refill the finished goods stock (Rahman et al., 2021a). Supplier agents manufacture the components (in a make-to-order setting) and transport them through trucks to the relevant manufacturer. Manufacturer trucks transport finished items to retail agents through these agents. Order supplier agents represent orders from manufacturers to suppliers for components and raw materials required for final product manufacturing. Suppliers use truck agents to carry components or raw materials to manufacturers (Arvitrida, 2018). To keep track of the current SC's key performance metrics, the evaluation agent connects with the other agents in the system. Manufacturing costs (MCs), sourcing costs, transportation costs (TCs) at the manufacturing and supplier stages; inventory costs (ICs) at the supplier, manufacturer, and retail stages; shortage costs (ShCs), discount costs (DisCs), and products/components produced/shipped/received at the various SC stages are all taken into account by this evaluation agent (Rahman et al., 2021a).

This simulation-optimisation model aims to minimise total supply chain costs (TSCCs). During the simulation, the model optimises the reordering level *(sj)*, order size *(Sj),* and number of trucks *(l)* when implementing strategies to maximise raw material supply from suppliers, number of finished products to produce in manufacturing facilities, inventory level, and products to deliver to retailers, thus minimising TSCCs. The proposed ABM-based simulation-optimisation is developed in Anylogic software (Version 8.3.2.). The model's parameters are shown in Table 6.1. The cost metrics used in this model are presented in Table 6.2.

Table 6.1: Model parameters

Notations	**Descriptions**
$\boldsymbol{i}$	Retailers
$\boldsymbol{j}$	Manufacturers
$\boldsymbol{k}$	Suppliers
$\boldsymbol{l}$	Manufacturer trucks
$\boldsymbol{m}$	Supplier trucks
$\boldsymbol{D}$	Demand
$\boldsymbol{C_i}$	i^{th} Supplier's capacity
$\boldsymbol{IR_i}$	Holding costs for inventories for i^{th} retailer (each item, per day)
$\boldsymbol{\varphi_j}$	Fixed operating cost for j^{th} manufacturer
$\boldsymbol{\vartheta_j}$	Manufacturing cost per unit for j^{th} manufacturer
$\boldsymbol{IM_j}$	Inventory holding cost for j^{th} manufacturer (each item, per day)
$\boldsymbol{\psi_j}$	Fixed cost associated with managing transport services at j^{th} manufacturer
$\boldsymbol{\omega_j}$	Variable transportation cost at j^{th} manufacturer (per unit item per unit time)
$\boldsymbol{\eta_j}$	Shortage cost for j^{th} manufacturer (per unit item)
λ_j	Discount cost for j^{th} manufacturer (per unit item)
$\boldsymbol{\rho_k}$	Cost of manufacturing raw materials supplied by k^{th} supplier
$\boldsymbol{\theta_k}$	Fixed cost associated with managing transport services at k^{th} supplier
$\boldsymbol{v_k}$	Variable transportation cost k^{th} supplier (per unit item per unit time)
$\boldsymbol{s_j}$	ROP at j^{th} manufacturer
$\boldsymbol{S_j}$	Order-size at j^{th} manufacturer
$\boldsymbol{a_j}$	Per unit manufacturing time at j^{th} manufacturer
$\boldsymbol{b_k}$	Per unit manufacturing time at k^{th} supplier
$\boldsymbol{p_j^t}$	Manufactured item by the j^{th} manufacturer
$\boldsymbol{\alpha_{ijl}^t}$	Transport time by truck l to carry items x_{jk}^t from j^{th} manufacturer to i^{th} retailer in time window t
$\boldsymbol{\beta_{jkm}^t}$	Transport time for supplier truck m to carry items y_{jk}^t from k^{th} supplier to j^{th} manufacturer in time window t
$\boldsymbol{x_{ij}^t}$	Items transported from j^{th} manufacturer to i^{th} retailer in time window t
$\boldsymbol{y_{jk}^t}$	Items transported from k^{th} supplier to j^{th} manufacturer in time window t

$\boldsymbol{\tau}$	Time window
$\boldsymbol{Q_j^t}$	Average inventory level at j^{th} manufacturer in time window t
$\boldsymbol{R_i^t}$	Average inventory level at i^{th} retailer in time window t
$\boldsymbol{d_j^t}$	Undelivered items to retailer within a week at j^{th} manufacturer in time window t
$\boldsymbol{w_j^t}$	Undelivered items to retailer within a specified time at j^{th} manufacturer in time window t (for the consideration of discount cost)
$\sum_j \boldsymbol{x_{jk}^t}$	Items supplied to the i^{th} retailer
$\sum_j \boldsymbol{y_{jk}^t}$	Raw materials supplied by the k^{th} supplier
$\boldsymbol{E_j^t}$	CO_2 emission within a week at j^{th} manufacturer in time window t
$\boldsymbol{F_j^t}$	Fossil fuel depletion within a week at j^{th} manufacturer in time window t
$\boldsymbol{E_l^t}$	CO_2 emission within a week at *l* manufacturer trucks in time window t
$\boldsymbol{F_l^t}$	Fossil fuel depletion within a week at *l* manufacturer trucks in time window t
$\boldsymbol{E_m^t}$	CO_2 emission within a week at *l* supplier trucks in time window t
$\boldsymbol{F_m^t}$	Fossil fuel depletion within a week at *l* supplier trucks in time window t
$\boldsymbol{P_j^t}$	Employee needed within a week at j^{th} manufacturer in time window t

Table 6.2: Cost metrics assessed by agents in each of the periods

SC costs	**Equation**
Manufacturing cost in time window t	$\sum_j \varphi_j.\tau + \sum_j \vartheta_j.p_j^t + \sum_j \sum_k \rho_k.y_{jk}^t$
Manufacturing inventory cost in time window t	$\sum_j IM_j.Q_j^t$
Retailer inventory cost in time window t	$\sum_i IR_i.R_i^t$
Transport cost at the manufacturing stage in time window t	$\sum_j \psi_j.\tau + \sum_l \sum_i \sum_j \omega_j.x_{ij}^t.\alpha_{ijl}^t$
Transport cost at the supplier stage in time window t	$\sum_k \theta_k.\tau + \sum_m \sum_j \sum_k \upsilon_k.y_{jk}^t.\beta_{jkm}^t$
Shortage cost at the manufacturing stage in time window t	$\sum_j d_j^t.\eta_j$
Discount cost at the manufacturing stage in time window t	$\sum_j w_j^t.\lambda_j$
Total supply chain cost in time window t	$\sum_j \varphi_j.\tau + \sum_j \vartheta_j.p_j^t + \sum_j \sum_k \rho_k.y_{jk}^t + \sum_j IM_j.Q_j^t +$ $\sum_i IR_i.R_i^t + \sum_j \psi_j.\tau + \sum_l \sum_i \sum_j \omega_j.x_{ij}^t.\alpha_{ijl}^t + \sum_k \theta_k.\tau +$ $\sum_m \sum_j \sum_k \upsilon_k.y_{jk}^t.\beta_{jkm}^t + \sum_j d_j^t.\eta_j + \sum_j w_j^t.\lambda_j$

6.3.2. Proposed framework

The components of a resilient facemask SC are proposed in this section. In the model, the SC has seven suppliers in different locations near the customer zones where the manufacturers source their raw materials. The primary attribute of the suppliers is responsiveness. Three dispersed manufacturing facilities with integrated high inventory capacities are located in three distinct locations. Just-in-time (JIT) production mechanisms are used in every manufacturing facility. The manufacturing team upholds a dynamic inventory policy. If the inventory level falls below the reordering level, a request for a preset number of raw materials and/or components to restock the finished goods stock is sent to the suppliers. The manufacturers and suppliers both have their own trucks and have agreements with other transporters for smooth delivery assistance. Table 6.3 describes the resilience strategies' specific roles. Table 6.4 describes the proposed recovery plans to be implemented in the three scenarios of this simulation-optimisation model.

Table 6.3: Synopsis of the resilience strategies to manage large-scale SC disruptions

Levels of SCs	Proposed resilient strategies	Main features	Simplified meaning	References
Procurement	Multiple suppliers	Responsive supplier	Multiple suppliers allow manufacturers to acquire smooth raw materials even if some fail due to various disturbances.	Namdar et al., 2018)
Manufacturing	Decentralised manufacturing facility	Just-in-time production	Several decentralised production sites add to SCs' resiliency. When there is severe disruption, like the COVID-19 pandemic, decentralised manufacturing facilities help to keep production going.	Rahman et al., 2022
Inventory	Dynamic inventory policy	Integrated inventory capacity	A flexible and dynamic inventory policy is an essential component of resilient SC. Efficient and effective inventory management makes SCs robust and sustainable.	Dolgui et al., 2020
Distribution	Collaboration with transporters	Timely delivery	In addition to manufacturers having their own transportation, maintaining relationships with other transporters helps to deliver items efficiently and on schedule.	Zhen et al., 2016

Table 6.4: Recovery plans considered in different scenarios

Scenarios	Increased operational inputs	Increase in production capacity	Optimisation of raw materials supply, inventory, and trucks: lower and upper limits		
			ROP	**Order-size**	**Trucks**
Scenario 1 (S1)	High	Max: +75.00% Avg: +66.25%	Min: 1375 - Max: 1750	Min: 4125 - Max: 5250	Min: 14 - Max: 18
Scenario 2 (S2)	Medium	Max: +50.00% Avg: 44.17%	Min: 1250 - Max: 1500	Min: 3750 - Max: 4500	Min: 13 - Max: 15
Scenario 3 (S3)	Low	Max: +25.00% Avg: +22.08%	Min: 1125 - Max: 1250	Min: 3375 - Max: 3750	Min: 12 - Max: 13

We will assess the sustainability performance of SCs using economic, environmental, and social metrics. The following are the SC performance evaluation measures used in our analysis.

- **Evaluation of economic performances of SCs**

The economic performances of SCs are evaluated by the following cost metrics (please refer to Table 6.2) in this study.

Total supply chain costs, TSCCs = MCs + ICs + TCs + ShCs + DisCs

Where, MCs = Manufacturing costs, ICs = Inventory costs (manufacturing and retailer ends), TCs = Transportation costs (manufacturing and supplier ends), ShCs = Shortage costs, and DisCs = Discount costs.

- **Evaluation of environmental performances of SCs**

Life cycle analysis (LCA) is a critical component in determining the environmental sustainability of SCs. CO_2 emissions, fossil fuel depletion, metal depletion, water depletion, freshwater ecotoxicity, marine ecotoxicity, human toxicity, waste generated, and other factors have been utilised in the literature to evaluate the LCA of a facemask SC (Lee et al., 2021). According to Lee et al. (2021), CO_2 emissions and fossil fuel depletion have the greatest environmental effect on facemask SC. Therefore, we will examine how much CO_2 is emitted and fossil fuel is depleted in the environment during sourcing, manufacturing, and transportation (from suppliers to manufacturers and manufacturers to retailers) following the implementation of resilience strategies. The related secondary data for evaluating the environmental sustainability of facemask SC is derived from Lee et al. (2021).

- **Evaluation of social performances of SCs**

Customer service via fulfilling demand and minimising backorder levels, as well as employment creation inside SCs, are two critical factors for the social sustainability of SCs (Sabouhi et al., 2021). In this study, we will examine the social performances of SCs in terms of demand fulfilment, backorder reduction, and job opportunity creation.

6.4. Results, scenario analysis, and discussions

This section discusses results, scenario analysis, and the synopsis of the interaction between resilience and sustainability in managing large-scale SC disruptions.

6.4.1. Analysing impacts of large-scale disruptions on SCs

Compared to the normal baseline scenario, we investigate the impacts of large-scale disruption in SC performances in the proposed ABM model.

Analysis of SC dynamics in the normal baseline scenario

The simulation is performed for 5 years under the normal baseline condition to properly visualise the SC dynamics. Total supply chains costs (TSCCs) are consistent with normal baseline conditions, and the facemask SC functions properly, as seen in Figure 6.1. Due to the low level of backorders, the shortage costs (ShCs) and discount costs (DisCs) are also observed to be normal. With an appropriate inventory policy, the production facilities can produce as many products as are required. As seen in Table 6.5, manufacturing costs (MCs), inventory costs (ICs), and transportation costs (TCs) all remain normal. Figure 6.1. shows TSCCs in a baseline, normal SC condition.

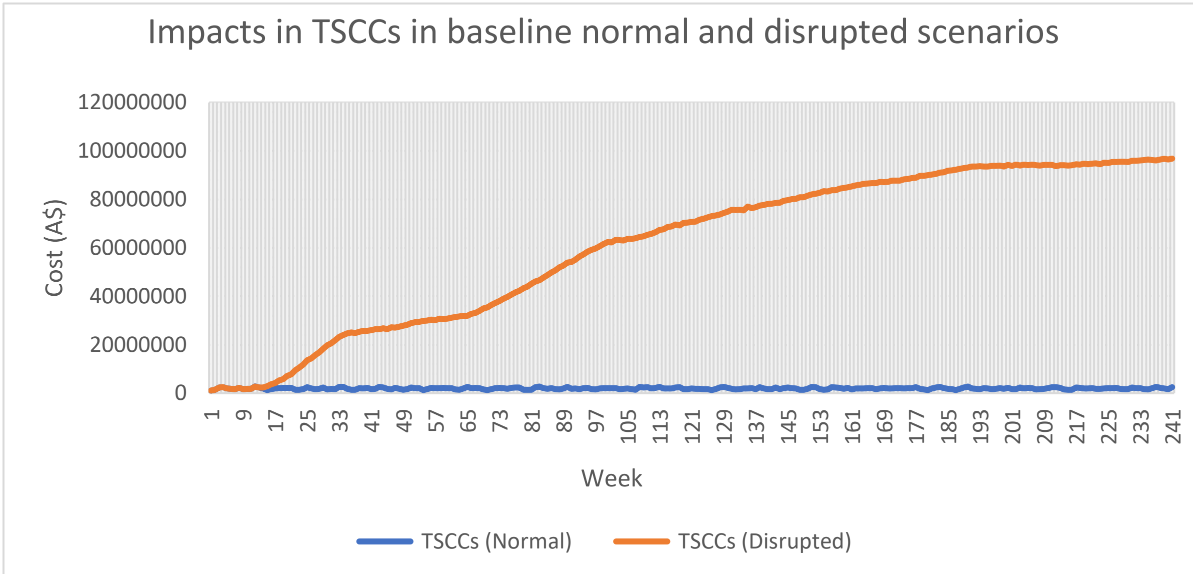

Figure 6.1: Impacts of large-scale disruptions in TSCCs

Analysis of SC dynamics in baseline disrupted scenario (large-scale disruption)

We also ran simulations lasting 5 years in a disrupted situation to provide a more precise comparison with the normal baseline situation. We simulated a large-scale SC disruption and used the COVID-19 pandemic as an example in our proposed model. The assumed fluctuations in demand, manufacturing capacity, and supply flow because of large-scale global SC disruption are depicted in Figure 6.2. For a deeper understanding, we investigated the impacts of large-scale SC disruption on SC economic performance, which affects business performance significantly. Facemask demand increased up to 400% throughout the disruption, with an average increase of 155%. There was at least a 50% increase in demand in the last few months of the simulation as facemasks were required in all public transportation and other crowded places to stop the spread of the virus once COVID-19's emergence became the norm. Fear of stockout also led people to panic-purchase facemasks. The COVID-19 pandemic caused significant supply interruption in other nations under quarantine zones, significantly impacting manufacturing facilities. The manufacturing capacity decreased to an average of 13%, with a maximum reduction of 58%. In the simulation run of the baseline disrupted condition, supply flow was delayed to 86%, with an average delay of 33%. The SCs were severely disturbed by this breakdown of the demand-supply-manufacturing capacity.

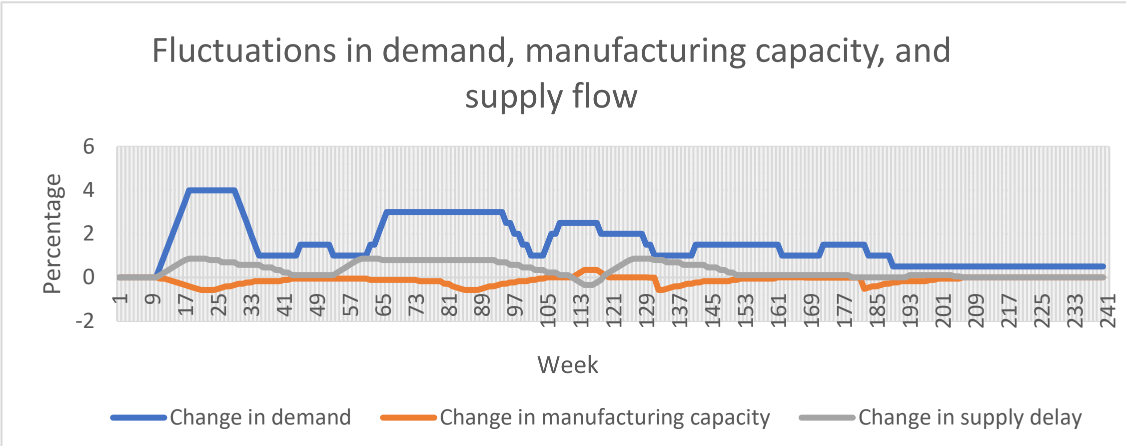

Figure 6.2: Fluctuations in demand, manufacturing capacity, and supply flow during disruption

We assessed the impact of the interruptions on the economic performances of the SCs after conducting the simulation in a baseline-disrupted situation. Due to a rapid rise in demand, severe lockdown, and the closing of the country's borders, there was a shortage of supplies, and manufacturers were unable to boost production capacity, increasing the number of backorders, as shown in Table 6.5. The increase in SC shortage costs as penalty costs were brought on by the high backorder level and lost sales. Manufacturing facilities struggled to manage enormous volumes of raw materials from suppliers, which prevented them from ramping up production. Therefore, they could only increase production by 41.82%, which is too low. As a result of their inability to increase inventory, the inventory cost only increased to 39.82%. This also caused them to slowly introduce their products to the market, resulting in high discount costs to sell to customers because of the long lead time. The fact that transportation expenses decreased to 28.09% suggests that SCs have not been very active and that there have been fewer transportation-related activities due to the tight restrictions on social distancing. Companies could not deliver the final goods to retailers on time, which greatly impacted the SC's performance. The TSCCs were raised to 2997.38% because of these multiple SC disruptions. The impacts of large-scale disruptions on SCs' economic performance can be found in Table 6.5.

Table 6.5: Impacts of large-scale disruptions in SCs

	Impacts of large-scale disruptions in SCs		
	Backorders (Units/Week)	**Economic performances (A$/Week)**	**Production level (Units/Week)**

	Unfulfilled demand	TSCCs	MCs	ICs	TCs	ShCs	DisCs	Products manufactured
Normal situation	921.16	1978582.28	1754319.50	120291.73	93139.61	3684.65	7146.78	12560.17
Disrupted situation	13332861.58	61284123.03	2482796.68	168195.12	66979.66	53331446.31	5234705.26	17813.28
Changes (%)	+1447296.23%	+2997.38%	+41.52%	+39.82%	-28.09%	+1447296.23%	+73145.60%	+41.82%

6.4.2. Resilience strategies, operational inputs, and recovery plans implementation

The recovery plans and resilience strategies to manage the impacts of large-scale disruptions in SCs, as analysed in section 6.4.1., have been discussed as operational inputs in section 6.3.2. The different recovery plans considered during the disruption scenarios are listed below.

Recovery plan 1: In scenario 1, we raised production capacity by an average of 66.25%, up to a maximum of 75%. Table 6.6 shows the optimal reorder point (s_j), order size (S_j), and trucks (l) for scenario 1.

Recovery plan 2: In scenario 2, we raised production capacity by an average of 44.17%, up to a maximum of 50%. Table 6.6 shows the optimal s_j, S_j, and l for scenario 2.

Recovery plan 3: In scenario 3, we raised production capacity by an average of 22.08%, up to a maximum of 25%. Table 6.6 shows the optimal s_j, S_j, and l for scenario 3.

Recovery plans and resilience strategies are implemented in the model to monitor improvements in SCs' economic, environmental, and social performance.

Table 6.6: Optimal value for decision variables

Scenarios	Optimal value for decision variables		
	ROP (s_j)	Order-size (S_j)	Trucks (l)
Normal situation	1000	3000	10
Scenario 1 (S1)	1433	4571	14
Scenario 2 (S2)	1351	4451	14
Scenario 3 (S3)	1161	3729	13

6.4.3. Impacts of strategies and recovery plans on SC networks, resilience, and sustainability

The effectiveness of resilience strategies and the execution of recovery plans in enhancing the resilience and sustainability performances of SCs are examined in this section.

- **Evaluation of SCs' resilience performance**

Expanding capacity is crucial in measuring improvements in SCs' resilience performance (Kaviani et al., 2020). Our proposed simulation-optimisation model identified the optimal ROP, order size, and trucks were placed in multi-supplier settings and decentralised manufacturing facilities when the capacity was increased to high in scenario 1. This helped to increase the number of products manufactured to 79.84% in scenario 1. The recovery plan in scenario 1 displays the best outcome that significantly improved resilience performance. However, the recovery plans in scenarios 2 and 3 also increased the production rate, enhancing the SCs' performance in terms of resilience. Table 6.7 and Figure 6.3 show how the implementation of the strategy and recovery plans improved resilience performance.

Table 6.7: Improvement in manufacturing capacity

Scenarios	Increase in production capacity	Improvement in production level (Avg-Units/Week)
		Changes in products manufactured
Scenario (S1)	High	+79.84%
Scenario (S2)	Medium	+69.21%
Scenario (S3)	low	+26.38%

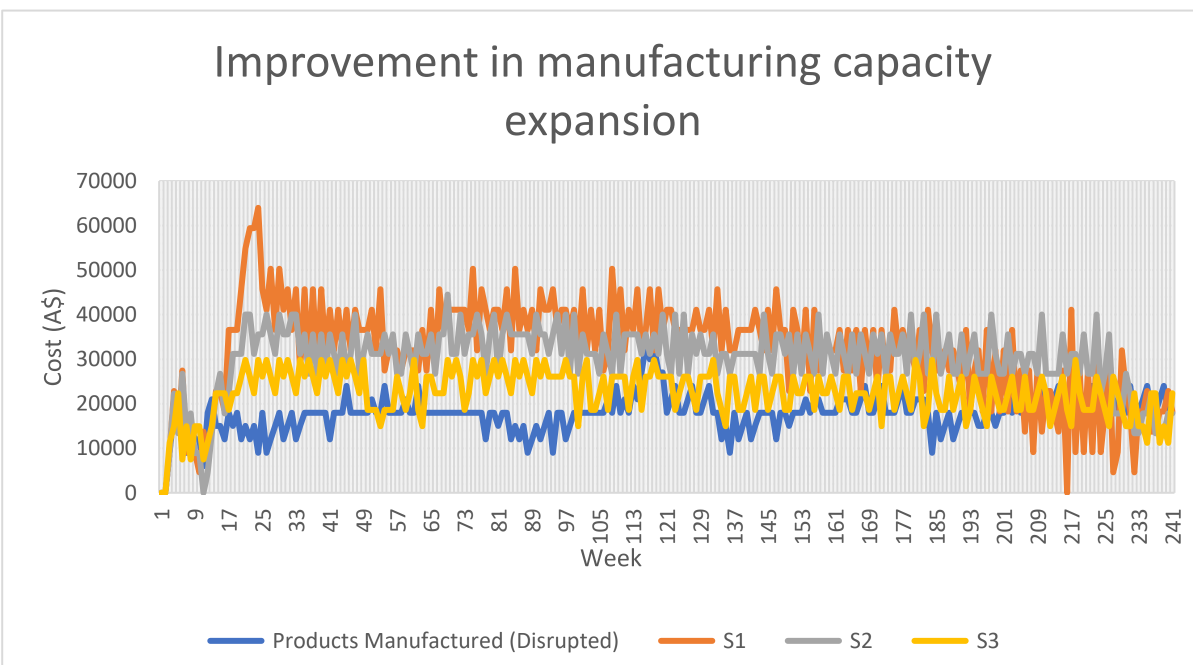

Figure 6.3: Improvement in manufacturing capacity expansion

Analysis of simultaneous improvement in SC sustainability performance

The effectiveness of resilience strategies and the execution of recovery plans in enhancing the sustainability performances of SCs are examined in this section.

- **Evaluation of economic performances**

Evaluation of total supply chain costs (TSCCs):

Enhancing SC sustainability performance requires reducing TSCCs. The recovery strategy in scenario 1 decreased TSCCs to 82.51%, necessitating increased ROP to 43.30%, order size to 52.37%, and number of trucks to 40.00% through optimisation. The manufacturers could get sufficient raw materials because of the inventory policy and transportation improvement. The manufacturers could supply the retailers with their finished goods on schedule because of the improved transportation policies. Although scenario 1's recovery plan yielded the best results, scenarios 2 and 3's recovery plans also decreased TSCCs to 63.72% and 28.48%, respectively. Table 6.8 and Figure 6.4 detail the evaluation of TSCCs after implementing the strategies and recovery plans.

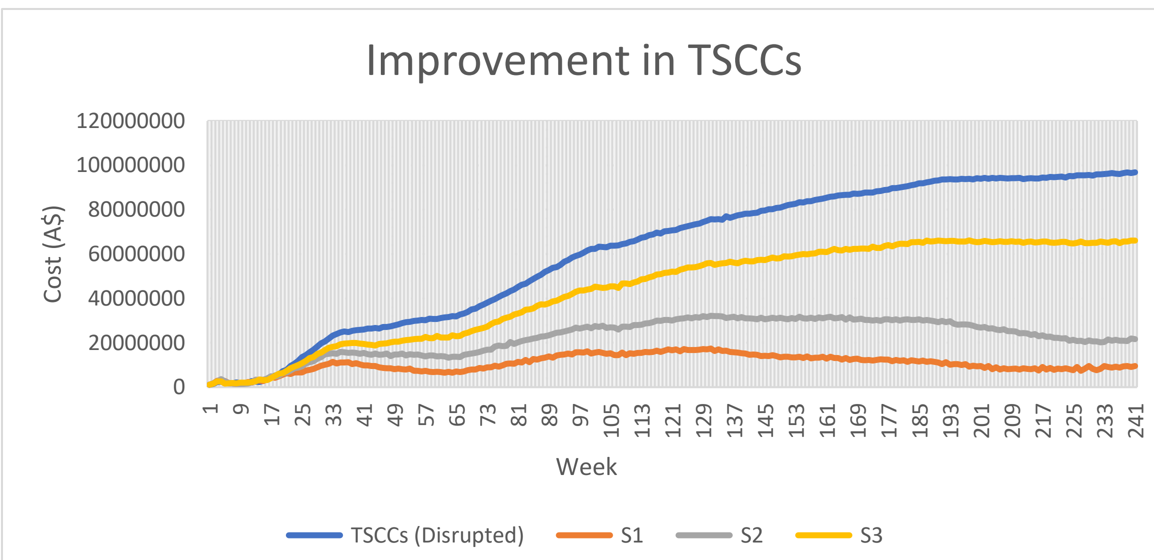

Figure 6.4: Evaluation of TSCCs for scenarios after implementing strategies

Evaluation of manufacturing costs (MCs)

After recovery plans were implemented, MCs increased to 14.15%, 14.12%, and 5.53% in scenarios 1, 2, and 3, respectively. The initial spike and subsequent average increase in MCs show that manufacturers produced more products because of their increased production capacity, inventory, and transportation, enabling them to meet more customer demand and experience lower backorder levels. In the end, this growth in manufacturing capacity and MCs helped to lower TSCCs and shortage costs (ShCs), helping to boost SCs' resilience and sustainability performances. Table 6.8 evaluates MCs in the interaction between the resilience and sustainability of SCs.

Evaluation of inventory costs (ICs)

As a result of the recovery plan in scenario 1, the ICs increased to 49.06%. The inventory was increased in response to the increased production rate that increased ICs. On the one hand, the ICs increased in scenario 1, but this increase in inventory helped produce more products to meet customer demand and reduce shortage costs on the other hand. When inventory and related costs were increased in scenario 1, TSCCs were ultimately reduced. Due to the lack of inventory, other recovery plans in scenarios 2 and 3 did not reduce TSCCs despite reducing ICs to 38.88% and 8.12%, respectively, compared to scenario 1. Table 6.8 summarises the ICs' evaluation.

Evaluation of transportation costs (TCs)

TCs increased to 43.55% due to the recovery plan in scenario 1. A higher inventory policy was implemented in scenario 1 in response to the increased production rate, enabling manufacturers to produce more products to meet retailer demand, thus reducing backorder levels. In scenario 1, the TCs increased. However, the increased number of trucks enabled manufacturers to deliver more finished products to retailers and to reduce backorder levels, which reduced shortage costs. The TSCCs were ultimately reduced when the number of trucks and related costs were increased in scenario 1. As a result of a shortage of trucks, other recovery plans in scenarios 2 and 3 did not reduce TSCCs despite reducing TCs to 36.76% and 11.25%, respectively, compared to scenario 1. Due to a lack of inventory, a slow production rate, and a lack of transport (trucks), the manufacturers in scenarios 2 and 3 could not supply more products to the retailers. The evaluation of the TCs is summarised in Table 6.8.

Evaluation of shortage costs (ShCs)

The recovery plan in scenario 1 reduced ShCs to 92.59%. The increase in production rate in scenario 1 with the optimal ROP, order size, and number of trucks enabled the manufacturers to produce products in demand while lowering expenses associated with shortages due to backorder levels. However, the recovery strategies in scenarios 2 and 3 reduced ShCs to 72.46% and 31.72 %, respectively. The production rate, inventory, and transportation policies in scenarios 2 and 3 were not much enhanced compared to scenario 1, which led to greater ShCs. Table 6.8 details the evaluation of ShCs.

Evaluation of discount costs (DisCs)

The recovery plan in scenario 1 reduced DisCs to 31.52%. With the optimal ROP, order size, and number of trucks, scenario 1's increased production rate allowed the manufacturers to produce products in demand while reducing the expenses of associated discounts brought on by the lengthy lead times. However, the recovery plans in scenarios 2 and 3 lowered DisCs to 16.27% and 13.32%, respectively. The production rates, inventory, and transportation policies in scenarios 2 and 3 were not much improved over scenario 1, causing a delay in the delivery of products to the retailers that increased DisCs in those scenarios. Table 6.8 provides an evaluation of DisCs.

Table 6.8: Impacts of implementation of resilience strategies on economic performances

Scenarios	**Improvement analysis of implementing strategies in SCs**					
	Economic performances (Avg-A$/Week)					
	TSCCs	**MCs**	**ICs**	**TCs**	**ShCs**	**DisCs**
Scenario (S1)	-82.51%	+14.15%	+49.06%	+43.55%	-92.59%	-31.52%
Scenario (S2)	-63.72%	+14.12%	+38.88%	+36.76%	-72.46%	-16.27%
Scenario (S3)	-28.48%	+5.53%	+8.12%	+11.25%	-31.72%	-13.32%

- **Evaluation of environmental performance**

We chose two factors—CO_2 emission and the depletion of fossil fuels—excluding metal depletion, water depletion, freshwater ecotoxicity, marine ecotoxicity, human toxicity, and waste generation, which were also mentioned in the literature, to evaluate facemask SCs' environmental performances (Lee et al., 2021). Among all factors, CO_2 emissions and the depletion of fossil fuels have the most impact on the facemask SC's environmental performance. Total CO_2 emissions and the depletion of fossil fuels increased to 54.42% and 53.82%, respectively, when production capacity was raised in scenario 1 with the rise in inventory policy and the number of trucks from the disrupted state. Although the recovery strategy in scenario 1 leads to increased CO_2 emissions and the depletion of fossil fuels, production capacity growth decreased TSCC significantly. On the other hand, CO_2 emissions and the depletion of fossil fuels decreased in scenarios 2 and 3 due to the lack of an inventory, delivery, and transportation support system and lower production capacity, as shown in Table 6.9. The trajectory of rising CO_2 emissions and the depletion of fossil fuels in response to increased production capacity is nonlinear. Figure 6.5 details an evaluation of CO_2 emission following the implementation of strategies.

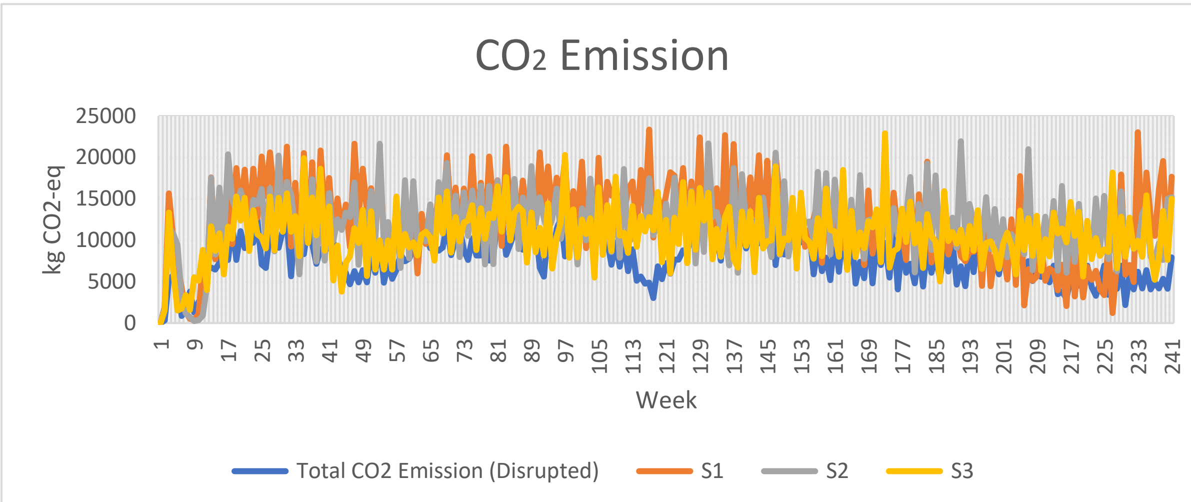

Figure 6.5: Total CO_2 emission after implementing strategies

Table 6.9: Impacts of implementation of resilience strategies on environmental sustainability

Impact category	Units	Environmental Impacts (Avg-Weekly)			
		Disrupted situation	Scenario 1	Scenario 2	Scenario 3
Climate change (CO_2 Emission)	kg CO_2-eq	7948.99	12275.15 (+54.42%)	11865.93 (+49.28%)	10638.65 (+33.84%)
Fossil fuel depletion	kg Oil-eq	7001.62	10769.59 (+53.82%)	10383.18 (+48.30%)	9343.69 (+33.45%)

- **Evaluation of social performance**

We focused on two factors to evaluate facemask SCs' social performances: demand fulfilment and the creation of employment opportunities (Kaur & Singh, 2019). In scenario 1, where production capacity was enhanced due to an increase in inventory policy and the number of trucks from the disrupted state, demand fulfilment and employment opportunities increased to 83.94% and 45.80%, respectively. Consequently, the backorder level in scenario 1 dropped to 92.59%. Our model assumes that the company's employees can boost productivity by up to 50%. On the other hand, as shown in Table 6.10, due to a lack of a stock of products in inventory, delivery, and transportation support system and reduced production capacity, demand fulfilment and job opportunities increased in scenarios 2 and 3, but at a lower rate than those in scenario 1. Compared to recovery plan 1, the recovery strategies in scenarios 2 and 3 could not reduce the number of backorders. However, the SCs' social performances were improved by the recovery plans. Figure 6.6 shows an evaluation of demand fulfilment once strategies have been implemented.

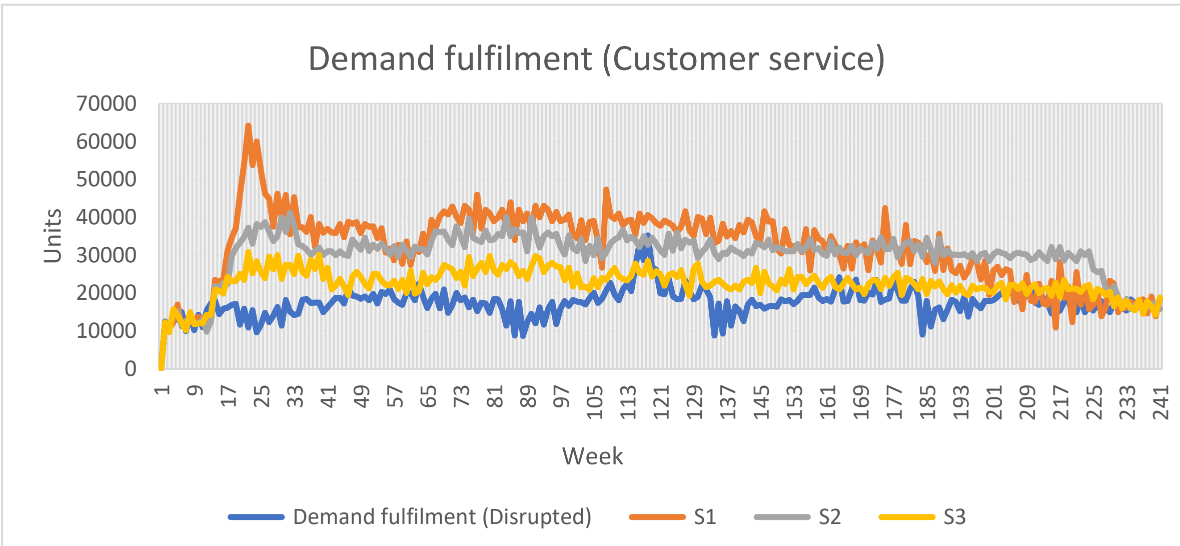

Figure 6.6: Impacts of implementing strategies in demand fulfilment (customer service)

Table 6.10: Impacts of implementing strategies on social performances

Impact category	Impact on social performance (Avg-Weekly)		
	S1	S2	S3
Demand fulfilment (Customer service)	+83.94%	+73.32%	+29.50%
Employees needed (Job opportunity)	+45.80%	+41.80%	+22.16%

6.4.4. Analysis of impacts of different kinds of responsiveness on SC performances

This section investigates how different levels of responsiveness, such as the timing of strategy and recovery plan implementation, affected the SC performance per our ABM model. In scenario 1, TSCCs were reduced to 82.51% to deploy strategies immediately. On the other hand, the TSCCs were reduced to 79.20% for delayed implementation of strategies in the same scenario (Scenario

1), such as a wait of 6 months. The TSCCs in delayed implementation are greater than those in quick implementation of strategies. Figure 6.7 shows further details on how various types of responsiveness affect SC performances.

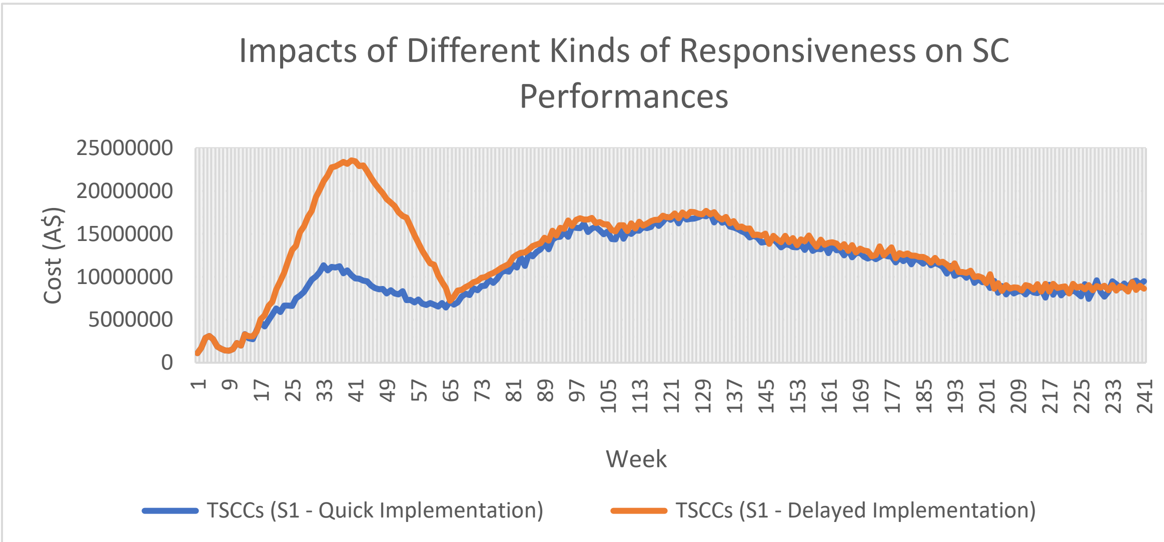

Figure 6.7: Impacts of different kinds of responsiveness on SC performances

6.4.5. Analysis of the interaction between sustainability and resilience in handling large-scale SC disruptions

SCs are significantly impacted by large-scale global disruptions. As stated in section 6.2, essential product manufacturers are subject to severe simultaneous and numerous consequences (Scala & Lindsay, 2021). The recovery process begins in SCs when a proper combination of resilience strategies and operational recovery plans are implemented (Moosavi & Hosseini, 2021). How resilience and sustainability within SCs interact with one another through the implementation of resilience strategies, recovery plans, and corresponding responsiveness is discussed in sections 6.4.3, the synopsis of which is summarised in Figure 6.8. The study shows that one of the most significant factors for measuring resilience in SCs—capacity within SCs—expands when resilience strategies and recovery operational plans improve. As seen in Table 6.7, manufacturers' capacity increases in every scenario. It is also noted that quick strategy adoption enhances SC resilience.

The study also indicates the impacts of increased resilience capabilities on SCs' economic, environmental, and social performance. These three are the most crucial sustainability performance indicators (Karmaker et al., 2021). The increase in resilience from scenario 3 to scenario 1 resulted in a considerable decrease in TSCCs, as shown in Figure 6.8, demonstrating the significant impact that increased resilience capabilities inside SCs have on economic performance. In scenario 1, expanding production capacity, inventory levels, and transportation regulations led to a higher decline in TSCCs, significantly improving the SCs' economic performance. Similarly, the improvement in resilience from scenario 3 to scenario 1 resulted in a significant improvement in the social performances of essential SCs, including job creation and demand fulfilment. For example, the enhanced resilience capabilities in scenario 1 significantly expanded the opportunity for job creation and meeting consumer demand. However, the analysis also demonstrates that the increase in production, inventory, and transportation capabilities that resulted from the rise in resilience from scenario 3 to scenario 1 led to increased CO_2 emissions to the environment. This is indicative for the essential product manufacturers that an increase in resilience within their traditional SCs enhances their performance in most sustainability factors, such as economic and social performances, with a decline in environmental performance. The model considers the decline in environmental performance along with the improvement in the economic and social performance of SCs. A compromise has been made between resilience and sustainability here. This result recommends manufacturers boost resilience capabilities to balance SCs' overall sustainability performances. To ensure that improved resilience does not compromise environmental performance and guarantees lower environmental emissions, the SCs of MNEs should also adopt regulations to include clean energy, green production, green procurement, and green transportation practices while increasing resilience in a balanced way. To balance sustainability even in disruptive situations and recovery periods, MNEs need to figure out the optimal level of resilience increase. Figure 6.8 presents an overview of how resilience and sustainability performances interact in managing large-scale SC disruptions.

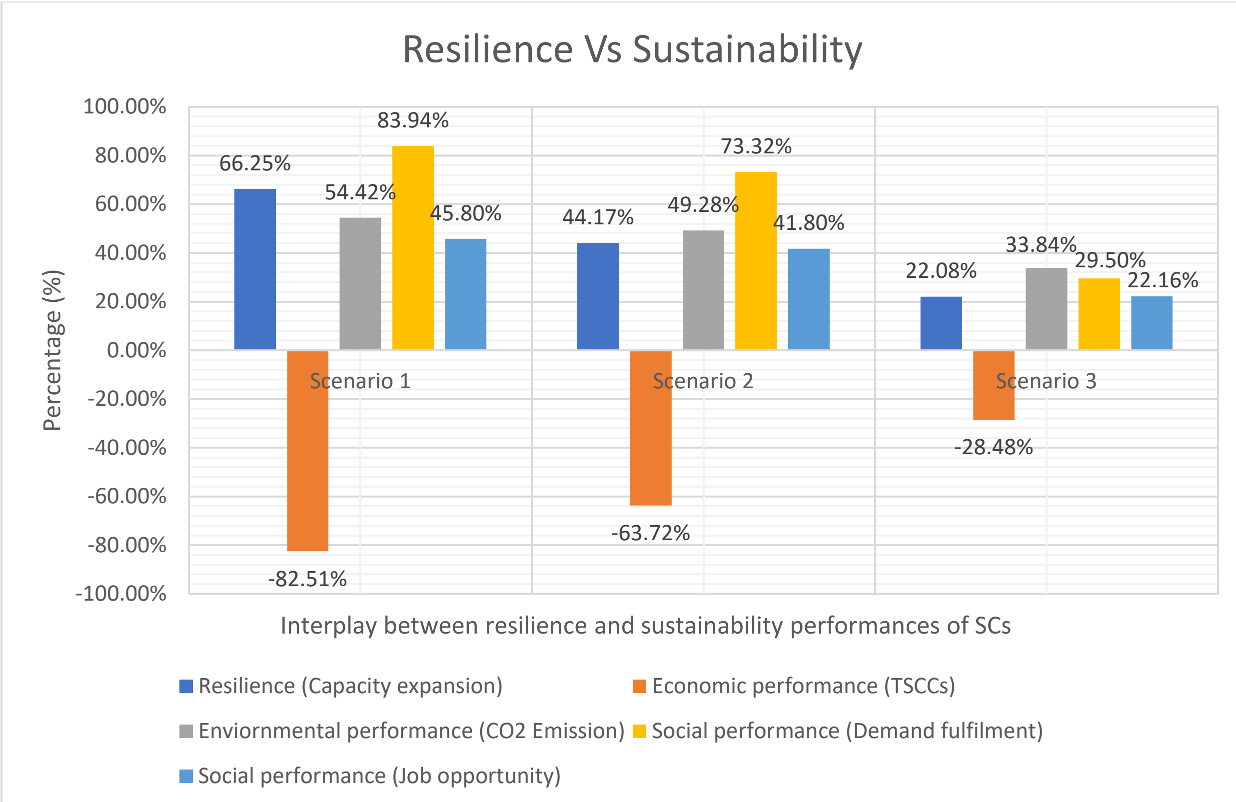

Figure 6.8: Analysis of 'Resilience' versus 'Sustainability' in managing large-scale SC disruptions

6.4.6. Sensitivity analysis

We performed several sensitivity analyses using the one-factor-at-a-time (OFAT) method to assess the proposed model's robustness. To observe the changes in sustainability performances in SCs compared to disrupted situations, we implemented a ± 20% change in demand and inventory policies. The summaries of the sensitivity analyses of the sustainability performances of SC and the details of the changes in the SC's economic performance are shown in Tables 6.11 and 6.12, respectively.

The sensitivity analysis indicates that if parameters like inventory levels and manufacturing capacity are not increased, a rise in demand significantly raises TSCCs and backorder levels. However, because neither the production capacity nor the inventory levels are enhanced, CO_2 emissions are not significantly raised. Similarly, a demand reduction reduces TSCCs and backorders but does nothing to reduce CO_2 emissions because manufacturing capacity is not reduced. According to our findings, the main way that CO_2 emissions change is when production capacity varies. It is evident from the analysis of changes in SCs' economic performance that ShCs and DisCs also increased in response to the rise in demand, while ICs decreased. Similarly, as demand decreased, ShCs and DisCs likewise decreased while ICs increased. As the inventory policy had not been changed and there was excess stock in the inventory, ICs were increased where demand decreased. As the production capacity was not enhanced, changes in the inventory policy had limited effect on sustainability performances. Nevertheless, a slight increase in inventory enhanced production capacity, resulting in increased MCs. As there was a shortage of inventory stock in the case of a decline in inventory policy, the MCs were slightly reduced. The model is largely sensitive to changes in demand, as shown by the sensitivity analysis. This observation shows a somewhat consistent pattern throughout the parameter changes based on the outcome of the changes. As a result, we can conclude that the model is robust, which implies that the study's findings and analyses are robust.

Table 6.11: Synopsis of sensitivity analysis of the SC's sustainability performances

Parameters	**Variations in each parameter**	**Variations in SC sustainability performances**		
		Economic performance	**Environmental performance**	**Social performance**
		Total supply chain costs (TSCCs)	Total CO_2 emission	Customer service (Reducing backorder level)
Demand disruption (D)	+20%	+22.36%	+0.82%	+24.49%
	-20%	-21.25%	-0.92%	-22.43%
Inventory policy (*s, S*)	+20%	-0.70%	+2.37%	-1.29%
	-20%	-0.12%	-3.72%	+0.54%

Table 6.12: Details on the variations in the SC's economic performance

Parameters	**Variations in each parameter**	**Variations in the SC's economic performance**					
		TSCCs	MCs	ICs	TCs	ShCs	DisCs
Demand (D)	+20%	+22.36%	-1.85%	-20.15%	-3.78%	+24.49%	+13.87%
	-20%	-21.25%	-5.25%	+41.50%	+3.90%	-22.43%	-19.16%
Inventory policy (*s, S*)	+20%	-0.70%	+11.86%	+9.48%	-0.16%	-1.29%	-0.97%
	-20%	-0.12%	-14.79%	-1.93%	-1.35%	+0.54%	+0.21%

6.5. Theoretical and managerial implications

The following sub-sections will elaborate theoretical and managerial implications of the findings of this chapter.

6.5.1. Theoretical implications

The study contributes to the literature in three ways. First, this study attempts to identify the components of a resilient SC. The model for the case example incorporates four resilience strategies identified in the literature. To observe improvements in resilience and sustainability, several operational recovery plans have been implemented in the model to accelerate resilience strategies. Disruptions of the SC on a large scale, such as the COVID-19 pandemic, have both immediate and post-disruptive impacts. SCs need more resilience to withstand large-scale SC disruptions in the future. Based on the results of our current study, resilient strategies such as multiple suppliers, decentralised manufacturing facilities, dynamic inventory policies, and collaborative transportation and distribution support systems can help SCs cope with large-scale SC disruptions if decision-makers take the right recovery plan in the quickest possible time. Combining the right combination of resilience strategies is vital to surviving disruptive situations.

Second, this study develops an agent-based simulation model to estimate SC economic performance following large-scale disruptions such as the COVID-19 pandemic. Using this model, we can examine the impact of large-scale disruptions on an SC's whole network and suggest ways to increase the resilience of those systems. Large-scale disruptions in SCs can have unpredictable impacts. Due to the lack of historical data, decision-makers could not predict the impact of COVID-19 on SCs during the early stages of the pandemic. Using ABM, decision-makers with little information can explore future impacts based on a bottom-up data analysis. Our study's findings demonstrate how decision-makers may forecast the impact of a significant interruption in SCs using data analytics. For the SCs to recover quickly, the decision-makers may use this analysis to guide recovery strategies.

Lastly, this ABM model uses optimisation and includes recovery plans to examine the interaction between SC resilience and sustainability. SCs need to be resilient and sustainable to survive any disruptive situation. The COVID-19 pandemic and other significant SC disruptions have shown that increasing resilience is the key factor to surviving such prolonged disruption. Improving manufacturing resilience after COVID-19 has also evidently led to higher emissions and environmental waste disposal. The results show how recovery strategies can be included in ABM-based simulation and optimisation models to increase resilience and how they impact SC sustainability regarding their economic, environmental, and social performances. The outcome also identifies the sustainability-related elements that have improved and declined. There are several managerial implications based on the theoretical contributions.

6.5.2. Managerial implications

This study has several managerial implications that decision-makers of SC manufacturers in an MNE setting can consider. The findings will help the decision-makers of these SCs put necessary resilience plans to ensure sustainability in place along with a balanced setup to withstand any future large-scale disruptions. The managerial implications resulting from the study's findings are listed below:

Managerial insight 1: Large-scale disruptions like the COVID-19 pandemic in SCs have numerous, long-lasting consequences. As such massive disruptions are challenging to predict, managing different forms of resilience and sustainable strategies to deal with the impacts immediately is difficult (Ivanov, 2020b). If decision-makers are not proactive in taking appropriate actions, there will be financial repercussions, and goodwill will suffer greatly.

The study's analysis of the impacts of large-scale disruption in SCs also shows that there will be serious repercussions if no strategies and recovery plans are planned when dealing with SC disruptions. The results show that facemask SC manufacturers had a severe supply shortage, manufacturing capacity deterioration, and limited inventory due to the impacts of the COVID-19 pandemic, which prevented them from increasing production to satisfy the increased customer demand. Due to this, the SCs' overall SC costs and shortage costs increased. Decision-makers must quickly implement the appropriate action plans and dynamic strategies to facilitate recovery processes and shorten recovery periods.

Managerial insight 2: SCs require more resilience to endure significant disruptions (Ivanov & Dolgui, 2021a). Businesses must have a resilient SC structure like that described in this study. SCs with multiple suppliers, decentralised manufacturing facilities, dynamic inventories, and transportation policies can withstand major SC disruptions if recovery operations plans are implemented appropriately. The study's results show that increasing production capacity plus having an optimal ROP, order size, and trucks boosted manufacturing capabilities, which helped to lower overall SC costs. Increasing resilience can aid company SCs in gradually recovering from financial shocks (Paul, Chowdhury et al., 2021). SC decision-makers in MNE settings should strengthen their SCs' resilience as the likelihood of encountering SC disruptions is continuously rising, occurring every 3.7 years globally on average (Rahman et al., 2021a). Enhancing resilience through dynamic inventory policies, coordination with other transporters, and having a manufacturing capacity cushion may increase some prices in typical SCs, but this resilience will help them survive future disruptive situations.

Managerial insight 3: The study's findings show that when manufacturers of crucial medical products, like facemasks, strengthen their resilience and put quick recovery plans into place during major disruptions, the SCs' economic performances considerably improve. When the production capacity, inventory capacity, and transportation and distribution support system are increased, TSCCs are reduced significantly in all scenarios. This is illustrated in Figure 6.8. A long-term increased production capacity of up to 75% significantly improved the economic performances of SCs.

It is evident that many manufacturers had to cut down their production during major SC disruptions like the COVID-19 pandemic and, as a result, failed to sell products to retailers. This led to several global factories, businesses, and retailers closing. Manufacturers' goodwill suffered greatly due to the growing order backlog and lost sales. To increase or at least maintain production capacity during times of significant disruptions, decision-makers of critical product manufacturers in MNE settings should include a logical capacity cushion, dynamic inventory, and transportation policy in their plan. This will enable them to increase SC resilience to survive, balance SC costs, and recover from disruptions quickly.

Managerial insight 4: The study's findings demonstrate that even when manufacturers of essential medical products, such as facemasks, increase their resilience and implement speedy recovery strategies during significant disruptions, the environmental performances of the SCs deteriorate if they do not use sustainable sourcing, procurement, inventory management, and transportation methods. Total CO_2 emissions grew non-linearly in every scenario (as seen in Figure 6.8) when production capacity, inventory capacity, and the transportation and distribution support system were all enhanced. The most significant rise in CO_2 was caused by a long-term increase in production capacity of up to 75%, indicating a decline in the environmental performance of SCs.

Many firms do not use green suppliers or green and renewable energy sources in their manufacturing facilities (Yavari & Ajalli, 2021). When capacity was raised to meet the additional demand, this increased environmental emissions in output. Manufacturers' contribution to environmental deterioration can significantly damage their reputation. For instance, Australia previously placed a carbon tax/price on a limited number of fossil fuels used by significant industrial emitters and governmental organisations, such as councils, with a predetermined fee of AUD$23 per ton of released CO_2 to motivate them to reduce emissions (Choi, 2020). Decision-makers of critical product manufacturers in MNE settings should logically limit their CO_2 emissions to the environment. To do this, businesses can purchase raw materials from suppliers that only use renewable energy sources, use more biodegradable packaging, operate their manufacturing facilities with renewable energy sources, and employ electric transportation. They need to boost capacity to a point where resilience and sustainability are balanced, which entails increasing resilience. By doing so, they can improve SCs' capacity for survival, maintain environmental balance, swiftly bounce back from disruptions, and fulfil sustainable development goals (SDGs).

Managerial insight 5: The findings also show that when manufacturers of crucial medical goods, like facemasks, strengthen their resilience and put quick recovery plans in place during major disruptions, SCs perform considerably better in fulfilling demand and creating jobs. Figure 6.8 shows that manufacturers can fulfil more demand and create more jobs within their facilities when production capacity, inventory capacity, and transportation and distribution support system capacity increase. In SCs, a long-term increase in production capacity of 75% significantly improved social performance and customer service.

Manufacturers in multinational settings can increase production to meet their customers' demands if they have some capacity cushion. Additionally, they can increase the number of jobs within their manufacturing facilities. People suffered much to continue their jobs during COVID-19 (Golan et al., 2020). The demand for food and personal protective equipment was high; so manufacturers and producers needed more employees to keep up with the demand (Poudel et al., 2020). Thus, companies were motivated to produce more products to increase revenue while also creating more job opportunities. It is always advantageous for manufacturers to have a capacity cushion since it increases their resilience and sustainability.

Therefore, it is recommended that decisionmakers of SCs prioritise strategies to increase their resilience while remembering that sustainability performance must be balanced to make more revenue, maintain goodwill, and have a huge social impact to maintain sustainable development goals (SDGs).

6.6. Chapter summary

This chapter aimed to primarily identify and assess SC strategies to mitigate the impacts of large-scale SC disruptions and reveal how sustainability and resilience interact to manage disruptions in facemask SCs. It provided a comprehensive combination of resilience strategies and recovery operation plans for SC risk management and planning framework, and balancing resilience and sustainability within SCs. It also examined how strategies and recovery plans were implemented and measured the effects of improving resilience on the sustainability performances of SCs, including their economic, environmental, and social impacts.

The global COVID-19 pandemic is unprecedented, so recovery strategies have not been comprehensively evaluated. Due to its uniqueness, it is difficult to predict the outcome and potential challenges for recovery from this crisis. Since during an interruption, increasing resilience is prioritised over sustainability to assure the operation of SCs, it remains unknown how far this change can impact the sustainability indicators. To understand the impacts of large-scale SC disruptions like COVID-19, an agent-based simulation model was developed in this study. Optimisation within the ABM simulation model was further developed to explore the interrelationships between resilience and sustainability and to analyse the implementation of resilience strategies and recovery plans in improving SC performances. This exploratory study contributed to the literature by exploring a new and recent topic and integrating optimisation with ABM simulation to identify potential research and practical implications.

The study primarily identified and confirmed four resilience strategies and three recovery plans by reviewing existing literature to handle the significant disruptions directly associated with the COVID-19 pandemic for the healthcare industry's SC (facemask SC). The results showed how resilience and sustainability were related to managing major disruptions. The pandemic impacted global SCs, resulting in a lack of raw material supply, a decline in manufacturing facilities, a sharp rise in demand over an extended period, reduction in inventory, transportation, and delivery support systems due to the increase in shortage costs and TSCCs. Improving resilience and recovery plans by boosting production capacity with optimal reordering point, order size, and number of trucks significantly improved SC resilience in such situations. Moreover, it was shown that SCs economic and social performance and resilience were improved considerably, while environmental performance declined, indicating the need for green production, transportation, and distribution support systems and optimal increase of capacity to balance SCs' resilience and sustainability. The sensitivity analysis examined changes in the parameters of recovery strategies. The sensitivity analysis showed that a rise in demand is always the most complex challenge to overcome, proving that the interruptions in supply and demand can be resolved through a constant supply of products in the market.

The findings are helpful in real-world situations, providing decision-makers with possible recovery strategies to deal with the impacts of COVID-19 during and after the pandemic. Understanding these impacts might help them develop successful strategies and reevaluate their SC networks in the post-COVID-19 era. The study's findings will benefit from adopting a combination of recovery strategies and plans to combat large shocks and maintain SCs' balanced resilience and sustainability in the future.

There are some limitations to this research. As the results are based on a simulation model at a certain moment, such results may be limited because they represent a snapshot in time. The connections between the different recovery strategies can shift as the pandemic advances. Therefore, it is recommended to conduct empirical research on these shifts. Additionally, only companies that experienced increased market demand due to the pandemic, like producers of healthcare products (facemasks), may benefit from the study's findings and recommendations. Other industries, including food and clothing, could have experienced diverse impacts and difficulties, which future studies might examine. This research can also be expanded into a comprehensive empirical study to assist in developing recovery strategies and assessing how they impact SCs' resilience and sustainability. This larger investigation may make it easier to extrapolate the results to other recent crises. The data is based on secondary data for one industry is another drawback. Future studies can use the same technique to identify and evaluate recovery plans and strategies for various SCs, including those in the food, clothing, pharmaceutical, and electronics industries.

Chapter 7

Conclusions and Future Research Directions

The purpose of this chapter is to provide a brief overview of the research conducted in this thesis, as well as its contributions, findings, and limitations. In addition, it includes suggestions for future research.

7.1. Summary of research and conclusions

This thesis investigates, evaluates, and develops large-scale disruption management models for essential supply chains (SCs). The models are developed for managing real-time manufacturing disruption, demand fluctuation, and supply disruption. In addition to predicting the simultaneous and dynamic effects of the COVID-19 pandemic on supply, manufacturing, demand, transportation, and inventory systems, the model includes managing the simultaneous and dynamic impacts of the worldwide pandemic and finding the interaction between resilience and sustainability in managing large-scale SC disruptions. There were several steps in the process of developing the models. A critical literature review was conducted for this thesis to find out the latest findings related to SC resilience strategies and initiatives. Initially, an agent-based simulation model was used to develop a business-as-usual plan without any disruption. Following this, several scenarios represented supply-demand-manufacturing disruptions during a pandemic as disrupted scenarios. Several recovery strategies and plans were devised in the simulation model to solve the problem. The agent-based modelling (ABM) approach was also extended to include multiple, simultaneous, and dynamic disruptions on a real-time basis, one after another as a series. A final optimisation experiment was conducted within the simulation model, using various dynamic and adaptive strategies to observe the improvement of the SC conditions in various scenarios. A framework was applied to solve four SC problems. As part of the initial stage of the pandemic triggered by COVID-19, an agent-based simulation model was developed to manage large-scale disruptions to demand, supply, and manufacturing. Second, a simulation-optimisation model was designed by ABM to deal with the simultaneous and dynamic impacts of the COVID-19 pandemic on supply, demand, manufacturing, transportation, and inventory. Third, the model was extended to manage panic-buying-related instabilities in large-scale disruptions. Fourth, the ABM model was extended to evaluate the interaction between resilience and sustainability in managing large-scale SC disruptions. For the above-mentioned models, some managerial insights have been provided regarding how a decision-maker should respond to all types of disruptions during large-scale SC disruptions. Simulation outcomes and optimisation methods also provided several insights. The experimental findings and conclusions of the above contributions are summarised below.

7.1.1. An agent-based model for SC recovery in the wake of the COVID-19 pandemic

Global SCs faced extraordinary disruptions caused by COVID-19. The worst sufferers are the manufacturers of essential items, such as facemasks. Chapter 3 sought to determine essential item manufacturers' congruent strategies and recovery plans to meet high demands and mitigate financial shocks. At the pandemic's beginning, there was increased demand for the facemask. Within a few days, demand surged by 400%. First, the chapter developed a typical SC of a facemask with an agent-based simulation model. The model was able to predict the impact of increased demand amid the supply and manufacturing capacity disruptions during the COVID-19 pandemic on SC performance. For the simulation model to recover the impacts, two recovery strategies were taken into account—increasing emergency production and increasing raw material supply. We tested several recovery plans based on the main strategies to see if the SCs improved. Simulated results demonstrated that increasing emergency production to 100% in a short period could significantly offset demand-supply disruptions. The results also indicate that when disruptions occur, the fastest and best way to increase production is to take immediate action. As a result, delaying and failing to implement the strategies increase the shortage costs of the SCs and degrade their performance. The study's results can assist the essential manufacturers in designing strategies to deal with sudden supply-demand and capacity-related disruptions in the face of extraordinary disruptions such as the COVID-19 pandemic.

7.1.2. Dynamic SC risk management plans for mitigating the impacts of the COVID-19 pandemic

Following the onset of the COVID-19 pandemic, global SCs have experienced multiple and simultaneous disruptions. The demand for healthcare products, such as facemasks and ventilators, soared, and raw materials supply flows were delayed. A lack of optimal inventory management and the inability to manage transportation and delivery support systems resulted in increased SC costs and diminished performance for manufacturers. Four adaptation strategies were examined in this study to improve production capacity, raw materials supply, inventory levels, and transportation. To predict the simultaneous and dynamic impact of the COVID-19 pandemic in the SCs, we simulated the planning of a typical facemask manufacturer based on different strategies. In Chapter 4, an optimisation experiment was conducted within the simulation model to optimise several parameters based on the adaptive strategies to find an inventory policy and transportation strategy that minimises the total costs and maximises the SC performance. The chapter revealed that facemask manufacturers need to evaluate their current SCs and resources to identify dynamic combining strategies for increasing production capacity on a long-term basis using an optimal inventory policy and transportation strategy to reduce the simultaneous impacts of the pandemic. Further, the findings indicate that optimising reordering points and order sizes will increase raw material supply and maintain maximum stock levels for continued production to reduce the disruption's negative effects. By maximising their capabilities, essential manufacturers can reduce the simultaneous effects of the pandemic by determining the dynamic and optimal required number of raw materials, quantity of inventory, and transportation costs of products. Consequently, these findings will help manufacturers predict the impacts of long-term disruptions of SCs and design adaptive strategies to manage future disruptions on a large scale.

7.1.3. A viable SC model for managing panic-buying related challenges: Lessons learned from the COVID-19 pandemic

Global SCs were affected by shortages in raw materials, disruptions in production and delivery, social restrictions, and panic-buying by consumers during the COVID-19 pandemic. Chapter 5 identifies and models viable recovery strategies for critical SCs to reduce the impact of panic-buying during significant scale disruptions. The major impacts of panic-buying on SCs are identified by integrating ABM and optimisation. During large-scale disruptions, this study evaluated four viable SC strategies and three operational recovery plans to monitor improvement in SC performance. The findings show that increasing production at decentralised manufacturing facilities and collaborating with third-party transporters can mitigate the effects of panic-buying in SCs by increasing the supply of critical items. In addition, increasing the frequency of orders to multiple and alternative suppliers can increase raw material supplies. Decision-makers can use the developed models during large-scale disruptions to analyse policies considering agility, responsiveness, flexibility, resilience, and survivability.

7.1.4. Evaluating resilience and sustainable performance in managing large-scale SC disruptions

The COVID-19 pandemic exposed the fragility of SCs when faced with material/component supply shortages, production and delivery disruptions, and social restrictions. Chapter 6 aims to enhance the awareness of increasing resilience and sustainability by identifying and modelling recovery strategies in the multi-national healthcare enterprise. This study used the integrated ABM and optimisation approach to identify the major impacts of the COVID-19 pandemic on SCs. It examined four resilience strategies and three recovery plans to monitor the improvement and interactions between resilience and sustainability when the SC is subjected to large-scale disruptions. The study reveals that increased resilience in healthcare SCs improved economic and social sustainability while decreasing environmental sustainability. Decision-makers can use this study to develop strategic policies considering resilience and sustainability post-COVID-19.

7.1.5. Summary of the research of this thesis

This thesis has made several contributions to the SC large-scale disruption management literature. ABM methods have been developed to address the real-world disruptions companies face across their SCs due to large-scale disruptions like the COVID-19 pandemic. During any large-scale disruption, multiple disruptions can occur, one after another. Developing a plan for this scenario is the most challenging as both previous and current disruptions must be considered. As part of this thesis, we developed models considering this complex scenario of multiple disruptions in SCs. In this thesis, a solution approach has been developed for managing multiple disruptions. Another novel contribution of this thesis is the development of these new solution approaches. Simulation models can be run immediately after large-scale disruptions have occurred, and then the customised outputs will provide decisions without further processing. By using the solution approaches, academics and practitioners can solve such models easily without acquiring costly software while achieving a real-time recovery schedule during large-scale disruptions with dynamic approaches on a real-time basis.

Whenever a single or multiple disruption occurs in an SC network during a large-scale disruption, the dynamic approaches proposed to offer a potentially very useful quantitative method for helping decision-makers formulate a real-time recovery plan. By using the developed models, an organisation can quickly return to its normal supply, production, and delivery schedule after a large-scale disruption, thereby decreasing its total SC costs and enhancing its reputation.

7.2. Future research directions

As with all research, this one has some limitations. Therefore, this thesis provides several avenues for further research. Different approaches can be used to extend the current research. Several potential directions are outlined below.

In this study, simulation and optimisation-based models using ABM were developed to manage large-scale SC disruptions on a real-time basis after the occurrence of the disruptions. Other methods, such as mathematical modelling and empirical methods, could be used to validate the results and find more dynamics from the findings. In addition to combining the predictive mitigation approach with real-time disruption management techniques, extending the models to develop a new approach to use predictive mitigation with real-time disruption management would be beneficial. This research did not consider consumers' preferences, that is, consumer behaviour. In future research integrating consumer behaviour into the SC model can bring more dynamics and findings. This research pointed out the importance of collaboration of SCs but did not propose any contractual frameworks for SCs for better visibility in SCs. This research attempted to optimise the number of transportation to manage the delivery to the consumers during disruptions. However, it did not focus on optimising transportation routes, which could be a future research avenue. The study extensively examined the multiple and simultaneous impacts of large-scale disruptions on SCs; however, examining ripple effects could be a future research topic. This research has used hypothetical data derived from secondary data due to the unavailability of data during the COVID-19 pandemic. Considering this limitation, future primary data can be used to find more dynamics. This research has evaluated the sustainability performances, such as economic, social, and environmental performances in SCs, while managing large-scale disruptions in SCs. In addition, it would make sense to examine sustainability issues, such as reducing carbon emissions, product waste, and unplanned activities and enhancing social values and economic resources. It would also be interesting to explore how large-scale disruptions would affect different types of items in multitier SCs, instead of considering only one type and assuming only a single item. In addition, the developed models could incorporate several additional aspects, including those listed below.

1. Transforming SCs by integrating the preferences of consumers into existing business settings, typically known as 'Outside-in' designs for SCs.
2. Contractual mechanisms in SCs in pandemic settings.
3. Transportation and routing optimisation in the settings of SC pandemic-like crises.
4. Analysing ripple effects of the large-scale disruptions in SCs.
5. Taking the developed models and implementing them in various real-life SC systems, such as food and vaccine SCs.
6. Managing COVID-19 pandemic-related large-scale SC post-disruption instabilities and sustainability.

Future studies can be carried out to develop techniques for collecting and interpreting consumer behaviour-related data, which will aid in SC design and decision-making. The effect of consumer preferences on SC performance indicators, including lead time, inventory levels, and cost, might be the subject of more research. Another topic for research is how to integrate customer preferences into SC processes by using IoT, AI, and blockchain technologies. The constraints and restrictions of adopting 'Outside-in' designs in various sectors and SC settings must be identified and addressed to evaluate whether they are appropriate for enterprises. Outside-in designs also have the potential to boost sustainability, save costs, and improve consumer happiness.

Evaluating the effectiveness of various contractual arrangements in the SC, such as back-to-back contracts, long-term agreements, and relational contracts, in lowering risk and uncertainty can be a significant area of research in future. A prominent field of research can consider how institutions and the government impact or hinder the adoption of such contractual agreements during pandemics. Analysing the pandemic's potential long-term impacts on SC contract design and governance is also essential.

Developing optimisation models and algorithms for routing and scheduling in the face of large-scale disruptions is an area of study that can be particularly interesting in the future. Real-time data and machine-learning approaches could be used in this regard. The dynamics of rerouting in emergency scenarios can be better understood by looking at the trade-offs between cost, service level, and resilience in transportation and routing decisions. Investigating how digital technologies, like IoT, AI, and blockchain, enable transportation and routing optimisation under crisis situations would be another worthwhile line of research, with the goal of boosting SCs' resilience. In the future, it could also be fruitful to analyse how transportation and routing choices affect SC sustainability and performance in emergencies.

A crucial field of study is identifying and quantifying how disruptions, such as changes in demand, capacity, and lead times, affect various SC components. Especially in the case of pandemics or large-scale disruptions, developing simulation and modelling tools to analyse the transmission of disruptions across the SC might be a key research area. Another interesting area of study is how digital technologies, like IoT, AI, and blockchain, may be used to monitor and control ripple effects. Future studies can also find value in analysing the consequences of ripple effects for SC performance, resilience, and sustainability.

Using the models developed and evaluated in this study and applying them to actual SC systems is referred to as 'taking established models and putting them in real-life supply chain systems'. For instance, the distribution of food or vaccinations might be optimised using these models to ensure prompt and effective delivery to the targeted customers.

An essential component of combating the COVID-19 pandemic is managing post-disruption instabilities in broad SC networks. The pandemic has severely disrupted global supply networks, hurting certain industries more than others. Ensuring people still have access to essential commodities and services may depend on implementing models that may help manage these disruptions and restore stability to SCs. Sustainability is a crucial factor when applying these models to actual SC systems. Future models might be developed to guarantee that resources are used effectively and that adverse environmental effects are reduced to a minimum. This might involve eliminating waste, cutting down on transportation-related emissions, and ensuring that materials utilised in the SC are procured sustainably for further studies.

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Appendix A

Table A1: Definitions of SCRES by researchers

Reference	Definition of SCRES	Resilience strategies focused
Machowiak (2012)	'Resilient supply chains that can withstand the impact of major supply chain disruptions and catastrophes, without impacting the end customer and without incurring excessive recovery costs'.	Responsiveness of SC
Ivanov and Sokolov (2013)	'The ability to maintain, execute and recover (adapt) the planned policies along with achievement of the planned (or adapted, but yet still acceptable) performance'.	Responsiveness of SC
Hohenstein *et al.* (2015)	'Supply chain resilience is the supply chain's ability to be prepared for unexpected risk events, responding, and recovering quickly to potential disruptions to return to its original situation or grow by moving to a new, more desirable state in order to increase customer service, market share and financial performance'.	Preparedness, responsiveness, and recovery of SC
Ambulkar, Blackhurst, and Grawe (2015)	'Firm's resilience to supply chain disruptions is defined as the capability of the firm to be alert to, adapt to and quickly respond to changes brought by a supply chain disruption'.	Responsiveness of SC
Kamalahmadi and Mellat-(Parast, 2016)	'The adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations'.	Responsiveness and recovery of SC

Table A2: Consolidated summary and categorisation of the SCRES strategies

SC level of disruptions / Category of resilience strategy	Macro	Supply	Demand	Manufacturing	Information	Transportation	Financial	References
Preparedness	• Establish risk-management culture • Contingency planning • Customised training on disruptions handling • Internal and external strategic collaboration • Build security against theft, terrorism, and the infiltration of counterfeit • Invest in infrastructure, capital, and resources before they are needed • Localise SCs	• Diversify and increase parallel importing routes and sources • Increase national demand storage, keep foreign dependence at a safe level • Strategic reserve/storage • Multiple suppliers • Contract with back-up suppliers • Strong supply base • Failure to supply penalties • Geographical segregation for selecting suppliers • Collaborative supplier relationship • Selecting responsive supplier	• Establish more processing facilities • Decentralise the manufacturing network • Mandatory redundancy (multiple suppliers) • Price increases (low price is a reason behind product shortage) • Forecasting and replenishment • Contract of receiving products from partner facilities or plants • Increase customer interaction • Customisation of products • Make alternative services ready	• Increase production capacity • Product substitution • Prepare to increase extraordinary production in the time of strong shocks • Technological improvement • 3D printing and computer-aided engineering-technology integration • New product development and introduction • Establish a quality plant which can generate capacity flexibility • Eliminate functional silos • Back-up emergency equipment • Production of semi-manufactured products • Decentralise manufacturing capacity • Establish multiple product lines	• Information sharing • Investment in ICTs for better transparency • Early warning signals • Cyber-security • Maintain an integrated database to facilitate information sharing across internal functions	• Freight/physical security (insurance of products) • Excess capacity in transportation • Implement a parallel transportation system • Use of multi-port calling • Use of a mix of sea and air freight • Invest in online distribution channels • Consider reliable distribution centres • Hold extra inventory at distribution centres • Multimodal transportation • Multicarrier transportation • Multiple routes	• Revenue sharing • Increase financial strength • Liquidity reserve	Ding *et al.* (2020), Chen *et al.* (2020), Soni, Jain, and Kumar (2014), Dixit, Verma, and Tiwari (2020), Valipour Parkouhi and Safaei Ghadikolaei (2017), Thomas *et al.* (2015), Fazli-Khalaf *et al.* (2020), Tucker *et al.* (2020), Pettit, Croxton, and Fiksel (2013), Rajesh (2020), Das and Lashkari (2015), Siva Kumar and Anbanandam (2020), Hosseini *et al.* (2019), Pereira *et al.* (2020), Hasani and Khosrojerdi (2016), VanVactor (2011), Piprani, Jaafar, and Mohezar Ali (2020), Asamoah, Agyei-Owusu, and Ashun (2020), Dong *et al*. (2018), Cavalcante *et al*. (2019), Can Saglam *et al*. (2020), Taleizadeh *et al*. (2020), Kumar *et al*. (2014), Gunasekaran *et al*. (2015), DuHadway *et al*. (2019), Bag *et al*. (2022), Sonar *et al*.(2022), Chen *et al*. (2022), Longo *et al.* (2022), Hsu *et al.* (2022), Qi *et al*. (2022), Song *et al.* (2022), Ghufran *et al.* (2022), Bygballe *et al.* (2023)
Response	• Increase the level of knowledge created and shared among partners • Collaboration with other firms • Lobby and influence constitutional change • Scenario analysis and simulations	• Consider disruption during the designing and planning of procurement and material flow • Reroute • Alternative supplier • Substitute supplier/facilities (hedging strategies) • Using multiple sourcing	• Consider disruption during the designing and planning of the demand forecast • Reduce pipeline times to respond to changing demands or supplies • Virtual stockpile pooling (VSP) and virtual trans-shipment • Share operational information with key customers	• Back-up technologies • Parallel processes or concurrent processes instead of sequential processes • Production capacity increase • Produce output with minimum resources	• Predict SCRES performance by assessment through Big Data • Vivid view of SC inventories and other settings • Information gathering and sharing to identify	• Establish more fortified warehouses close to the customer zones • Customer integration, logistics collaborator integration, internal and external collaborations • Consider multiple transport routes • Apply the lateral trans-shipment between DCs	• Have the knowledge of market position and act accordingly • Public-Private Collaboration • Revenue sharing among SC partners	Soren and Shastri (2019), Fattahi, Govindan, and Keyvanshokooh (2017), Amindoust (2018), Mohammed (2020), Rajesh (2016), Rajesh (2019), Sahu, Datta, and Mahapatra (2016), Zainal Abidin and Ingirige (2018), Liu and Lee (2018), Li *et al.* (2017), Liu, Song, and Tong (2016), Sabouhi *et*

	• Alternative operational policy, computation and simulation	• Contract with back-up suppliers • Share operational information with key suppliers • Identify reliable and proactive supplier	• Accurate demand forecasts • Flexible support by digital platforms • Co-ordination with suppliers • Promotional offers	• Use other facilities in the SC network to back up the primary facilities • Add extra production capacity in factories • Design generic products • Reduce manufacturing lead times • Reduce product development cycle time • Change production formula and fix when needed • Change production volume capacity as needed	opportunities and threats • Share operational information across internal functions • Share risk-management information • Synchronisation of production plans with SC partners • Joint electronic data interchange • Use blockchain technology	• Allow the direct shipment of products from factories to customers • Change in manufacturing throughput times to satisfy customer delivery • Customer order fulfilment from an alternate facility • Alter global delivery capacity • Redistribution of logistics network • Modified process for last-mile delivery		*al.* (2020), Piprani, Jaafar, and Mohezar Ali (2020), Adobor and McMullen (2018), Ali, Nagalingam, and Gurd (2018), Hendry *et al.* (2019), Chunsheng *et al.* (2019), Aggarwal and Srivastava (2019), Kumar and Anbanandam (2019), Lee and Rha (2016), Majumdar *et al*. (2021), Mohammed *et al*. (2021), Moosavi and Hosseini (2021), Razavian et al. (2021), Zhang *et al*. (2021), Chopra *et al*. (2021), Shen and Sun (2021), Vecchi *et al*. (2020), Khan *et al*. (2021), Njomane & Telukdarie (2022), Furstenau *et al.* (2022), Nayeri *et al.* (2022), Ambrogio *et al*. (2022), G. Li *et al.*, (2022), Cohen *et al.* (2022), Belhadi *et al.* (2022), Kent *et al.* (2022), Bastas & Garza-Reyes (2022), Ahmed *et al.* (2023), Ghanei *et al.* (2023)
Recovery	• Improve integrated supporting system • Enhance bargaining and communication power • Crisis team formation • Horizontal and vertical collaboration • Public-private partnership • Information and knowledge sharing • Collaboration with international organisations • Quick SC redesign • Share risk and outcome • Resource reconfiguration • SC optimisation • Long-term disruption impact estimation • Simulation of transition from recovery to normal operational policy	• Multiple sourcing • Quantity discount to purchase of raw material • Emergency planning to source • Strategic-level risk-sharing between manufacturer and supplier • Switch to cheaper sources • Deploy buffer stocks • Dual sourcing • Expedite orders • Resource investment for faster supplier recovery • Collaboration between buyer and supplier by exchanging resources and materials in stock to reduce or avoid operations interruptions • Spot purchase • Switch to an alternative supplier	• Production capacity expansion • Quick response to unpredictable demand change • Take from the pre-reserved capacity of other facilities or plants owned in neighbouring areas • Negotiation with customers about the order • Collaboration between franchises to exchange needed materials • Increase customer communication • Dynamic pricing and assortment planning • Silent product rollovers • Incentive alignment • Collaborative forecasting	• Pilot production • Exchange of input, knowledge, and labour • Contract with back-up facilities • Back-up technology for production to switch to another level of technology to continue the production in any disruption • Optimised capacity utilisation • Horizontal collaboration amongst manufacturers • Vertical collaboration with processors/producers and retailer • Identify, authenticate, and track using RFID to stop counterfeiting • Flexibility to change the product's features or even create a substitutable product • Alternative bill of material (BOM) • Produce cheap products compared to others for market capture	• Accurate information sharing • Big data for quality information sharing • Share database • Share predictive capacity • Transparent view of upstream and downstream inventories • Clear view of demand and supply conditions • Clear view of production and purchasing schedules	• Quick delivery • Establish regional distribution hubs for quick delivery • Trans-shipment • Just-in-time delivery • Airplane transportation and flexibility to receive the ordered material in different volumes • Flexibility to change the delivery routes • Collaboration with other logistics service companies • Pre-booking containers as soon as possible (maritime) • Back-up transportation	• Government aid • Business-government collaboration • Business interruption insurance	Chen, Das, and Ivanov (2019), Yang and Xu (2015), Lücker and Seifert (2017), Sabouhi, Pishvaee, and Jabalameli (2018), Rezapour, Farahani, and Pourakbar (2017), Parast (2020), Li and Zobel (2020), Papadopoulos *et al.* (2017), Zahiri, Zhuang, and Mohammadi (2017), Leat and Revoredo-Giha (2013), Polyviou, Croxton, and Knemeyer (2019), Vanpoucke and Ellis (2019), Machado, Jafarnejad *et al.* (2019), Ivanov (2020a), Ivanov (2021a), Mehrjerdi and Shafiee (2021), Rahman *et al*. (2021), Lohmer *et al*. (2020), van Hoek and Dobrzykowski (2021), Zhen *et al*. (2016), DuHadway *et al*. (2019), Tseng *et al.*(2022), Rahman & Paul (2022), K.E.K *et al*. (2022), Juan & Li (2023), Vicario *et al.* (2023)

Table A3: Synopsis of the industries of SCs studied by the researchers

Area of application	**References**
ICT	Chen, Das, and Ivanov (2019), Chunsheng *et al.* (2019), Modgil *et al*. (2021)
Electronics	Chen, Das, and Ivanov (2019), Rajesh (2016), Rajesh (2019), Chunsheng *et al.* (2019), Namdar *et al.* (2018), Pettit, Croxton, and Fiksel (2013), Rajesh (2020), Rajesh (2021), Hasani (2021), Moosavi and Hosseini (2021), Rajesh (2020b)
Energy	Ding *et al.* (2020), Soren and Shastri (2019), Chen *et al.* (2020), Zalitis *et al.* (2022), Al-Haidous, Govindan, *et al*. (2022)
Food	Yang and Xu (2015), Pereira *et al.* (2020), Leat and Revoredo-Giha (2013), Hendry *et al.* (2019), Chunsheng *et al.* (2019), Scholten and Schilder (2015), Xu *et al.* (2020), Gholami-Zanjani *et al.* (2020), Kumar and Kumar Singh (2021), Ivanov (2021a), Michel-Villarreal *et al.* (2021), Ivanov and Rozhkov (2020), Yavari and Ajalli (2021), Arabsheybani and Arshadi Khasmeh (2021), Manning and Soon (2016), Khan *et al*. (2021), Mu *et al*. (2021), Njomane & Telukdarie (2022), Bender *et al.*(2022), Kent *et al.* (2022), Vicario *et al.* (2023)
Pharmaceutical	Lücker and Seifert (2017), Sabouhi, Pishvaee, and Jabalameli (2018), Zahiri, Zhuang, and Mohammadi (2017), Xu *et al.* (2020), Tucker *et al.* (2020), Zhu, Chou, and Tsai (2020), Lücker *et al*. (2019), Vann Yaroson *et al.* (2023)
Automotive	Amindoust (2018), Rezapour, Farahani, and Pourakbar (2017), Hosseini *et al.* (2019), Machado, Paiva, and da Silva (2018), Chunsheng *et al.* (2019), Aggarwal and Srivastava (2019), Lee and Rha (2016), Xu *et al.* (2020), Haldar *et al.* (2014), Siva Kumar and Anbanandam (2020), Kaviani *et al.* (2020), Belhadi *et al*. (2021), Frieske & Stieler (2022)
Chemical	Mohammed (2020), Jüttner and Maklan (2011), Chunsheng *et al.* (2019), Ambulkar, Blackhurst, and Grawe (2015), Pettit, Croxton and Fiksel (2013), van Hoek and Dobrzykowski (2021), Sabouhi *et al*. (2021), Razavian *et al*. (2021), Lu *et al*. (2015)
Wood and paper	Valipour Parkouhi and Safaei Ghadikolaei (2017), Jüttner and Maklan (2011), Dubey, Gunasekaran, Childe, Papadopoulos, *et al.* (2019), Longo *et al.* (2022)
Medical equipment and healthcare	Hasani and Khosrojerdi (2016), Polyviou, Croxton, and Knemeyer (2019), Jafarnejad *et al.* (2019), Xu *et al.* (2020), Pettit, Croxton, and Fiksel (2013), Scala and Lindsay (2021), Rehman and Ali (2021), Salama and McGarvey (2021), Rahman *et al*. (2021), Sazvar *et al*. (2021), Aldrighetti *et al*. (2019), Vecchi *et al*. (2020), Furstenau *et al.* (2022), Nayeri *et al.* (2022), Rahman & Paul (2022), Nayeri *et al.* (2023), Ash *et al.* (2023)
Electrical	Jüttner and Maklan (2011), Polyviou, Croxton, and Knemeyer (2019), Kumar and Anbanandam (2019), Lee and Rha (2016)
Textile	Piprani, Jaafar, and Mohezar Ali (2020), Tseng *et al.* (2022)
SMEs	Asamoah, Agyei-Owusu, and Ashun (2020), Ali, Nagalingam, and Gurd (2018)
Construction	Papadopoulos *et al.* (2017), Zainal Abidin and Ingirige (2018), Chunsheng *et al.* (2019), Lee and Rha (2016), Pettit, Croxton, and Fiksel (2013), van Hoek and Dobrzykowski (2021)
Cold chain logistics	Ali, Nagalingam, and Gurd (2018)
Hospital logistics	VanVactor (2011)
Plastic	Polyviou, Croxton, and Knemeyer (2019), Chunsheng *et al.* (2019), Hosseini and Khaled (2019)
Fashion and apparel	Polyviou, Croxton and Knemeyer (2019), Machado, Paiva, and da Silva (2018), Zhang *et al.* (2021), Majumdar et al. (2021), Dohale *et al*. (2021), Hsu *et al*. (2021), Choksy *et al*. (2022)
Toys	Machado, Paiva, and da Silva (2018)
Rubber	Lee and Rha (2016), Dubey, Gunasekaran, Childe, Papadopoulos, *et al.* (2019)

Metal	Lee and Rha (2016), Dubey, Gunasekaran, Childe, Papadopoulos, *et al.* (2019), Werner *et al.* (2021), K.E.K *et al*. (2022)
Maritime	Omer *et al.* (2012)
Retail	Ambulkar, Blackhurst, and Grawe (2015), Shen and Sun (2021)
Logistics/transporter	Papadopoulos *et al.* (2017), Liu and Lee (2018), Lee and Rha (2016), Ambulkar, Blackhurst, and Grawe (2015), Azadeh *et al.* (2014)
Aircraft	Boone *et al.* (2013)
Port	Colicchia, Dallari, and Melacini (2010)
Tire	Fazli-Khalaf *et al.* (2020), Mehrjerdi and Shafiee (2021)
Personal care products	Pettit, Croxton, and Fiksel (2013)
Pet product company	Kumar *et al*. (2014)
Industrial paint	Sabouhi *et al.* (2020)

Table A4: Synopsis of the geographical locations of the application-focused by researchers

Geographical location of the application	**References**
Global	Xu *et al.* (2020), Ivanov and Dolgui (2020), Colicchia, Dallari, and Melacini (2010), Sharma *et al.* (2020), Zhu, Chou, and Tsai (2020), Pettit, Croxton, and Fiksel (2013), Haldar *et al.* (2014), Das and Lashkari (2015), Ivanov (2020b), Kumar and Kumar Singh (2021), Abe and Ye (2013), Das *et al*. (2021), Seuring *et al.* (2022)
Taiwan	Chen, Das, and Ivanov (2019), Liu and Lee (2018), Chunsheng *et al.* (2019), Chen *et al*. (2022)
China	Ding *et al.* (2020), Yang and Xu (2015), Chen *et al.* (2020), Liu, Song and Tong (2016), Shen and Sun (2021), Hsu *et al.* (2021), Shih & Lin (2022), G. Li *et al.*, (2022), Hsu *et al.* (2022), Qi *et al*. (2022), Song *et al.* (2022), Rujeerapaiboon *et al.* (2023)
USA	Ni, Howell, and Sharkey (2018), Parast (2020), VanVactor (2011), Adobor and McMullen (2018), Polyviou, Croxton, and Knemeyer (2019), Vanpoucke and Ellis (2019), Boone *et al.* (2013), Hosseini and Khaled (2019), Tucker *et al.* (2020), Zhu, Chou, and Tsai (2020), van Hoek and Dobrzykowski (2021), Schmitt *et al*. (2017), Lu *et al*. (2015), Bender *et al*.(2022)
Iran	Amindoust (2018), Sabouhi, Pishvaee, and Jabalameli (2018), Jafarnejad *et al.* (2019), Azadeh *et al.* (2014), Fazli-Khalaf *et al.* (2020), Sabouhi *et al.* (2020), Kaviani *et al.* (2020), Hasani (2021), Sazvar *et al*. (2021), Sabouhi et al. (2021), Moosavi and Hosseini (2021), Razavian *et al*. (2021), Yavari and Ajalli (2021), Arabsheybani and Arshadi Khasmeh (2021)
India	Dixit, Verma, and Tiwari (2020), Rajesh (2016), Rajesh (2019), Aggarwal and Srivastava (2019), Kumar and Anbanandam (2019), Dubey, Gunasekaran, Childe, Papadopoulos, *et al.* (2019), Dubey, Gunasekaran, Childe, Fosso Wamba, *et al.* (2019), Rajesh (2020), Siva Kumar and Anbanandam (2020), Rajesh (2021), Majumdar *et al*. (2021), Rajesh (2020b), Dohale *et al*. (2021)
Brazil	Pereira *et al.* (2020), Machado, Paiva, and da Silva (2018), Werner *et al*. (2021)
Nepal	Papadopoulos *et al.* (2017)
Middle East	Hasani and Khosrojerdi (2016)
France	Zahiri, Zhuang, and Mohammadi (2017)
Scotland	Leat and Revoredo-Giha (2013)
Pakistan	Piprani, Jaafar, and Mohezar Ali (2020), Choksy *et al*. (2022)
Ghana	Asamoah, Agyei-Owusu, and Ashun (2020)
Malaysia	Zainal Abidin and Ingirige (2018)
Australia	Ali, Nagalingam, and Gurd (2018), Rahman *et al.* (2021), Kent *et al.* (2022), Rahman & Paul (2022)
UK	Hendry *et al.* (2019), Brandon-Jones *et al.* (2014), Thomas *et al.* (2015), Scala and Lindsay (2021), Zhang *et al*. (2021), Vicario *et al.* (2023)
Turkey	Can Saglam *et al*. (2020)
Canada	Kumar *et al*. (2014), Ash *et al.* (2023)
Ecuador	Khan *et al*. (2021)
South Korea	Lee and Rha (2016)
South Africa	Njomane & Telukdarie (2022), Bag *et al.* (2022)
Uganda	Tukamuhabwa, Stevenson, and Busby (2017)
Netherlands	Scholten and Schilder (2015)
Germany	Ivanov (2021a)
Mexico	Michel-Villarreal *et al*. (2021)

Italy	Aldrighetti *et al*. (2019), Fernández-Miguel *et al.* (2022)
East Asian and North American ports	Omer *et al.* (2012)

Table A5: Selected annotated bibliography of the reviewed articles

Reference	Contributions	Methodologies used	Theories	Findings related to SCRES strategies
Colicchia, Dallari, and Melacini (2010)	This article proposed strategies to mitigate inbound supply risks in a global sourcing context.	Simulation	---	The global sourcing capabilities were increased by adopting the proposed strategies.
Wang *et al*. (2010)	The paper examined two mitigation strategies in a supply chain network: dual source and process improvement.	Mathematical and optimisation model	---	In the case of random capacity uncertainty, improvement is preferred as supplier cost heterogeneity increases, while dual sourcing is favoured if reliability heterogeneity is high.
Iakovou *et al*. (2010)	The paper examined how inventory policies and disruption risks may be traded off for an unreliable dual-sourcing supply network.	A single-period stochastic inventory decision-making model	---	Companies that do not take into account the risk of disruptions and their ramifications could suffer severe financial and market-share losses.
Jüttner and Maklan (2011)	This paper aimed to conceptualise SCRES strategies, and to identify and explore empirically their relationship with the related issues of SC vulnerabilities and SC risk-management.	Interview	---	Flexibility, collaboration, and visibility are intangible dynamic SC capabilities that generate competitive advantages in normal and routine operating times.
VanVactor (2011)	This paper conveyed a message of preparedness and mitigation strategies to key stakeholders throughout the healthcare SC and community.	Case study	---	Collaborations and contingency plans help to recover from the disaster.
Leat and Revoredo-Giha (2013)	The paper examined and aimed to identify the potential risks and challenges involved in forming a resilient agri-food supply system (a case of one of Scotland's major port SCs).	Interview	---	Producers improved market and price security and pig performance through horizontal collaboration between the processor and retailer.
Omer *et al.* (2012)	This paper proposed several schemes that improved SCRES by reducing the system's vulnerability and increasing its adaptive capacity.	Networked infrastructure resiliency assessment framework	---	Diversity, collaboration, and resource allocation made the maritime SC more resilient.

Dong and Tomlin (2012)	This study examined business interruption insurance, inventory management, and emergency sourcing for managing disruption risk.	Mathematical and optimisation model (endogenous insurance pricing model)	---	The marginal value of inventory can be increased by insurance, increasing the value of emergency sourcing overall.
Saghafian and Van Oyen (2012)	The authors of this article developed a quantitative methodology to quantify the value of contracting a secondary flexible backup supplier and monitoring primary suppliers.	Newsvendor model	---	The flexibility of a backup supplier is highly beneficial to a firm whose primary suppliers are unreliable; obtaining perfect disruption risk information will result in an average cost reduction by the recourse option.
Azadeh *et al.* (2014)	SCRES strategies and modelling were proposed in this paper to recover from transportation disruptions.	Visual simulation language for analogue modelling (SLAM) and fuzzy data envelopment analysis (FDEA)	---	The findings revealed that visibility and redundancy were important SCRES strategies to recover from transportation disruptions.
Boone *et al.* (2013)	This paper investigated the impact of improved strategic alignment of inventory on SC resiliency and continuity.	Longitudinal field study	---	System approach resulted in fewer inventory flow and operational disruptions.
Pettit, Croxton, and Fiksel (2013)	This research developed a measurement tool titled the 'Supply Chain Resilience Assessment and Management (SCRAM)'.	Survey-based assessment tool—SCRAM and mixed method triangulation	---	The findings revealed that increasing collaboration, capacity, and flexibility made SCs more resilient.
Abe and Ye (2013)	Considering two recent natural disasters in Japan and Thailand, this article discussed how global supply chains can increase natural disaster risk and what the impact of natural disasters will be on global supply chains.	Case study	---	Firms and governments need to take disaster risks into account in supply chain management to avoid supply chain disruptions.
Soni, Jain, and Kumar (2014)	This paper proposed a model to analyse the enablers for SCRES for better preparedness to sustain any disruption.	Graph theory, interpretive structural modelling (ISM) approach	---	Measuring SCRES index helped the decision to take initiatives for better preparedness for any disruption.

Pereira, Christopher, and Lago Da Silva (2014)	This article aimed to understand the role of procurement in identifying and managing the intra- and inter-organisational issues which impact SCRES.	Systematic literature review	---	Proactive procurement strategies helped the SCs to be more resilient.
Tang *et al*. (2014)	The study presented a series of models that shed light on the best parameter choices for buyers and suppliers to mitigate supply chain disruption risks in a decentralised setting.	Mathematical and optimisation model	---	The study pointed out that direct buyer investment in suppliers' process improvement efforts was superior to indirect incentives. However, this was not universally true, particularly when the minimum yield was strictly positive. Despite the benefits of larger orders in single
Kumar *et al.* (2014)	The purpose of this paper was to provide the organisation with a framework for managing risk associated with their supply chain.	Case study	---	A company must assess the risk of supply chain disruptions and design strategies to mitigate the risk once the areas of risk have been identified.
Ambulkar, Blackhurst, and Grawe (2015)	This paper aimed to expand the understanding of factors contributing to the development of SCRES to SC disruptions.	Case study and structural equation model	---	Resource reconfiguration fully mediated the relationship between SC disruption orientation and firm resilience in high-disruption events.
Brandon-Jones *et al.* (2014)	This study aimed to understand the relationship between information sharing and connectivity, visibility, and performance in terms of SCRES and performance.	Survey, multiple regression analysis, and hierarchical moderation tests	Contingent resource-based view	SC connectivity and information-sharing resources led to an SC visibility capability which enhanced SC resilience and robustness.
Thomas *et al.* (2015)	This paper proposed a resilience 'Fit Operational Model' for UK manufacturers within a complex multi-channeled support system to drive businesses forward with increased competitiveness and resilience.	Survey and conceptual fitness model	---	The findings revealed that enhancing knowledge, capability, and technological capacity made the SCs more resilient.
Haldar *et al.* (2014)	This article developed a quantitative approach for strategic supplier selection in a fuzzy environment during disruptive events.	Fuzzy TOPSIS and aggregate fuzzy weight (AFW)	---	By selecting proper suppliers, organisations could devise resiliency plans to alleviate the vulnerability of the supply side of SCs.

Yang and Xu (2015)	A quantitative model and resilience strategies to mitigate supply disruptions of grain producers were proposed in this paper.	Multi-objective mathematical modelling	---	The findings revealed that back-up suppliers and government aid helped recover from supply-side disruption immensely.
Sahu, Datta, and Mahapatra (2016)	This paper focused on resilience strategies for evaluating and selecting resilient suppliers.	Fuzzy-VIKOR, Fuzzy-TOPSIS	---	Resilient supplier selection is of immense importance for competitive advantages and survival of disruptions.
Lee and Rha (2016)	This paper applied dynamic capabilities and organisational ambidexterity theories to examine mitigation strategies for SC disruptions.	Field survey and structural equation model	Dynamic capability theory and organisational ambidexterity	SC ambidexterity is essential for firms to reduce the negative impact of SC disruptions, whereas dynamic SC capability-building processes are antecedents of SC ambidexterity.
Scholten and Schilder (2015)	This paper aimed to explore how collaboration influences SCRES.	Case study	---	The study revealed that information sharing and collaborative communication improved SC visibility, flexibility, velocity, and overall SCRES.
Das and Lashkari (2015)	This paper proposed SC risk-readiness and resiliency measures and formulated a model for planning and controlling factors to mitigate SC after-affects.	Mixed-integer programming model	---	Risk-readiness measures made the SCs more resilient to respond to disruptions.
Lu *et al*. (2015)	This paper presented a model for correlated disruptions with uncertain joint distributions and used distributionally robust optimisation to minimise the expected cost under the worst-case distribution with marginal disruption probabilities.	Mathematical and optimisation model (distributionally robust optimisation)	---	The consequences of ignoring disruption correlation could be significant losses in key factors, such as source disaster probabilities, disruption propagation effects, and service interruption penalties.
Gao (2015)	This paper studied dynamic risk-management in coordination with inventory hedging, contracting, and collaborative forecasting.	Mathematical and optimisation model	---	Using collaborative forecasting to trigger stock buildup in light of looming disruptions reduces shortages more rapidly than conventional inventory hedging.
Gunasekaran *et al.* (2015)	This paper examined how global sourcing impacts supply chains rather than reporting trends and the implications described in the literature.	Conceptual framework	---	The study shows that researchers are more concerned with proactive strategies than dealing with complex elements; no studies capture the holistic effects.
Manning and Soon (2016)	This paper aimed to provide innovative methods to drive business performance in the food supply chain by considering strategic business resilience.	Conceptual	---	By integrating resilience capabilities into food supply chains, supply chains can be more agile, stable, and long-lasting, leading to continuous improvement.

Rezapour, Farahani, and Pourakbar (2017)	This paper proposed recovery strategies to mitigate automobile upstream supply disruption that led to disruption at downstream retailers.	Mixed-integer non-linear method	---	The study revealed that downstream 'emergency stock' is the preferred SCRES strategy for unreliable suppliers.
Papadopoulos *et al.* (2017)	This research investigated the use of big data in explaining resilience in SC networks for sustainability.	Data collection and survey from social media	---	Big data and public-private partnership are crucial for enhancing the SCRES for post-disaster quick recovery.
Hasani and Khosrojerdi (2016)	A model and resilience strategies for robust global SC network design were proposed in this paper.	Mixed-integer non-linear model, parallel hybrid Taguchi-based memetic algorithm, fitness landscape analysis, LAGRANGIAN relaxation heuristic methods	---	Dual or multiple sourcing strategies, semi-manufactured production and alternative BOM adoption strategies have more impacts on the GSC performance than the extra inventory strategy or single sourcing strategy.
Rajesh (2016)	This research analysed and predicted the indicators of SC resilience for firms from secondary data.	Grey's prediction method	---	Flexibility, responsiveness, and accessibility were preferred attributes from the customer view for resilient SCs.
Zhen *et al*. (2016)	This study examined how ex-ante business interruption (BI) insurance can affect the ex-post recovery of transportation and compared BI insurance with ex-post compensation based on backup transportation.	Mathematical and optimisation model	---	BI insurance and transportation recovery are complementary, but BI insurance and backup transportation are substitutable, as are backup transportation and transportation recovery.
Hosseini and Khaled (2019)	This research aimed to select resilient suppliers based on the SCRES capacities.	Literature review and case study, AHP, predictive analytics models, and ensemble methods	---	Robustness, reliability, and rerouting are the most important enablers of supplier resilience.
Li *et al.* (2017)	This paper aimed to investigate the importance of information sharing in a generalised three-echelon SC regarding resiliency.	System dynamics and multi-objective simulation-based optimisation	---	Information sharing in SCs reduced back-order amount and duration when target inventory levels were specified.
Liu, Song, and Tong (2016)	This study presented a new approach for managing stockpiles called 'virtual stockpile pooling' (VSP).	Multi-location stochastic inventory model for optimal stockpile allocation	---	VSP effectively maintained the stockpile and provided significant cost savings.

Fattahi, Govindan, and Keyvanshokooh (2017)	This study proposed SCRES strategies to meet the demand of customers with responsiveness.	Multi-stage stochastic programming	---	Establishing more fortified warehouses close to customer zones increases the SCRES during disruptions.
Ni, Howell, and Sharkey (2018)	This paper aimed to optimise pre-event mitigation and post-event restoration decisions for disruptive events impacting SCs.	Two-stage stochastic programming model	---	An annual contract with a back-up facility is the most desired strategy to meet customer demand in any disruption.
Lücker and Seifert (2017)	This research aimed to propose and design resilient SC and mitigation strategies to meet the drug shortage of pharmaceutical companies.	Mathematical modelling	---	A second manufacturing site reduces the need for additional inventory and keeping reserve capacity.
Valipour Parkouhi and Safaei Ghadikolaei (2017)	This paper proposed a model for the best supplier selection.	Fuzzy analytic network process, Grey VIKOR method	---	Proper supplier-selection assessments can make the supply side resilient and SCs more agile.
Zahiri, Zhuang, and Mohammadi (2017)	This paper proposed a resilient SC network for pharmaceutical products under uncertainty.	Multi-objective integrated sustainable-resilient mixed-integer linear programming model, fuzzy possibilistic stochastic programming approach, Pareto-based lower bound method NP hard	---	The findings recommended that products in the production units be assigned to technology levels with a lower probability of failure as back-up technologies and the rearrangement processes are costly.
Schmitt *et al.* (2017)	The paper examined adjustments in order activity across four tiers to help respond and recover from a disruption.	Simulation	---	In lieu of expediting interventions, dynamic order-up-to policies offer adaptive mitigation potential.
Serpa and Krishnan (2017)	The paper showed that, in a multi-firm setting, insurance can be strategically used as a commitment mechanism to prevent excessive free-riding by other firms.	Mathematical and optimisation model	---	Insurance can increase the efficiency of risk-management efforts by reducing free-rider problems by other wealthy firms.
Ali, Nagalingam, and Gurd (2018)	This paper bridged the current research gap by developing a model of the interplay between cold chain logistics risks, resilience, and firm performance in perishable product SCs.	Interview and exploratory factor analysis and confirmatory factor analysis (CFA)	Contingency theory and resource-based theory	A strong collaboration and resource-sharing mechanism among internal as well as external SC partners are important to meet customer demand.

Liu and Lee (2018)	This paper developed and assessed a conceptual model for the relationships between different types of integration, SCR, and service performance from the perspective of third-party logistics providers.	Partial least squares structural equation modelling	---	Customer integration has immense benefits for the resilience of SCs.
Machado, Paiva, and da Silva (2018)	This paper analysed the development of mitigation capabilities to reduce the negative impacts of counterfeiting.	Interview and case study	---	Allocating resources in the earlier phases reduces the possibility of counterfeiting.
Tukamuhabwa, Stevenson, and Busby (2017)	This paper empirically investigated SCRES in a developing country context.	Case study and interview	---	Understanding the interconnectedness of threats, strategies, outcomes, and embeddedness of the supply network is necessary for SCRES.
Jain *et al.* (2017)	This study developed a hierarchy-based model for SCRES explaining the enablers of SCRES.	Integrated interpretive structural modelling, MICMAC analysis and structural equation model	Information processing theory, high-reliability theory, social exchange theory	Information sharing is vital to enhance SCRES. Trust, collaboration, visibility, and risk-management culture are also important.
Amindoust (2018)	This article proposed a resilient-sustainable framework and approaches in supplier selection decisions during disruptions.	Hybrid intelligent method, fuzzy interface system, data envelopment analysis	---	Responsiveness, back-up supplier contracting, and surplus inventory are vital SCRES indicators.
Sabouhi, Pishvaee, and Jabalameli (2018)	This paper proposed an integrated hybrid approach for best supplier selection and provided SCRES strategies to mitigate supply-side disruptions.	Data envelopment analysis and mathematical programming modelling	---	Usage of multiple sources, pre-positioning of emergency inventory, and fortification of suppliers help to meet the demand and thus reduce lost sales and total SC costs.
Zainal Abidin and Ingirige (2018)	This study investigated and assessed the critical vulnerabilities and capabilities that formulate the level of resilience in handling disruptive events in construction projects.	Mann–Whitney U and Kruskal–Wallis tests	---	Building information modelling (BIM) improves transparency in information flow and encourages collaborative decision-making that improves SC visibility.
Adobor and McMullen (2018)	This paper presented a conceptual framework for SCRES types.	Complex adaptive systems perspective	---	The authors mentioned another level of SCRES called 'Growth and renewal'.
Dong *et al*. (2018)	This study examined inventory, preparedness, and insurance in a two-stage production chain that is subject to	Mathematical and optimisation model	---	Inventory and preparedness protect against financial consequences and the goodwill impact of customer shortages, while

	disruption at either the upstream or downstream stages.			insurance only guards against financial consequences.
Demirel *et al*. (2018)	This paper evaluated the costs and benefits of flexible sourcing when suppliers are strategic price-setters.	Mathematical and optimisation model	---	When each supplier announces a single (wholesale) price, such a game leads to a conflict of incentives and is unrealistic in most real-world settings. The contingent-pricing game reflects a more intuitive practical relationship.
Ledwoch *et al*. (2018)	This paper aimed to explore the relationship between the topological characteristics of complex supply networks and their ability to recover through inventory mitigation and contingent rerouting.	Agent-based simulation model	---	In complex supply networks, contingent rerouting is less efficient than inventory mitigation.
Bimpikis *et al*. (2018)	This article aimed to investigate firms' sourcing decisions when procurement is subject to disruption risk in a multitier supply chain.	Mathematical and optimisation model	---	The downstream manufacturers need to provide their suppliers with better contract terms to reduce the likelihood of production disruptions. By using cross-contingent contracts, companies could maintain some coordination in their supply chains.
Macdonald *et al*. (2018)	The paper used structured experimental design and discrete-event simulations to further our understanding of how disruptions impact supply chain performance through direct and interaction affects.	Discrete event simulation	---	Despite not being significant for recovery time, buffer size has a positive coefficient for the three dependent variables: total loss, average loss per time unit, and resilience.
Hendry *et al.* (2019)	This paper investigated how local SCs respond to constitutional changes.	Interview, case study	Dynamic capability theory	The findings revealed the importance of vertical and horizontal collaboration among SC actors.
Vanpoucke and Ellis (2019)	This paper provided insights into the risky decision-making process that underlies buyers’ decisions to adopt SC mitigation tactics for creating supply-side resilience.	Delphi and empirical quantitative	---	Buyers need to implement risk-mitigation tactics to build resilient SCs.
Namdar *et al.* (2018)	This article examined the use of sourcing strategies to achieve SCRES under disruptions.	Two-stage stochastic programming	---	Buyer’s warning capability plays an important role in enhancing SCRES.

Chen, Das, and Ivanov (2019)	This paper investigated the post-disruption stages and SCRES strategies to recover from these disruptions.	Interview	---	Industrial clustering, back-up supplier, collaboration within SCs, and verification of material speed-up the recovery processes.
Soren and Shastri (2019)	An optimisation model for the biomass industry to response to supply and financial disruption was proposed in this paper.	Multi-objective optimisation model	---	Considering disruption when planning and designing the SC structure increases SCRES.
Hosseini *et al.* (2019)	This paper proposed resilience strategies for supplier selection under disruption.	Probabilistic graphical model, stochastic bi-objective mixed integer programming model	Bayesian network theory	SCs need to enhance the recovery capacity to sustain in and after disruptions, as higher pre-disaster resilience strategies do not have a higher restoration rate.
Rajesh (2019)	This paper identified critical attributes affecting resilience in SCs.	Resilient fuzzy index, performance fuzzy index	---	Proper utilisation of available buffers, such as capacity, inventory, and time, in the SC increases SCRES.
Polyviou, Croxton, and Knemeyer (2019)	This paper explored resources and capabilities that enable medium-sized firms to resist disruptions.	Case study and interview	Internal social capital	Structural capital grounded in small network size, geographical vicinity among decision-makers and low hierarchy; relational capital grounded in immediate relationships, commitment and respect, and cognitive capital grounded in longer employee incumbency enable SCs to be resilient.
Chunsheng *et al.* (2019)	This paper investigated the importance of internal and external integration, risk-management culture, and SC flexibility in ensuring SCRES.	Interview, case study, and structural equation model	Organisational culture and resource orchestration	The present study empirically confirmed that SCRES positively affects the firm's financial performance.
Aggarwal and Srivastava (2019)	This paper explored the phenomenon of collaborative resilience by using a case study.	Case study and Grey-based DEMATEL	---	Collaborative culture and design resilience in operations enhance other factors of collaborative resilience.
Jafarnejad *et al.* (2019)	This study aimed to find and investigate the key factors affecting the SCRES of medical equipment companies and to scrutinise the dynamic relations among these factors.	Survey, hesitant fuzzy Delphi method, system dynamic simulation	---	Enhancing the information flow among SC partners improves cooperative decision-making to grow SCRES.
Kumar and Anbanandam (2019)	This paper aimed to provide a framework to help organisations understand their SCRES level.	An integrated Delphi fuzzy logic approach	---	Sourcing, manufacturing, and logistic flexibility are the major contributors to SCRES index for firms.

Dubey, Gunasekaran, Childe, Papadopoulos, *et al.* (2019)	This paper offered a broad understanding of SCRES and the implications of SC visibility, cooperation, trust, and behavioural uncertainty.	Case study and hierarchical regression analysis	---	Appropriate technology, quality information sharing, reducing behavioural uncertainty, and proper integration of SC visibility, trust, and cooperation make the SCs more resilient.
Ivanov (2020a)	This paper investigated the inter-relations of structural and operational vulnerabilities in SCs.	Discrete event simulation	---	Demand decrease or increase influences the performance of SCs, causing disruptions and instability in post-disruption inventory dynamics.
Mackay, Munoz, and Pepper (2019)	This study proposed conceptual strategies to mitigate SC disruptions to improve post-disruption system performance.	Conceptual theory	---	Redundancy and flexibility ensure SC robustness and resilience.
Dubey, Gunasekaran, Childe, Fosso Wamba, *et al.* (2019)	This paper investigated the role of data analytics capability on SCRES.	Survey, partial least squares structural equation modelling	Organisational information processing theory	Safety stock, competitive advantages, and increasing information-processing capacity increase SCRES.
Shin and Park (2019)	This paper aimed to systematically identify and design improvement planning for SCRES.	Interpretive structural modelling	---	Visibility, velocity, and flexibility affect agility. Collaboration and integration affect visibility. Coordination affects responsiveness.
Aldrighetti *et al*. (2019)	This study examined the impact of severe disruptions on the healthcare supply chain performance	Simulation by Anylogistix	---	When dealing with short-term disruptions, activating a backup provider is the most effective mitigation strategy; for long-term disruptions, trans-shipment is more effective, but it costs more.
Bimpikis *et al*. (2019)	In this paper, multitier supply chain networks were examined under disruption risk, and endogenous supply networks were explored, as well as structures that maximise profits for suppliers of raw materials and downstream retailers, showing how different structures are viewed as optimally efficient.	Mathematical and optimisation model	---	The equilibrium state in SC may lead to fewer firms producing than would otherwise be optimal for overall welfare.
Gao *et al*. (2019)	This paper presented a framework for determining the optimal inventory allocation strategy so that lost sales are minimised.	Mathematical and optimisation model: Worst-case conditional Value at Risk (CVaR) and Conic programming	---	The optimal inventory strategy improves supply chains regardless of whether disruptions are independent or correlated.

Singh and Singh (2019)	This paper addressed how firms can develop resilience to supply chain disruptions by developing data analytics capabilities within their organisation.	Covariance-based structural equation modelling	---	Adopting big data analytics enhances pre-existing organisational capabilities and allows the firm to develop risk resilience against supply chain disruptions.
Lücker *et al*. (2019)	The purpose of this paper was to analyse optimal risk-mitigation inventory and reserve capacity decisions under stochastic demand under supply chain disruption risk.	Mathematical and optimisation model	---	Optimal reserve capacity increases with the coefficient of demand variation, whereas optimal risk-mitigation inventory decreases or increases according to inventory holding costs.
Sabahi and Parast (2020)	This paper investigated the capabilities of innovativeness of firms that support SCRES.	Preposition development and conceptual framework	Dynamic capability theory	Innovative firms are more resilient to SC disruptions. Knowledge sharing, agility, and flexibility enhance the innovativeness and resilience of the firms.
Zhao *et al*. (2019)	The purpose of this paper was to demonstrate how the model of firms' adaptive behaviours can leverage competition relationships within a supply chain network through an agent-based simulation.	Agent-based simulation model	---	Proactive strategies become more effective with even risk distribution, while the more multi-sourcing exists in the supply base, the less effective they become.
Cavalcante *et al*. (2019)	The paper described a hybrid method which combines simulation and machine learning to support data-driven decision-making in resilient suppliers' selections.	Simulation and supervised machine learning (SML)	---	Using supervised machine learning and simulation together improves delivery reliability.
DuHadway *et al*. (2019)	This paper developed a framework to comprehend effective risk-management strategies by analysing whether a disruption was intentionally or inadvertently caused and whether the source of the disruption was endogenous or exogenous.	Theoretical	Organisational Information Processing Theory	Risk mitigation and risk recovery are two different aspects of effective risk-management, while risk detection is critical for both intentional and unintentional disruptions.
Tucker *et al.* (2020)	This paper developed new SC design models that consider disruptions and recovery over time to reduce drug shortage.	Two- and multi-stage stochastic programs	---	Shortages of products may be reduced by implementing moderate failure-to-supply penalties, mandatory SC redundancy, considerable amounts of inventory, or large price increases.
Tan, Cai, and Zhang (2020)	This paper presented a simulation-based analysis to determine the strategies and	Discrete event and agent-based model (ABM)	---	The redundant capacity strategy enables the SC network less time to recover,

	parameters best suited to building resilience in SC networks.			whereas the back-up SC strategy has the lowest cost among all strategies.
Ding *et al.* (2020)	This paper proposed SCRES strategies and a framework to assess the resilience of natural gas importation under disruptions.	Network construction, topological property analysis, structural modification	---	Importing more natural gas for safety stock and increasing suppliers closer to the country helps to make the natural gas supply more resilient.
Chen *et al.* (2020)	This paper simulated and strategised the resiliency of oil imports under shocks.	System dynamic simulation	---	Extraordinary production during strong shocks, energy conversion efficiency, and strategic oil storage make the oil SCs resilient to external shocks.
Mohammed (2020)	This study proposed a model and resilience strategies to make the SCs green and resilient by selecting the best suppliers during disruptions.	VIKOR and DEMATEL	---	Resilient criteria attained the highest value when compared to general criteria to select the best supplier.
Dixit, Verma, and Tiwari (2020)	This study assessed and evaluated the SCRES strategies in pre- and post-disaster.	Conditional value at risk (CVaR), simulation-based approach, structural network design	---	Firms having the lowest density and centrality and the highest connectivity and network size show the greatest resilience.
Parast (2020)	This study evaluated how investment in R&D increases SCRES.	Dynamic capability theory	Dynamic capability theory	Investment in R&D mitigates the effect of process, supply, demand, and environmental disruptions by anticipating risks.
Li and Zobel (2020)	This study investigated the total SC network resilience and the phenomenon of spreading disruption to other firms.	Multi-dimensional quantitative methods	---	Enhancing the ability to tolerate the risks by adjusting network structure enhances SCRES effectively.
Pereira *et al.* (2020)	This paper identified the key capabilities that the purchasing and supply management function develops to increase resilience in the supply side of the buying firms.	Interview	---	Effective communication and intense collaboration among suppliers and internal customers reduce the barriers built by rigid hierarchy.
Piprani, Jaafar, and Mohezar Ali (2020)	This study determined and prioritised the resilient capability factors at different stages of SC disruptions.	Analytical hierarchy process	---	Manufactures need to focus on the readiness phase of resilience as it is considered the most significant phase.
Asamoah, Agyei-Owusu and Ashun (2020)	This research analysed the relationship between social network relationships, SCRES, and customer-oriented performance.	Empirical quantitative analysis	Social capital theory	Firm's external and internal social networks can be leveraged to enhance its SCRES and customer-oriented performance.
Xu *et al.* (2020)	This paper aimed to investigate the impacts of COVID-19 on the	Case study and critical reading	---	The findings suggest that the post-COVID-19 global SCs will tend to be

	effectiveness and responsiveness of global SCs and proposed a set of managerial insights.			shorter through revamped strategies focusing increasingly more on relocations and back-shoring.
Ivanov and Dolgui (2020)	This paper theorised the notion of a digital SC providing a conceptual model.	Theorising	---	The combination of simulation, optimisation, and data analytics constitutes a digital twin that helps to manage risks in SCs.
Gholami-Zanjani *et al.* (2020)	This study analysed integrating key features of location-allocation and inventory-replenishment decisions to make SCs resilient.	A generic two-stage mixed-integer mathematical model	---	Readiness, flexibility, and responsiveness together can dramatically increase the performance of the SC network.
Sharma *et al.* (2020)	This paper provided a conceptual framework of factors for enhancing the survivability of SCs during and after the COVID-19 pandemic.	Survey and stepwise weight assessment ratio analysis (SWARA) method	---	SC network viability is the most important criterion for developing sustainable SCs in the COVID-19 pandemic.
Fazli-Khalaf *et al.* (2020)	This paper provided a new maximal covering idea hybridised into the extended resilient SC network design aiming to maximise coverage of customers' demand even in disruptive situations.	A new mixed fuzzy possibilistic flexible programming method	---	Decentralising the manufacturing network could lead to a resilient SC for tyre companies.
Zhu, Chou, and Tsai (2020)	This paper investigated the relationship between SC operations and the ongoing COVID-19 pandemic focusing on the global shortage of essential goods, supply issues, and unsustainable just-in-time production.	Theoretical concept	---	Lack of SC transparency and reduced diversification result in a lack of SC resiliency.
Rajesh (2020)	This study proposed a decision support model for managers about understanding, measuring, and improving the level of resilience in manufacturing SCs.	Advanced analysis of grey incidences	---	Connectedness, information sharing, standardisation, regular vulnerability checks, and reviews can reduce SC risks.
Sabouhi *et al.* (2020)	This study proposed a model to design a resilient SC operating under random disruptions.	Two-stage stochastic optimisation model, a multi-cut L-shaped solution method, classical benders decomposition algorithm	---	This paper revealed the effectiveness of ensuring extra production capacity and multiple sourcing strategies for the SCs to respond more to customer demands.

Siva Kumar and Anbanandam (2020)	This paper proposed a method to enhance the understanding of the SCRES building capabilities and resilience improvement.	Case study and situation–actor–process–learning–action–performance (SAP–LAP) analysis	Social capital, relational view, contingent resource-based theory, information processing, complexity theory, and dynamic capability theory	The establishment of risk-management culture, building collaborative capabilities, introducing flexible contracts, increasing the awareness level of risks, security, and flawless information-sharing require significant attention to make the SCs resilient.
Kaviani *et al.* (2020)	This study evaluated two SCRES key elements (i.e. vulnerability and capability) in the automotive industry context.	Survey and fuzzy hypothesis tests	---	Outsourcing, flexibility, and visibility are vital to making SCs resilient, and recovery is the prime factor for SC resilience.
Ivanov (2020b)	This paper theorised a new notion—the viable supply chain (VSC).	Dynamic systems theory and SC structural-dynamics control approach	---	The VSC model can help firms to recover and re-build their SCs after global, long-term crises, such as the COVID-19 pandemic.
Lohmer *et al*. (2020)	Blockchain technology and supply chain resilience were discussed in this paper.	Agent-based simulation model	---	Resilience increases if time-efficient processes are used to support collaboration.
Ivanov and Rozhkov (2020)	With respect to SC planning and production-capacity disruption, this paper examined the trade-offs between write-off risks and resilience.	Discrete and agent-based simulation model	---	Stabilising inventory dynamics, improving on-time delivery, and reducing variation in customer service are all advantages of coordinated policy.
Rajesh (2020b)	The study presented a combined methodology that top managers can use to develop more resilient supply chain strategies.	Grey theory and layered analytical network process	---	Risk hedging and insurance were found to be the most effective resilience strategies.
Vecchi *et al*. (2020)	The study investigated the contracting issues experienced by Italian health care authorities and US procurement officials due to the COVID-19 crisis and gave lessons for enhancing procurement in disasters.	Case study	---	Innovation in government procurement is needed, focusing on the strategic role of procurement and the importance of public-private partnerships, both of which would be prioritised by public agencies if they were sophisticated buyers.
Can Saglam *et al*. (2020)	To bridge the gap between mitigation strategies and SCRM performance, this study examined the relationship between proactive risk-mitigation strategies,	PLS-based SEM	---	SC resilience and responsiveness positively affect SCRM performance; however, SC flexibility does not.

	namely supply chain (SC) flexibility, resilience, and responsiveness.			
Taleizadeh *et al*. (2020)	The impact of employing supply chain resilience strategies, such as stocking up on inventory at distribution centres and considering reliable distribution centres, was investigated in this paper.	Stackelberg game model, a two-phase bi-level mixed integer programming approach, Decomposition-based algorithm	---	SC decision-makers should be aware of proactive measures to mitigate disruption risks.
Namdar *et al*. (2021)	A framework was proposed that designs a resilient supply chain network under mixed uncertainties.	FDEMATEL, FANP, and novel two-stage mixed possibilistic-stochastic programing (TSMPSP) model	---	The SCs should prioritise the long-term disruptions closest to the customer when limited by funding.
Kamalahmadi *et al*. (2021)	This study examined an integrated approach to supplier selection, demand allocation, and the development of flexible capabilities to increase supply chain responsiveness.	Two-stage mixed-integer programming model	---	An effective practice is the combination of backup and flexible suppliers.
Ivanov (2021b)	Considering the COVID-19 pandemic, this study identified four major adaptability strategies: intertwining, scaling, substitution, and repurposing.	Conceptual framework	---	SC disruptions can be minimised by combining adaptability strategies with SC viability.
Kumar and Kumar Singh (2021)	This study aimed to investigate the impact of COVID-19 on Agri-Food supply chains and suggest ways of improving their resilience to COVID-19.	Best-worst method and quality function method	---	As a result of COVID-19's poor accessibility and availability, production and distribution costs increased significantly for Agri-Food SC.
Ivanov (2021a)	The pandemic was studied for its effects and supply chain behaviours, but little is known about supply chain management during the elimination and recovery phases.	Discrete event simulation	---	It is effective to ramp up capacity gradually before anticipated peaks of postponed demand to minimise disruptions.
Scala and Lindsay (2021)	This study aimed to illustrate resilience in a public sector healthcare organisation and provide lessons learned from the COVID-19 pandemic as a test of resilience.	Case study	---	It is recognised that collaboration plays a key role in resilience; public sector networks play an important role in this.
van Hoek and Dobrzykowski (2021)	This paper aimed to investigate whether the pandemic is driving reshoring decisions and, if so, which sectors of the	Case study	---	Reshoring decisions and implementation may lose relevance when supply normalises.

	supply chain will be relocated as a result.			
Rezaei *et al*. (2021)	Through risk-reduction strategies and coordination between the buyer and seller, this paper set out a framework for selecting reliable suppliers and order allocation that increases supply chain value.	Nonlinear mixed integer programming, failure modes and effects analysis (FMEA), and AHP	---	Strategically, choosing appropriate suppliers is important. Allocating orders optimally is a key issue.
Herold *et al*. (2021)	This article aimed to provide insights into how logistics service providers (LSPs) managed to maintain supply chain resilience during the COVID-19 pandemic.	Interview	---	Logistics service providers' resilience builds resilience during external shocks of high impact and low probability.
Rehman and Ali (2021)	This study aimed to identify which resilience strategies healthcare supply chains should prioritise.	Fuzzy AHP, Fuzzy TOPSIS, Fuzzy Quality function deployment (QFD)	---	The most significant resilience strategies identified through fuzzy multi-criteria decision-making analysis are Industry 4.0, multiple sourcing, risk awareness, agility, and global diversification of suppliers, markets, and operations.
Salama and McGarvey (2021)	Based on an analysis of a set of pandemic scenarios, a stochastic mixed integer linear programming model was proposed to maximise SC profit conditional value at risk (CVaR).	A stochastic mixed integer linear programming model	---	To reduce transportation costs, sub-chains of nodes from the same region are established to maximise profits.
Modgil *et al*. (2021)	The study examined ways firms utilise AI to enhance supply chain resilience by enhancing visibility, risk management, sourcing and distribution capabilities.	Interview	---	Among respondents, transparency was identified as an essential factor to ensure inventory, delivery, and so on are transparent across supply chains.
Zhang *et al*. (2021)	In addition to contributing to the omni-channel and SCRES literature, this study provided insight into how an omni-channel strategy suits both stable and turbulent environments.	Case study	---	A well-enacted omni-channel strategy was the key to giant apparel companies' growth despite the COVID-19 pandemic.
Belhadi *et al*. (2021)	A study of the COVID-19 outbreak's impact on the automobile and airline supply chains was conducted.	Interview	---	COVID-19 posed immediate business continuity challenges for the airline industry, which they prepared by defining

				aviation operations both at airports and in flights.
Mehrjerdi and Shafiee (2021)	This paper simultaneously discussed sustainable and resilient aspects of a closed loop supply chain.	Multi-objective mixed-integer programming model, fuzzy TOPSIS	---	Combined sustainability and resilience are needed in the closed-loop supply chain.
Michel-Villarreal *et al*. (2021)	This paper explored the different resilience capabilities that Short Food Supply Chains possess and how digital technology may enable them to be more resilient.	Case study	---	The importance of low-cost digital technologies (such as freeware and social media) for increasing flexibility, collaboration, visibility, and agility is clear.
Rajesh (2021)	Flexible business strategies supporting resilience in supply chains were examined in this paper.	Exploratory factor analysis, confirmatory factor analysis	---	It is possible to enhance resilience in supply chains by building flexibility in them, but for that to happen, it has to be kept in mind to reduce the complexity of supply chains as much as possible.
Chopra *et al*. (2021)	Using multiple channels for the flow of information and products, the authors explained how firms achieve efficiency in dealing with normal variations in demand and supply and resilience in dealing with disruptive changes.	Theoretical	---	Multiple channels of flow are enabled by a commons while also reducing the cost to build resilience through investing in flexibility, caution, risk-mitigation inventory, or reserve capacity.
Rahman *et al*. (2021)	A set of congruent strategies and recovery plans was examined to minimise costs and maximise the availability of essential items in the face of global SC disruptions.	Agent-based simulation model	---	Using the best production capacity and minimised risk-response times, essential item manufacturers could meet consumers' soaring demands and timely supply, reducing financial shock to their firms.
Peng *et al*. (2021)	This paper aimed to determine the resilience of the Physical Internet-enabled integrated production-inventory-distribution system under various disruption risks.	A two-stage stochastic programming model (a two-level heuristic algorithm to optimise)	---	A pre-event mitigation strategy works better than a post-event mitigation strategy.
Hasani (2021)	A fuzzy multi-objective mathematical programming model was presented to design an efficient and resilient global supply chain network structure based on service-oriented considerations.	A fuzzy multi-objective mathematical programming model, fuzzy best-worst method technique, augmented ε-constraint	---	Global supply chains should be flexible enough to respond to changing business environments and demand.

		method, and VIKOR technique		
Sazvar *et al*. (2021)	The paper showed how to design a sustainable-resilient supply chain based on strategic and tactical levels of decision-making.	Multi-objective mathematical and optimisation modelling	---	Supply chain redundancies do not always increase costs.
Sabouhi *et al*. (2021)	This paper presented a resilient supply chain design using a hybrid methodology to withstand disruptions.	Multi-objective optimisation model	---	SCs with greater robustness can be more cost-efficient.
Majumdar *et al*. (2021)	The study prioritised several risk-mitigation strategies based on their contributions to mitigating various risks.	Fuzzy TOPSIS	Organisational theory	A supply chain strategy that develops agility mitigates risk the best.
Mohammed *et al*. (2021)	A study of suppliers' vis-`a-vis resilience pillars and companies' adaptability to unpredictable demand was attempted in this paper.	DEMATEL-TOPSIS and possibilistic bi-objective programming model	---	Assessing suppliers' resilience pillars and companies' ability to cope with uncertainty is important.
Moosavi and Hosseini (2021)	A simulation was used to measure supply chain resiliency.	Discrete event simulation by Anylogistix	---	Simulation results show that an extra inventory provides greater resilience and lower costs than a backup supplier.
Razavian *et al*. (2021)	The paper proposed a supply chain model that deals with disruptions well and combines material and financial decisions.	Two-stage stochastic programming	---	Different financing strategies can also increase the profitability of supply chains, according to the experiments.
Yavari and Ajalli (2021)	Under the scenario of disruption, this study investigated the design of a green-resilient supply chain network, introducing a new strategy of 'coalition' between suppliers in a bi-objective mixed integer linear programming model to reduce total costs and carbon emissions.	Bi-objective mixed-integer linear programming model	---	A coalition strategy in the upstream supply chain helps achieve economic objectives and environmental concerns. A slight improvement in the performance of the downstream supply chain can be achieved by multi-sourcing.
Werner *et al*. (2021)	This study aimed to examine non-financial KPIs' role in establishing organisational resilience.	Case study	---	Redundancy and agility can help prevent stock-related disruptions, while maintaining suppliers' performance requires collaboration and flexibility.
Shen and Sun (2021)	The paper examined quantitative operational data to assess the impact of the pandemic on supply chains; it	Measuring quantitative operational data	---	When dealing with an outbreak of COVID-19, firms should focus on

	discussed the challenges that supply chains faced during the pandemic in China; it also presented practical responses during the pandemic.			operational flexibility and collaboration beyond the supply chain.
Wang and Webster (2021)	The paper examined the value of flexibility with primary and backup suppliers separately.	Mathematical and optimisation model (normative model)	---	Incorporating flexibility in either primary or backup suppliers is always beneficial.
Arabsheybani and Arshadi Khasmeh (2021)	A robust bi-objective and multiple-product mathematical model was developed in this paper to analyse resiliency and uncertainty in multi-period, multiple-item supply chain networks simultaneously.	Bi-objective multi-period robust optimisation model, ε-constraint method, Fuzzy Analytic Hierarchy Process (AHP) and Fuzzy Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA)	---	To increase the resiliency of the model, SCM preferred to use a multitude of suppliers as opposed to monopoly sourcing and tried to keep more inventory in the warehouses to keep it resilient.
Das *et al*. (2021)	This paper identified critical factors affecting global supply chains and evaluated strategies for reducing risk in the supply chain network.	AHP and DEMATEL	---	In the pandemic, government support is one of the most important factors that can eliminate supply chain issues.
Dohale *et al*. (2021)	The paper evaluated the risk-mitigation strategies to overcome the prominent supply chain risks using a multi-criteria decision-making model.	Fuzzy AHP	---	In this study, flexibility and postponement are prioritised for reducing risk.
Hsu *et al*. (2021)	This study explored the resilience of fashion supply chains by considering supply chain risk, resilience capabilities, and resilience-enhancing features.	Integrated quality function deployment (QFD) approach, the House of Quality (HOQ), KJ method/Affinity Diagram, Failure Modes and Effects Analysis (FMEA), the finite difference method (FDM), VIKOR	---	The top four resilience factors are reconfiguring company resources, on-site risk monitoring, real-time job sharing, and establishing an incentive system.

Khan *et al*. (2021)	This study examined the role of business data analytics (BDA) and technological innovation (TI) on the firm's performance during COVID-19.	Covariance-based structural equation modelling (CB-SEM)	---	Companies with the most extraordinary technological production processes were the least affected during COVID-19.
Mu *et al*. (2021)	This study defined resilient food supply chains within the context of food safety, a method for assessing food safety resilience, and an example of how a resilient food supply chain can be quantified and improved.	Monte Carlo Simulation	---	A system that can adapt and be resilient to food safety shocks is more practical than one that focuses only on building resistance.
Um and Han (2021)	This study aimed to theoretically hypothesise and empirically explore the relationships among global supply chain risks, supply chain resilience, and mitigation strategies.	Structural equal modelling (SEM)	---	For high manufacturing and delivery risks, the postponement strategy improves supply chain resilience but does not significantly increase supply chain resilience for sourcing risks.
Njomane & Telukdarie (2022)	By comparing the use of IoT in three South African supermarkets, this article aimed to identify the impacts of the global pandemic on food safety.	Comparative research approach	---	Panic buying at the beginning of the lockdown caused the supply chain cadence to shock, causing the food shortage during the COVID-19 pandemic. Food availability and socioeconomic problems caused by loss of income are other aspects of food security.
Nayeri *et al.* (2022)	This article proposes a framework for global responsive SC, which considers resilience and sustainability.	Multi-objective mathematical modelling	---	SC responsiveness can improve job opportunities, safety, carbon emissions, and economic aspects of sustainability.
Vali-Siar & Roghanian (2022)	A mixed-integer linear programming model is proposed in this paper for designing responsive, resilient and sustainable supply chain networks.	Multi-objective mixed-integer linear programming model	---	It is essential that SCs remain resilient for them to remain sustainable in the future.
Tseng *et al.* (2022)	By developing data driven SSCM indicators under industrial disruption and ambidexterity, this paper contributes to the existing knowledge in this field.	Fuzzy-Delphi method	---	Under industrial disruption and ambidexterity, financial vulnerability, supply chain uncertainty, risk assessment, and resilience are key factors ensuring SSCM effectiveness.
Bag *et al.* (2022)	The study examines the role of big data and predictive analytics in developing a resilient supply chain network in the	Partial least squares structural equation model (PLS-SEM)	Dynamic capability theory	To meet social sustainability responsibilities, firms in the industry need a high level of SC visibility.

	South African mining industry in the face of extreme weather conditions.			
Sonar *et al.* (2022)	This paper identified several criteria for selecting suppliers using the lean, agile, resilient, green, and sustainable paradigm in supplier selection.	Interpretive structural modelling (ISM)	---	Choosing a supplier is influenced heavily by geographical location, which is placed at the bottom of the hierarchy.
Z. Li *et al.* (2022)	A dual-channel fresh-food SC (FSC) under disruption is examined in this paper.	Mathematical modelling	---	The SC profit can be significantly increased by considering quality preference disruptions.
Cohen *et al.* (2022)	This paper examines how managers actually think about resilience strategies by analysing the relationship between supply-chain characteristics, operational characteristics, and the strategies implemented.	Interview and data analysis	---	Developing an effective supply-chain resilience strategy may be facilitated by a dialogue between supply-chain scholars and practitioners.
Longo *et al.* (2022)	This paper proposed a simulation-based framework to investigate the benefits of digital models.	Simulation	---	Productivity can be reduced due to a lack of system preparedness.
Belhadi *et al.* (2022)	This paper aims to develop different SC resilience strategies using a multicriteria decision-making (MCDM) technique powered by AI algorithms.	MCDM and AI-based algorithm	---	The most promising SC resilience strategies are fuzzy logic programming, machine learning, and agent-based systems.
Seuring *et al.* (2022)	A global perspective on the pandemic's impacts on SCs and their management is sought in this study.	Delphi method	---	Geographically, the impact of the COVID-19 pandemic varies. Compared regionally, China and Iran, as well as Africa, stand out, but also Europe/North America, India/Pakistan, and Brazil exhibit geographical characteristics.
Bastas & Garza-Reyes (2022)	An investigation of the challenges and strategies formulated by manufacturing organisations in the Northern region of Cyprus is presented in this paper.	Interview	---	Textiles' demand declined significantly, while sanitisers, ventilators, and critical food items' demand skyrocketed due to the shift in consumer behaviour during the COVID-19 pandemic.

Rahman & Paul (2022)	The paper examines panic-buying-related instabilities in SCs during the COVID-19 pandemic and strategies for managing them.	Agent-based model		SCs can reduce panic-buying by increasing the production capacity of critical items.
K.E.K *et al*. (2022)	Using an agent-based simulation software anyLogistix, this study analyses the ripple effect in the copper industry while considering various key performance indicators.	Discrete event simulation	---	The disruptions are caused by the lack of safety stocks and the multi-sourcing of copper during the COVID-19 pandemic.
Hohenstein (2022)	This paper aims to examine the impacts of the COVID-19 pandemic on supply chains (SCs) and which SC risk management (SCRM) approaches have succeeded.	Case study	Dynamic capability theory	Defining an SCRM design in response to acute disruption requires robustness and agility while learning from experience is essential.
Bygballe *et al.* (2023)	This paper aims to demonstrate how the resource interaction approach (RIA) can enhance the understanding of resources in supply chain disruptions and propose an alternative approach to managing such disruptions in a turbulent business environment.	Conceptual analysis	---	Instead of considering it merely as one of several alternative approaches, it is proposed that collaboration should begin by leveraging the dynamic relationship between temporary and permanent organising.
Alikhani *et al.* (2023)	This paper aims to propose a multi-methodological approach, utilising resource dependence theory and two-stage stochastic programming, for selecting appropriate resilience strategies in resilient supply chain network design (RSCND) to address the challenges that have received little attention in the literature, particularly in the context of natural, man-made, and pandemic-oriented disruptions.	Mathematical modelling	---	This study presented a novel approach that considers the positive and negative synergistic effects of resilience strategies, referred to as supply chain dynamics, and examines their interactions under resource constraints. This approach enables the determination of the most suitable combination of resilience strategies and investigates the criticality of nodes and the network's susceptibility across different echelons.
Gupta *et al.* (2023)	This study aims to identify and prioritise critical criteria that impact the performance of food supply chains under uncertainty, focusing on ensuring food security and safety in Supply Chain Management (SCM).	Delphi method and fuzzy AHP	---	This study identified and classified the predominant criteria affecting food supply chains into four groups: Resilience and Flexibility, Transparency and Traceability, Communication and Collaboration, and Regulation and Standardization. This

				categorisation provides insights into managing uncertainty and avoiding undesirable consequences in SCM.
Rujeerapaiboon *et al.* (2023)	This study aims to investigate the resiliency of long chains in dealing with demand uncertainty and plant disruptions, considering their effectiveness compared to fully flexible manufacturing systems, despite being sparse and economical.	Mathematical modelling	---	This research contributes twofold: firstly, establishing the connection between long and open chains, and secondly, proposing a simple greedy algorithm to characterise the performance of an open chain given plant disruptions and product demands. Additionally, a pair of Markov chains is developed to compute the load of the open chain's dedicated and flexible arcs, enabling a detailed examination of the expected performance of the long chain.
Li *et al.* (2023)	This study investigates the impact of private demand information sharing on the supplier's decision to adopt backup production in a supply chain context with supply disruption risk during crisis-like situations such as the COVID-19 outbreak.	Mathematical modelling	---	This research contributes by uncovering the cutoff structure of the supplier's equilibrium decision regarding adopting backup production when the manufacturer shares demand information. Additionally, the study examines the effect of information sharing on backup decisions, revealing that it can either impede or promote the adoption of backup production depending on the demand potential.

Appendix B

Table B1: Studies on recovery strategies and modelling for supply chain risks

Authors	Nature of Contributions	Methodology Used
Munir et al. (2020)	Provided the framework on how to predict the consequences of the pandemic on SCs	AnyLogistix simulation and optimisation software
Paul et al. (2020b)	Proposed strategies to mitigate the impacts of disruptions on SCs during COVID-19	Mathematical modelling
Siva Kumar et al., (2020)	Proposed a framework called SAP-LAP to analyse the SC resilience building and improvement	Theory building
Alix et al. (2019)	Provided a synopsis of the methodologies that are presently used for alleviating SC disruptions	Literature review
Ivanov (2020b)	Offered a visible SC framework that can help firms to recover and rebuild their SC after global pandemics like COVID-19	Model development
Ortega-Jimenez et al. (2020)	Contributed to determining how reconfigurable technology is effective in achieving plant responsiveness as a part of resilient SC	Empirical study by cross-sectional questionnaire
Remko (2020)	Suggested a strategy for dissolving the gap between SC resilience research and attempts in industry to develop a more resilient SC	Survey
Ivanov (2020)	Offered an analysis for anticipating both short- and long-term consequences of the pandemic on the SCs, together with managerial insights	Simulation by AnyLogistix simulation and optimisation software
Hobbs (2020)	The consequences of demand side shocks on food SCs are discussed, which included a study of consumer panic-buying behaviours concerning essential items and the sudden change in consumption patterns	Survey
Sharma et al. (2020)	Discovered that firms are facing difficulties regarding demand-supply fluctuation, and formation of a resilient SC based on data from NASDAQ 100 firms	Social network survey
Mani et al. (2020)	Developed and empirically examined a model that proposed social network relationships and consumer-oriented performance as the antecedent and result, respectively, of SC resilience	Review and survey
Fosso Wamba et al. (2020)	Aimed to scrutinise the probable influence of blockchain on SC performance	Survey and model testing
Parast (2020)	Building on dynamic capability theory revealed that a firm's financing in R&D can be regarded as strengthening the firm's resilience capability	Structural equation modelling
Voldrich et al. (2020)	Proposed numerically how to decrease the processing time and cost by a minor increase in the operational risk of a food manufacturing industry	Optimisation by CPLEX (Linear Programming)

Kittipanya-ngam et al. (2020)	Discussed a framework for food SC digitalisation in the context of Thailand's food manufacturing	Case study by triangulation of data collection through semi-structured interviews, direct observations
Kamble et al. (2020)	Proposed a structure for the professionals involved in the agri-food SC that identified SC visibility and resources as the major motivation for developing data analytics potentiality and attaining the sustainable performance	Systematic literature review
Sayed et al. (2020)	Explored the effect of outsourcing versus in-house implementation modes for sustainable procurement	Multiple case study, transaction cost economics, and principal agency theory were used to justify the relationships.

Table B2: Model parameters

Notations	Descriptions
i	Retailers
j	Manufacturers
k	Suppliers
l	Manufacturer trucks
m	Supplier trucks
IR_i	Inventory holding cost for i^{th} retailer per item per day
φ_j	Fixed cost for running j^{th} manufacturer
ϑ_j	Per unit production cost of j^{th} manufacturer
IM_j	Inventory holding cost for j^{th} manufacturer per item per day
ψ_j	Fixed cost for managing transport operations at j^{th} manufacturer
ω_j	Variable cost for transporting products at j^{th} manufacturer (per unit product per unit time)
η_j	Shortage cost for j^{th} manufacturer (per unit product)
ρ_k	Production cost for raw materials supplied by k^{th} supplier
θ_k	Fixed cost for managing transport operations at k^{th} supplier
υ_k	Variable cost for transporting products at k^{th} supplier (per unit product per unit time)
s_j	reordering point at j^{th} manufacturer
S_j	order size at j^{th} manufacturer
a_j	Per unit production time at j^{th} manufacturer
b_k	Per unit production time at k^{th} supplier
p_j^t	Number of products manufactured by the j^{th} manufacturer
α_{ijl}^t	Transportation time taken by truck l to transport products x_{jk}^t from j^{th} manufacturer to i^{th} retailer in time window t
β_{jkm}^t	Transportation time taken by supplier truck m to transport products y_{jk}^t from k^{th} supplier to j^{th} manufacturer in time window t
x_{ij}^t	Products transported from j^{th} manufacturer to i^{th} retailer in time window t
y_{jk}^t	Products transported from k^{th} supplier to j^{th} manufacturer in time window t
τ	Time window
Q_j^t	Average inventory level at j^{th} manufacturer in time window t

R_i^t	Average inventory level at i^{th} retailer in time window t
d_j^t	Number of products that were not delivered to the retailer within a week at j^{th} manufacturer in time window t
$\sum_j x_{jk}^t$	Number of products supplied to the i^{th} customer
$\sum_j y_{jk}^t$	Number of products supplied by the k^{th} supplier

Table B3: Description of agents

Agent Name	Attributes	Functions
Retailer agents	Name, location (latitude and longitude), inventory holding cost (IR_i), order size distribution and inter-arrival time distribution for the orders.	These agents generate orders (represented as an order agent) continuously in time to satisfy customer demand. When the order agent is generated at a given time at the retail agent, the order is allocated to the most preferred manufacturer.
Manufacturer agents	Name, location (latitude and longitude), reordering point (s_j), order size (S_j), inventory holding cost (IM_j), shortage cost (per unit per day), production fixed cost (φ_j), production variable cost (ϑ_j), transportation fixed cost (ψ_j), transport variable cost (ω_j), production time (a_j), shortage cost (η_j) for the loss of goodwill/reputation due to delayed delivery.	Manufacturing agents receive an order from a retailer agent; they try to fulfil the order through its make-to-stock inventory of finished products (Q_j^t) and a set of available trucks. If the inventory levels drop lower than the reordering level (s_j), then an order is sent to the suppliers to supply a fixed quantity of raw material and/or components (S_j) required to replenish the stock of finished products.
Supplier agents	Name, location (latitude and longitude), production cost (ρ_k), transportation fixed cost (θ_k), transport variable cost (υ_k), production time (b_k).	The role of these agents is to produce the components (in a make-to-order environment) and transport it to the respective manufacturer through their set of trucks.
Order agents	Order ID, order size, and retail agent ID.	These agents act as a flow entity in the simulation model, representing the demand from the retailers. Order agents are created stochastically at the retail agents with predefined order size distribution and at the predefined inter-arrival time distribution. The order agents are passed on to relevant manufacturers for order fulfilment.
Truck agent at manufacturers	N/A	These agents represent the manufacturer-owned trucks needed to ship the finished goods to the retail agents.
Order supplier agent	N/A	These agents act as another flow entity in the simulation model, which represents the orders made by manufacturers to the suppliers to get the stock of components/raw materials needed for manufacturing the finished products.
Truck agents at suppliers	N/A	These agents represent the supplier-owned trucks that ship the components/raw materials to the manufacturer.
Evaluation agent	N/A	This agent interacts with all the agents in the system to record key performance indicators of the agents in the current SC. They assess key metrics in the respective SC stages, including MCs, sourcing cost, TC at the manufacturing and supplier stage, ICs at supplier,

		manufacturer, and retail, ShCs, products/components produced/shipped/received.

The following equations present the cost metrics that were evaluated by the agent in each of the periods:

Manufacturing Cost in the time window t $= \sum_j \varphi_j . \tau + \sum_j \vartheta_j . p_j^t + \sum_j \sum_k \rho_k . y_{jk}^t$

Manufacturing Inventory Cost in the time window t $= \sum_j IM_j . Q_j^t$

Customer Inventory Cost in the time window t $= \sum_i IR_i . R_i^t$

Transport cost at the manufacturing stage in the time window t $= \sum_j \psi_j . \tau + \sum_l \sum_i \sum_j \omega_j . x_{ij}^t . \alpha_{ijl}^t$

Transport cost at the supplier stage in the time window t $= \sum_k \theta_k . \tau + \sum_m \sum_j \sum_k \upsilon_k . y_{jk}^t . \beta_{jkm}^t$

Shortage cost at the manufacturing stage in the time window t $= \sum_j d_j^t . \eta_j$

Total cost in time window t $= \sum_j \varphi_j . \tau + \sum_j \vartheta_j . p_j^t + \sum_j \sum_k \rho_k . y_{jk}^t + \sum_j IM_j . Q_j^t + \sum_i IR_i . R_i^t + \sum_j \psi_j . \tau + \sum_l \sum_i \sum_j \omega_j . x_{ij}^t . \alpha_{ijl}^t + \sum_k \theta_k . \tau + \sum_m \sum_j \sum_k \upsilon_k . y_{jk}^t . \beta_{jkm}^t + \sum_j d_j^t . \eta_j$

Table B4: Parameters used for customer agents

Customer ID	Customer name	State code	Postcode	Latitude	Longitude	Initial demand (cartons)	Demand rate (cartons per day)
378	Ashby Heights	NSW	2463	-29.4137	153.179	250	Uniform (1,4)
379	Ashby Island	NSW	2463	-29.431	153.203	250	Uniform (1,4)
380	Ashcroft	NSW	2168	-33.9176	150.899	250	Uniform (1,4)
382	Ashfield	NSW	2131	-33.8895	151.126	250	Uniform (1,4)
383	Ashfield	QLD	4670	-24.8728	152.396	250	Uniform (1,4)
385	Ashford	NSW	2361	-29.3213	151.096	250	Uniform (1,4)
386	Ashford	SA	5035	-34.9487	138.574	250	Uniform (1,4)
387	Ashgrove	QLD	4060	-27.4456	152.992	250	Uniform (1,4)
388	Ashley	NSW	2400	-29.3178	149.808	250	Uniform (1,4)
389	Ashmont	NSW	2650	-35.1232	147.33	250	Uniform (1,4)
390	Ashmore	QLD	4214	-27.9864	153.382	250	Uniform (1,4)
391	Ashton	SA	5137	-34.9397	138.737	250	Uniform (1,4)
392	Ashtonfield	NSW	2323	-32.7738	151.601	250	Uniform (1,4)
393	Ashville	SA	5259	-35.5105	139.366	250	Uniform (1,4)
394	Ashwell	QLD	4340	-27.6285	152.56	250	Uniform (1,4)
395	Ashwood	VIC	3147	-37.8647	145.093	250	Uniform (1,4)
396	Aspendale	VIC	3195	-38.0265	145.102	250	Uniform (1,4)
397	Aspendale Gardens	VIC	3195	-38.0235	145.118	250	Uniform (1,4)

Table B5: Parameters used for manufacturing agents

Manufacturer name	Latitude	Longitude	Number of trucks	Production capacity (Cartons)	State	Manufacturing fixed cost (A$)	Manufacturing item cost (A$ per carton)	Holding cost (A$ per carton per day)	Shortage cost (A$ per carton per day)	Transportation cost to customer (A$)	Minimum inventory policy (s)	Maximum inventory policy (S)	Initial inventory amount (cartons)
Melbourne	-37.7459	144.77	15	50	VIC	A$50000	5	0.75	4	500	1800	3000	5000
Sydney	-33.8688	151.209	10	50	NSW	A$51000	5	0.75	4	550	1500	3200	5000
Brisbane	-27.4698	153.025	12	100	QLD	A$53000	5	0.75	4	520	1600	3600	5000

Table B6: Parameters used for supplier agents

Name of supplier	**latitude**	**longitude**	**State**	**Production time (hour)**	**Number of trucks**	**Manufacturing close**	**Material cost (A$ per carton)**	**Transportation costs to manufacturer (A$)**
Gosford	-33.425	151.342	NSW	1.1	5	1	25	500
Bendigo	-36.7578	144.279	VIC	1.05	6	0	25	500
Gladstone	-23.8431	151.268	QLD	1.12	6	2	25	500
Glenore Grove	-27.53	152.407	QLD	0.95	6	2	25	500
Bankstown	-33.9173	151.036	NSW	0.99	7	1	25	500
Mildura	-34.2068	142.136	VIC	0.97	5	0	25	500
Wollongong	-34.4251	150.893	NSW	0.9	8	1	25	500

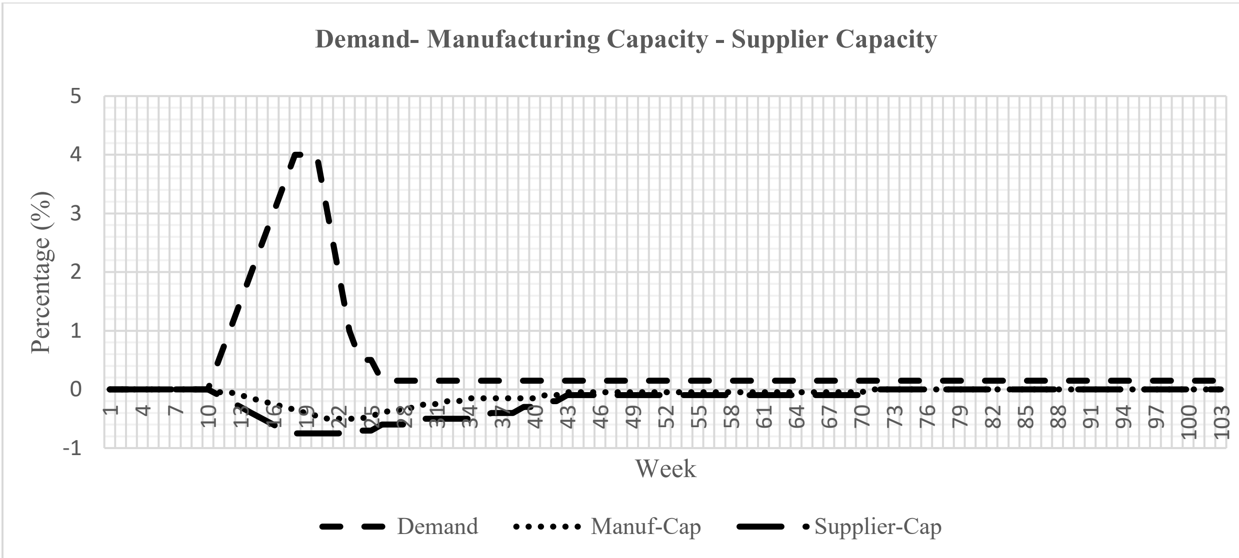

Figure B1: Changes in demand, production, and supply caused by COVID-19 pandemic situation

Appendix C

Table C1: Studies on risk management in SCs

References	Contributions/findings
Wang & Yao (2021)	This study reveals that collaborating (intertwining adaptation strategy) with other industries' transportation facilities will help fulfil delivery demands in an emergency and reduce transportation-related risks.
Papadopoulos et al. (2017)	Aid from the government can support the manufacturers in scaling up and repurposing production capabilities and reduce financial risks.
Ivanov (2020)	As an intertwining adaptation strategy, resource sharing can be easily done by horizontal and vertical collaboration to enhance sourcing and production to meet consumers' demands during a pandemic and reduce manufacturing-related risks.
Ivanov (2019)	This research finds that sub-contracting (substitution adaptation) helps to continue production during primary manufacturing facility disruption to reduce manufacturing facilities-related risks.
Ivanov (2021b)	Robot-enabled manufacturing can be adopted with human skills and intelligence to enhance production capacity even during super disruptions. Further, to make the delivery smooth during disruption, multimodal and multi-route shipments allow changes to transportation plans with alternative routes or modes of transport.
Durach et al. (2021)	Major findings of this study reveal that blockchain and advanced tracking technology help to create SC visibility, disruption identification, and recovery support. This reduces information-related risks in SCs.
Paul et al. (2017)	More collaborative distribution centres close to customer zones help increase logistics resilience and ensure smooth delivery during a disruptive situation.
Dolgui & Ivanov (2021)	With multiple suppliers as part of a substitution strategy, manufacturers can replace their suppliers in case of extraordinary disruptions and recover from supply-related risks.
Dolgui et al. (2018)	Backup sourcing as a substitution adaptation strategy helps to continue supply in case of a primary supplier failure.
Ivanov (2021c)	Local sourcing helps to enhance higher supply flexibility at lower transportation costs which may create robust redundancy in the case of the COVID-19 pandemic.
Dolgui & Ivanov (2020)	As part of the repurposing adaptation strategy, reshoring and back-shoring are used to reduce vulnerabilities and increase robustness, which helps when a super disruption such as the COVID-19 pandemic exists.
Chowdhury et al. (2021)	Nearshoring and domestic production help to reduce production vulnerability and increase robustness during disruptions. Strategic stock/risk inventory may aid in meeting fluctuating demand and eliminate stockout.
Paul & Chowdhury (2020a)	Producing adequate alternative items may aid in fulfilling the extra demand during any disruption. This is a good example of a substitution adaptation strategy to reduce production-related risks.
Aldrighetti et al. (2021)	Backup facilities (substitution adaptation strategy) help the distribution process even after the primary warehouse disruption recovery from distribution-related risks.
Tarafdar & Qrunfleh (2017)	The findings reveal that postponement helps manufacturers to respond quickly to unpredictable customer demand and improve inventory efficiency.

Manuj et al. (2014)	Product line flexibility and modularisation help respond to the fluctuation of consumers' demand during disruptions.
Ivanov & Sokolov (2019)	Keeping reserve liquidity allows the business to continue chain activities even during a pandemic and reduces financial risks.
Pavlov et al. (2019)	This study suggests that decentralised manufacturing facilities increase robustness during super disruptions and reduce manufacturing-related risks.
Ivanov (2021a)	Increasing and decreasing inventory policy during and post-disruptions will help maintain a sustainable inventory level to meet the demand that surges or decreases.
Furstenau et al. (2022)	This study examines the impact of digital technologies on the resilience of healthcare supply chains and offers guidance for decision-makers.
Bender et al. (2022)	This research examines how households have adapted to the COVID-19 pandemic by increasing food prepared at home and identifying strategies that align with practices that enhance resilience in the food supply chain.
Bag et al. (2022)	It examines how big data and predictive analytics can improve supply chain visibility and resilience in the South African mining industry under extreme weather conditions.
Ivanov & Keskin (2023)	The study presents new research on efficient, resilient supply chains in long-term crises, such as the COVID-19 pandemic.
Bastas & Garza-Reyes (2022)	This paper investigates the impact of COVID-19 on manufacturing organisations in Northern Cyprus and presents strategies used to respond to the pandemic, contributing to knowledge on manufacturing management and resilience.
Longo et al. (2022)	This article presents a simulation-based framework for manufacturing design and resilience assessment, demonstrated through a case study in the wood sector, showing that preparedness can limit damage and increase productivity in the face of disruptions.

Table C2: Adaptation strategies for supply chain risk management

SC risk level	Sub-strategies	Purposes	References
Manufacturing	Ramp-up emergency production	To meet the demand surge to avoid high shortage costs.	(Ivanov, 2021a; Pavlov et al., 2019; Rahman et al., 2021; Choi et al., 2021; Bastas & Garza-Reyes, 2022)
	Decentralising manufacturing facilities	To increase the production capacity during an emergency.	
	Sub-contracting facilities and backup factory	To continue production in the time of failure of the primary manufacturing facility due to uncertain disruption.	
	Human-robot collaboration	To maintain social distancing to stop the virus's spread and continue production during a pandemic.	
	Reshoring and nearshoring	To reduce the dependencies on manufacturing facilities in other countries	
	Product diversification and substitution	A large number of alternative items may aid in fulfilling the extra demand for essential items.	
	Re-purposing production capability	To unlock opportunities to increase production of other/similar items to meet the extra demand.	
Supply of raw material	Alternative supplier or backup sourcing	To manage sudden supply-side disruptions in existing suppliers to sustain production during disruptions.	(Chowdhury et al., 2021; Ivanov & Sokolov, 2019; Rahman et al., 2021; Wang & Yao, 2021; Choi, 2019; Bender et al., 2022)
	Multiple suppliers	If there is any disruption in one or some suppliers, other active suppliers can help supply raw materials.	
	Local sourcing	To enhance supply flexibility at lower transportation costs, which may create robust redundancy during a pandemic.	
	Emergency sourcing from other relevant industry	To increase raw material supply to meet the demand surge. In an emergency like COVID-19, facemask manufacturers can get raw materials from the garment industry.	
Transportation	Collaboration with other transporters	Collaborating with other industries' transportation facilities will help fulfil the emergency delivery demand.	(Aldrighetti et al., 2021; Li et al., 2021; Xiaoyan Xu et al., 2021; Raj et al., 2022)
	Multimodal and multi-route shipment	To reduce the risks and uncertainties in fulfilling deliveries to the retailers and consumers during the lockdowns in a pandemic.	
	Establishing more collaborative distribution centres	More collaborative distribution centres close to customer zones help increase logistics resilience and ensure smooth delivery during disruptive situations.	

	Omni-channel	It provides a seamless customer experience to get their deliveries by using online platforms during a strict lockdown.	
Demand and inventory	Strategic stock, risk inventory, and redundancy	Manufacturers with a large inventory can withstand a long period of scarcity caused by a natural disaster or strike action.	(Liu et al., 2016; Wang & Yao, 2021; Furstenau et al., 2022)
	Maintaining minimum inventory policy	To have optimal inventory by increasing the frequency of orders to the suppliers.	
	Virtual stockpile pooling (VSP) system	To improve delivery in times of emergency.	

Table C3: Modelling methods to manage SC disruptions (Ivanov & Dolgui, 2021)

Network and complexity theories	Mathematical optimisation	Simulation
Bayesian networks Complexity theory Reliability theory Petri Nets Markov Chains	Mixed-integer linear programming Robust optimisation Stochastic optimisation	Agent-based simulation Discrete-event simulation System dynamics
Network-wise analysis	***Planning decisions***	***Process control***

Table C4: Parameters for manufacturing agents

Manufacturer name	Latitude	Longitude	Trucks	Manufacturing capacity (Units)	State	Manufacturing fixed cost (A$)	Manufacturing item cost (A$ per unit)	Holding cost (A$ per unit per day)	Shortage cost (A$ per unit per day)	Transportation cost to the retailer (A$)	ROP (s)	Order up to level (S)
Melbourne	-37.7459	144.77	10	90	VIC	50000	5	0.75	4	500	1000	3000
Sydney	-33.8688	151.209	10	80	NSW	51000	5	0.75	4	550	1000	3000
Brisbane	-27.4698	153.025	10	100	QLD	53000	5	0.75	4	520	1000	3000

Appendix D

Table D1: Summary of previous studies on SC disruption and panic-buying management strategies and methods

References	Contributions	Methods
Wang *et al*. (2010)	The paper examined two mitigation strategies using a supply chain network: dual sourcing and process improvement.	Mathematical and optimisation model
Dong and Tomlin (2012)	This paper proposes several schemes to improve SCRES by reducing its vulnerability and enhancing its adaptive capability.	Mathematical and optimisation model
Azadeh *et al.* (2014)	To recover from disruptions in transportation, resilience strategies and modelling were presented in this paper.	Fuzzy data envelopment analysis and visual simulation language for analogue modelling.
Brandon-Jones *et al.* (2014)	This study aimed to determine how information sharing impacts connectivity, visibility, and performance concerning SCRES.	Survey, multiple regression analysis, and hierarchical moderation tests
Gao (2015)	A combination of dynamic risk management, contracting, and collaborative forecasting was examined in this paper.	Mathematical and optimisation model
Serpa and Krishnan (2017)	The paper demonstrates how insurance can be used strategically to prevent excessive free-riding by other firms in a multi-firm setting.	Mathematical and optimisation model
Can Saglam *et al*. (2020)	This study aimed to bridge the gap between proactive risk-mitigation strategies and SC risk management performance, namely flexibility, resilience, and responsiveness in the supply chain (SC).	PLS-based SEM
Shen and Sun (2021)	As part of its analysis of quantitative operational data, the paper addressed challenges supply chains faced during the pandemic in China. Furthermore, it presented practical responses to the pandemic.	Measuring quantitative operational data
Moosavi and Hosseini (2021)	This study used a simulation to evaluate the resilience of the supply chain.	Discrete event simulation
Rahman *et al*. (2021)	This paper examined a set of congruent strategies and recovery plans to minimise the cost and maximise the availability of essential items caused by global SC disruptions.	Agent-based simulation model
van Hoek and Dobrzykowski (2021)	This paper aims to investigate whether the pandemic influences reshoring decisions, and if so, which supply chain sectors may be affected.	Case study
Karmaker *et al.* (2021)	The study aims to identify factors that enable sustainable SCs to solve COVID-19 disruptions in Bangladesh, highlighting the necessity for funding and formulating policies for sustainability over the long run.	Pareto analysis, fuzzy theory, TISM, and MICMAC
Barnes *et al.* (2021)	This study examines panic-buying during the COVID-19 pandemic by analysing Twitter data from Italy and finds that anxiety and lack of perceived control drive purchasing behaviour,	Compensatory control theory (CCT), text analytics, and advanced data modelling

	which is moderated by government announcements and the utilitarian qualities of the goods.	
Gupta *et al.* (2021)	The study investigates the impact of the COVID-19 pandemic on consumer stockpiling and impulse buying behaviour in India and finds that the pandemic had a significant impact on consumer behaviour, with implications for supply chain management and reducing consumer fear and anxiety.	Online survey questionnaire and structural equation modelling
Li *et al.* (2021)	This study aims to better understand the factors contributing to panic-buying during the COVID-19 pandemic. The findings indicate that these factors include reflective thinking, environmental stimuli, and perceptions of susceptibility, severity, social influence, social norm, affective response, and perceived lack of control, with the latter factor acting as a positive moderator of the affective response's impact on panic-buying.	Structural equation modelling
Dulam *et al.* (2021)	The authors have developed a model to study the impact of consumer behaviour during crises on supply chains and found that implementing a quota policy or rationing effectively reduces panic-buying, while controlling media reports or educating consumers can also reduce demand.	Agent-based model
Nasir *et al.* (2022)	The paper examines factors affecting the viability of supply chains for SMEs during the COVID-19 pandemic and finds that creating a digital twin, connecting SCs, funding SCs, and developing policies for health protocols are crucial elements.	Pareto analysis, grey theory, and total interpretive structural modelling (TISM)
Tian & Mei (2022)	To address the COVID-19 dilemma and aid in future national security decision-making, the research suggests a model for a government-led system that uses mixed-integer optimisation to choose partners for swift and reliable regional PPE manufacture.	Mixed-integer optimisation
Yuen *et al.* (2022)	The study explains the social determinants of panic-buying behaviour, including non-coercive social influence, social norms, and observational learning, and their impact on the perception of scarcity which can lead to panic-buying directly or indirectly through anticipated regret, and contributes to the limited literature on panic-buying, providing a theoretical model and analysis of data through an online survey.	Theoretical modelling and empirical analysis through an online survey
Li & Dong (2022)	A game-theoretic supply chain model is developed to evaluate the impact of government regulations on the shortage of life-saving goods and profit within the supply chain during a pandemic, considering consumer panic-buying, insufficient capacity, price surges, and controls on the supply and demand side, and providing simple prescriptions for policymakers to design effective regulation.	Game-theoretic supply chain model

Table D2: Description of agents of the proposed model (Rahman *et al*. 2021)

Agent Name	Functions
Retailer agents	Retail agents generate order agents continuously in response to customer demand. When an order is generated, it is allocated to the manufacturer with the highest preference.
Manufacturer agents	Once a manufacturing agent receives an order from a retailer agent, the agent tries to meet the order using its make-to-stock inventory of finished products (Q_j^t) and a set of available trucks. A request is sent to the suppliers if the inventory level drops below the reordering level (s_j), requesting a fixed amount of raw material and/or components (S_j) to replenish the stock of finished goods.
Supplier agents	The responsibility of this agent is to manufacture the components according to the specific order and deliver them to the relevant manufacturer via trucks. This takes place within a make-to-order environment.
Order agents	Retail agents randomly create order agents with predefined distributions for order size and arrival times. These order agents represent the retail demand in the simulation model. The order agents transfer the orders to the appropriate manufacturers to satisfy the order.
Truck agent at manufacturers	Using these agents, the completed goods are transported from the manufacturer to the retail agents via trucks.
Order supplier agent	In the simulation model, these agents function as an entity that stands for the orders from manufacturers to suppliers for the components and raw materials required for producing the final products.
Truck agents at suppliers	The suppliers employ these agents to transport the components or raw materials to the manufacturers.
Evaluation agent	To keep track of the main performance indicators of the current supply chain, this agent interacts with all the other agents within the system. These indicators include manufacturing costs (MCs), sourcing costs, transportation costs (TCs) at both the manufacturer and supplier levels, inventory costs (ICs) at the supplier, manufacturer, and retail levels, shipment costs (ShCs), distribution costs (DisCs), and the products/components produced, shipped, and received at each stage of the supply chain.

Table D3: Model parameters (Rahman *et al*. 2021)

Notations	**Descriptions**
i	Retailers
j	Manufacturers
k	Suppliers
l	Manufacturer trucks
m	Supplier trucks
D	Demand
C_i	i^{th} Supplier's capacity
IR_i	Holding costs for inventories for i^{th} retailer (each item, per day)
φ_j	Fixed operating cost for j^{th} manufacturer
ϑ_j	Manufacturing cost per unit of j^{th} manufacturer
IM_j	Inventory holding cost for j^{th} manufacturer (each item, per day)
ψ_j	Fixed cost associated with managing transport services at j^{th} manufacturer
ω_j	Variable transportation cost at j^{th} manufacturer (per unit item per unit time)
η_j	Shortage cost for j^{th} manufacturer (per unit item)
λ_j	Discount cost for j^{th} manufacturer (per unit item)
ρ_k	Cost of manufacturing raw materials supplied by k^{th} supplier
θ_k	Fixed cost associated with managing transport services at k^{th} supplier
υ_k	Variable transportation cost k^{th} supplier (per unit item per unit time)
s_j	ROP at j^{th} manufacturer
S_j	Order-size at j^{th} manufacturer
a_j	Per unit manufacturing time at j^{th} manufacturer
b_k	Per unit manufacturing time at k^{th} supplier
p_j^t	Manufactured item by the j^{th} manufacturer
α_{ijl}^t	Transport time by truck l to carry items x_{jk}^t from j^{th} manufacturer to i^{th} retailer in time window t
β_{jkm}^t	Transport time for supplier truck m to carry items y_{jk}^t from k^{th} supplier to j^{th} manufacturer in time window t
x_{ij}^t	Items transported from j^{th} manufacturer to i^{th} retailer in time window t
y_{jk}^t	Items transported from k^{th} supplier to j^{th} manufacturer in time window t
τ	Time window
Q_j^t	Inventory level on average at j^{th} manufacturer in time window t
R_i^t	Inventory level on average at i^{th} retailer in time window t
d_j^t	Undelivered items to retailer within a week at j^{th} manufacturer in time window t
w_j^t	Undelivered items to retailer within a specified time at j^{th} manufacturer in time window t (for the consideration of discount cost)
$\sum_j x_{jk}^t$	Items supplied to the i^{th} retailer
$\sum_j y_{jk}^t$	Raw materials supplied by the k^{th} supplier

Table D4: Cost metrics assessed in the ABM model agents (Rahman *et al*. 2021)

SC costs	**Equation**
Manufacturing cost in time window t	$\sum_j \varphi_j.\tau + \sum_j \vartheta_j.p_j^t + \sum_j \sum_k \rho_k.y_{jk}^t$
Manufacturing inventory cost in time window t	$\sum_j IM_j.Q_j^t$
Retailer inventory cost in time window t	$\sum_i IR_i.R_i^t$
Transport cost at the manufacturing stage in time window t	$\sum_j \psi_j.\tau + \sum_l \sum_i \sum_j \omega_j.x_{ij}^t.\alpha_{ijl}^t$
Transport cost at the supplier stage in time window t	$\sum_k \theta_k.\tau + \sum_m \sum_j \sum_k \upsilon_k.y_{jk}^t.\beta_{jkm}^t$
Shortage cost at the manufacturing stage in time window t	$\sum_j d_j^t.\eta_j$
Discount cost at the manufacturing stage in time window t	$\sum_j w_j^t.\lambda_j$
Total supply chain cost in time window t	$\sum_j \varphi_j.\tau + \sum_j \vartheta_j.p_j^t + \sum_j \sum_k \rho_k.y_{jk}^t + \sum_j IM_j.Q_j^t +$ $\sum_i IR_i.R_i^t + \sum_j \psi_j.\tau + \sum_l \sum_i \sum_j \omega_j.x_{ij}^t.\alpha_{ijl}^t + \sum_k \theta_k.\tau +$ $\sum_m \sum_j \sum_k \upsilon_k.y_{jk}^t.\beta_{jkm}^t + \sum_j d_j^t.\eta_j + \sum_j w_j^t.\lambda_j$

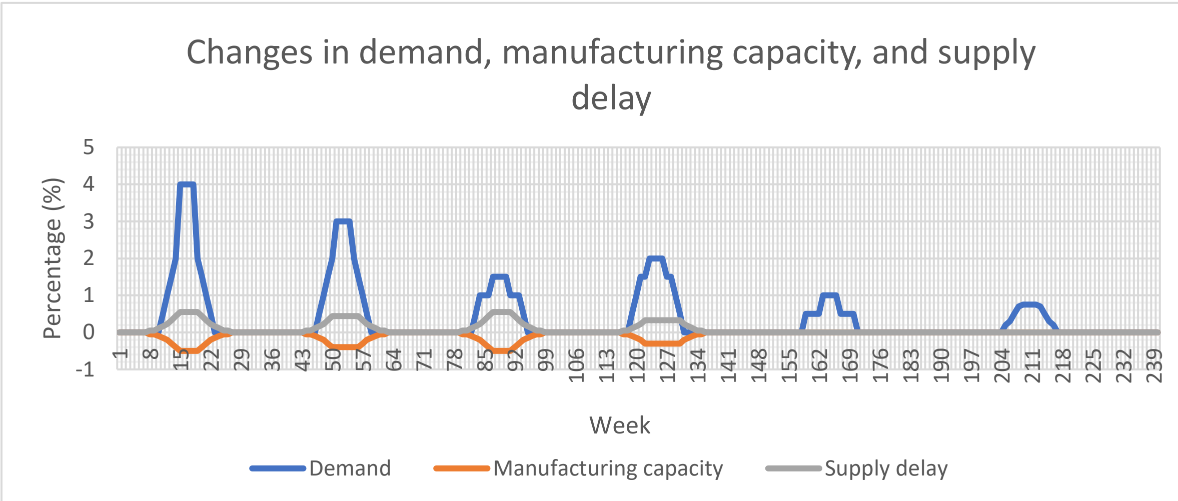

Figure D1: Changes in demand, manufacturing capacity, and supply delay

Table D5: Parameters used for retailer agents (Rahman *et al*. 2021)

Retailer ID	**Customer name**	**State code**	**Postcode**	**Latitude**	**Longitude**	**Initial demand (cartons)**	**Demand rate (cartons per day)**
378	Ashby Heights	NSW	2463	-29.4137	153.179	250	Uniform (1,4)
379	Ashby Island	NSW	2463	-29.431	153.203	250	Uniform (1,4)
380	Ashcroft	NSW	2168	-33.9176	150.899	250	Uniform (1,4)
382	Ashfield	NSW	2131	-33.8895	151.126	250	Uniform (1,4)
383	Ashfield	QLD	4670	-24.8728	152.396	250	Uniform (1,4)
385	Ashford	NSW	2361	-29.3213	151.096	250	Uniform (1,4)
386	Ashford	SA	5035	-34.9487	138.574	250	Uniform (1,4)
387	Ashgrove	QLD	4060	-27.4456	152.992	250	Uniform (1,4)
388	Ashley	NSW	2400	-29.3178	149.808	250	Uniform (1,4)
389	Ashmont	NSW	2650	-35.1232	147.33	250	Uniform (1,4)
390	Ashmore	QLD	4214	-27.9864	153.382	250	Uniform (1,4)
391	Ashton	SA	5137	-34.9397	138.737	250	Uniform (1,4)
392	Ashtonfield	NSW	2323	-32.7738	151.601	250	Uniform (1,4)
393	Ashville	SA	5259	-35.5105	139.366	250	Uniform (1,4)
394	Ashwell	QLD	4340	-27.6285	152.56	250	Uniform (1,4)
395	Ashwood	VIC	3147	-37.8647	145.093	250	Uniform (1,4)
396	Aspendale	VIC	3195	-38.0265	145.102	250	Uniform (1,4)
397	Aspendale Gardens	VIC	3195	-38.0235	145.118	250	Uniform (1,4)

Table D6: Parameters for manufacturing agents (Rahman *et al*. 2021)

Manufacturer name	**Latitude**	**Longitude**	**Trucks**	**Manufacturing capacity (Units)**	**State**	**Manufacturing fixed cost (A$)**	**Manufacturing item cost (A$ per unit)**	**Holding cost (A$ per unit per day)**	**Shortage cost (A$ per unit per day)**	**Transportation cost to retailer (A$)**	**ROP (s)**	**Order-size (S)**	**Initial inventory amount**
Melbourne	-37.7459	144.77	10	90	VIC	50000	5	0.75	4	500	1000	3000	5000
Sydney	-33.8688	151.209	10	80	NSW	51000	5	0.75	4	550	1000	3000	5000
Brisbane	-27.4698	153.025	10	100	QLD	53000	5	0.75	4	520	1000	3000	5000

Table D7: Parameters used for supplier agents (Rahman *et al*. 2021)

Name of supplier	**latitude**	**longitude**	**State**	**Production time (hour)**	**Number of trucks**	**Manufacturing close**	**Material cost (A$ per carton)**	**Transportation costs to manufacturer (A$)**
Gosford	-33.425	151.342	NSW	1.1	5	1	25	500
Bendigo	-36.7578	144.279	VIC	1.05	6	0	25	500
Gladstone	-23.8431	151.268	QLD	1.12	6	2	25	500
Glenore Grove	-27.53	152.407	QLD	0.95	6	2	25	500
Bankstown	-33.9173	151.036	NSW	0.99	7	1	25	500
Mildura	-34.2068	142.136	VIC	0.97	5	0	25	500
Wollongong	-34.4251	150.893	NSW	0.9	8	1	25	500

Table D8: Comparison of implemented strategies to baseline disrupted scenario using confidence intervals

Parameters	Confidence Interval [Percentile range of change] at 95% CI		
	Strategy 1	**Strategy 2**	**Strategy 3**
Backorder level	[-99.75%, -99.26%] at 95%	[-97.92%, -96.55%] at 95%	[-88.55%, -86.69%] at 95%
TSCCs	[-83.71%, -83.49%] at 95%	[-78.50%, -78.24%] at 95%	[-66.27%, -65.46%] at 95%
MCs	[-10.68%, -6.82%] at 95%	[-10.39%, -7.15%] at 95%	[-9.80%, -7.39%] at 95%
ICs	[-1.09%, 1.71%] at 95%	[-3.89%, 0.52%] at 95%	[37.49%, 41.50%] at 95%
TCs	[4.20%, 5.82%] at 95%	[6.14%, 6.52%] at 95%	[7.18%, 7.41%] at 95%
ShCs	[-99.75%, -99.26%] at 95%	[-97.92%, -96.55%] at 95%	[-88.69%, -86.55%] at 95%
DisCs	[-90.28%, -89.64%] at 95%	[-66.30%, -64.79%] at 95%	[-30.47%, -29.33%] at 95%
Output (Product manufactured)	[7.40%, 18.26%] at 95%	[9.51%, 17.01%] at 95%	[12.78%, 14.87%] at 95%

Table D9: t-test comparison of implemented strategies to baseline disruption

Parameters	P-values		
	Strategy 1	**Strategy 2**	**Strategy 3**
Backorder level	0	0	0
TSCCs	0	0	0
MCs	0.00000743	0.00000127	0.00000013
ICs	0.94593260	0.57293529	0
TCs	0.00062232	0.00016010	0.00002058
ShCs	0	0	0
DisCs	0	0	0
Output (Product manufactured)	0.00848306	0.00126331	0.00000273

Table D10: Synopsis of sensitivity analysis

Parameters	Rate of change	Variation in backorder level (Avg/Week)	Variation in economic performances of SCs (Avg/Week)						Variation in the number of products produced (Avg/Week)
		Unmet demand	**TSCCs**	**MCs**	**ICs**	**TCs**	**ShCs**	**DiCs**	**Number of products manufactured**
Demand	**+15%**	+17.92%	+13.36%	-0.15%	-2.28%	-2.04%	+17.92%	+6.71%	+0.73%
	-15%	-22.46%	-16.66%	-0.30%	-7.98%	+3.02%	-22.46%	-6.64%	-1.13%
Manufacturing capacity	**+15%**	-10.29%	-7.23%	+0.73%	-5.19%	+0.90%	-10.29%	-0.87%	+0.49%
	-15%	+0.83%	+0.51%	+0.29%	-3.91%	-0.11%	+0.83%	-0.42%	-0.89%
ROP (s_j)	**+15%**	-3.63%	-2.60%	+0.66%	-3.33%	+0.40%	-3.63%	-0.94%	-0.08%
	-15%	+1.17%	+0.91%	-0.39%	-5.95%	+0.18%	+1.17%	+1.41%	-0.32%
Order size (S_j)	**+15%**	-3.38%	-1.67%	+6.41%	+5.23%	+0.32%	-3.38%	-1.95%	-0.07%
	-15%	-5.70%	-4.93%	-5.97%	-13.08%	+0.55%	-5.70%	+0.01%	+0.20%
Combined change in demand, manufacturing capacity, ROP and order size	**+15%**	+17.36%	+13.58%	+7.05%	+4.65%	-2.32%	+17.36%	+3.48%	-0.07%
	-15%	-27.07%	-20.78%	-6.25%	-17.86%	+3.92%	-27.07%	-6.55%	+0.42%

Appendix E

Table E1: Summary of SC resilience and sustainable strategies from the literature

Authors	SC resilience and sustainable strategies to manage disruptions
Ghosh & Shah (2015)	In extreme disruption, meeting customers' excess demand (caused by panic purchasing) contributes to the supply chain's social performance.
Ivanov (2021b)	During mega disruptions like the COVID-19 pandemic, following health and safety guidelines throughout supply chains support the supply chain's social performance.
Vilarinho et al. (2018)	Increasing bio-degradable or organic product manufacturing capability aids the supply chain's environmental performance.
Pivnenko et al. (2016)	The circular economy, sustainable logistics, and waste management capabilities ensure the development of the supply chain's environmental performance.
Aldrighetti et al. (2021)	Reduced carbon emission measures promote greater environmental sustainability across the supply chain, particularly in the transportation sector.
Rahman et al. (2021)	Reducing shortfall costs by meeting consumer demand and orders rapidly improves the supply chain's economic performance.
Shahed et al. (2021)	Profit may be maximised by lowering overall supply chain expenses, and company diversification helps to preserve the supply chain's economic performance.
Mehrotra et al. (2020)	Increasing shared resources through vertical and horizontal collaboration helps to sustain economic performance during mega disruptions such as the COVID-19 pandemic.
Pettit et al. (2019)	Sharing financial resources among vertical supply chains and other horizontal organisations aids in maintaining economic performance even in the face of a super disruption such as the COVID-19 pandemic.
Ivanov (2021a)	Supplier segmentation aids in the identification of important suppliers and the development of an emergency plan.
Dolgui et al. (2018)	Backup sourcing aids in continuing supply during a primary source breakdown.
Dolgui & Ivanov (2020)	Reshoring and back shoring serve to minimise susceptibility and boost robustness during mega interruptions such as the COVID-19 pandemic.
Pavlov et al. (2019)	Decentralised manufacturing facilities improve resilience during major disruptions such as the COVID-19 pandemic.
Paul et al. (2017)	More distribution centers in customer zones help to boost logistics resilience and assure seamless delivery during turbulent situations.
Ivanov (2017)	Big-data analytics aid in the extraction of data for continuous monitoring, risk and opportunity mapping, and supply chain optimisation.
Ivanov & Sokolov (2019)	Keeping reserve liquidity helps the company to continue chain operations even during major disruptions like the COVID-19 pandemic.