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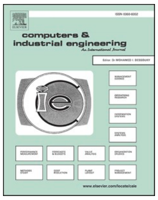

An agent-based model for supply chain recovery in the wake of the COVID-19 pandemic

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ABSTRACT

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, 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 study aimed to examine a set of congruent strategies and recovery plans to minimize the cost and maximize the availability of essential items to respond to global SC disruptions. We used facemask SCs as an example and simulated the current state of its supply and demand using the agent-based modeling method. We proposed two main recovery strategies relevant to building emergency supply and extra manufacturing capacity to mitigate SC disruptions. Our findings revealed that minimizing the risk response time and maximizing the production capacity helped essential item manufacturers meet consumers' skyrocketing demands and timely supply to consumers, reducing financial shocks to firms. Our study suggested that delayed implementation of the proposed recovery strategies could lead to supply, demand, and financial shocks for essential item manufacturers. This study scrutinized 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.

1. Introduction

> **'Companies need an understanding of their exposure, vulnerabilities, and potential losses to inform resilience strategies.' – McKinsey Global Institute Report (Aug 2020).**

New research from the McKinsey Global Institute states that supply chain (SC) disruptions lasting a month or longer occur every 3.7 years on average (McKinsey & McKinsey, 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, having a devastating impact on the SCs and operations of businesses globally (Ivanov, 2020a). 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).

Within the domain of risks and vulnerabilities, SC risks are mainly categorized as "operational" and "disruption" risks (Ivanov, 2020a). Operational risks refer to day-to-day disruptions in lead time, delivery, demand fluctuation, and so on (Govindan et al., 2020; Hobbs, 2020; Kilpatrick et al., 2020; F. Li et al., 2010). Disruption risks represent major interruptions caused by low-frequency, high-impact events (Candeias et al., 2018; Ivanov, 2020a). For example, cyber-attacks, the supplier's financial situation, political challenges, and natural

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catastrophes (Ivanov et al., 2017). The majority of SC risk literature has focused on risk identification, assessment, and mitigation to date, while minimal research regards the risk recovery topic (Ho et al., 2015). Risk recovery refers to an SC's capability to respond to a disruptive event effectively and efficiently so that it can return to its original or even better state (Hobbs, 2020; F. Li et al., 2010). The two main advantages of implementing a risk recovery strategy are 1) reducing the negative impacts of a risk event and 2) enabling the SC to quickly return to a new equilibrium status. Many firms and SCs can identify risk and make assessments. Still, most manufacturers of essential items, such as facemasks, struggle to identify appropriate risk recovery strategies to recover from the disrupted event caused by COVID-19, especially related to the demand spike (Wu et al., 2020).

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. How can SC decision-makers assess procurement and manufacturing improvements to meet the demand after implementing these strategies?

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). Thus, the present study aimed to understand and evaluate the appropriate recovery strategies for mitigating the supply–demand fluctuations for essential items and considered the following research objectives:

1. Determine the impacts of pandemic situations on the SCs of essential items and identify strategies to recover from disruptions based on the existing literature.
2. Propose appropriate strategies and recovery plans to promptly meet the growing demand for essential items during a global crisis.
3. Develop an agent-based simulation model to assist SC stakeholders as they manufacture essential products under such circumstances; henceforth, allow stakeholders to view and assess the prediction of disruption impacts, including the scenario analysis, which will enable them to assess the benefits of proposed strategies and recovery plans to recover from the COVID-19 pandemic disruptions.

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 simulation-based methodology can analyze and anticipate the impacts of a pandemic situation on SCs using AnyLogic—a simulation modeling software program. This simulation modeling was instrumental in highlighting different strategies that can bring resilience to SCs. They can then be implemented when there is a global shortage of essential items in the future.

The rest of the paper is organized as follows. In Section 2, we review the literature on the impact of extraordinary disruptions on SCs and the recovery strategies implemented. Section 3 presents a detailed description of the problem. Section 4 proposes strategies and recovery plans, while Section 5 assesses their performance in dealing with demand shortages. The results and findings are analyzed and discussed in Section 6, focusing on the impact of the proposed strategies and associated recovery plans. The concluding Section 7 focuses on the contributions made, practical implications, limitations, and future research directions.

2. Literature review

A literature review was conducted on various SC disruptions and their impacts and the recovery models of disruptions. We identified research gaps that will be addressed during the present study based on our review of the current literature.

2.1. *Supply chain (SC) disruptions*

SC disruptions and risks have been studied immensely in the literature. Researchers have defined another category of SC risks in recent studies, known as extraordinary risks (Ivanov, 2020a; Paul et al., 2020b, 2020a). These risks are global SC risks that influence every SC sector and result in a significant economic crisis.

The recovery plan for SC disruption varies depending on the disruption severity (Paul et al., 2020a). Recently, Ivanov (2020a) suggested that manufacturers should strategize more robust, dynamic, and timely plans to mitigate SC disruption caused by extraordinary situations, such as the COVID-19 pandemic. The WHO reported approximately 1400–1438 epidemics during the last decade, which have had an enormous impact on global SCs (Paul et al., 2020a). The Spanish flu global pandemic in 1918 was responsible for shortages of coal worldwide (Clay et al., 2018). The emergence of SARS in 2002 in China, the tsunami in Japan in 2011, the Middle East Respiratory Syndrome outbreak in 2012, and epidemics, such as Ebola in 2014, have all influenced global SCs (Govindan et al., 2020; Ivanov, 2020a; Queiroz et al., 2020). Recently, the COVID-19 pandemic has disrupted the entire SC worldwide, the severity of which is not known yet. A survey by the Institute for Supply Chain Management claimed that approximately 75% of the companies worldwide have faced capacity disruption in their SCs due to COVID-19-related transportation restrictions (Lambert, 2020).

SC disruption effects due to operational risks, such as long lead times and delivery delays, can be mitigated by appropriate strategies. Indeed, they can be anticipated and are more controllable (Ivanov et al., 2017). SC disruptions due to operational risks usually last for a short time and are referred to as short-term disruptions (Kilpatrick et al., 2020). In contrast, disruption risks (e.g., natural disasters, political instability, human-made catastrophes, strikes, and legislative problems) make the SC more vulnerable, less predictable, and less controllable (Ivanov et al., 2020). Disruption risks impose long-term effects on SCs, which call for more robust recovery planning to mitigate the normal state's disruption (Remko, 2020; Ivanov, 2019). The current pandemic has exposed global SCs to extraordinary disruptions, especially those related to the supply, production, demand, and capacity of the essential item manufacturers (Ivanov, 2020; Oxford Business Group, 2020).

The present study focused on the larger-scale disruptions of supply, production, capacity, demand, and transportation to the manufacturers caused by natural disasters, pandemics, or extraordinary disruptions. These disruptions are less predictable and controllable than the disruptions induced by operational risks in an SC.

2.2. *Impacts of extraordinary disruption on supply chains*

All disruptions have minor to severe impacts on SCs. These impacts can last for short-, medium-, and long-term durations, depending on the disruption's merit and severity (Kilpatrick et al., 2020; Li et al., 2020). Operational risks usually create short- to medium-term effects on SCs (Ivanov et al., 2014). In contrast, disruption risks caused by natural disasters and extraordinary pandemics impose long-term effects on global SCs, sometimes leading to an economic recession (Sarmah, 2020;

World Bank, 2020a). The International Monetary Fund (IMF) forecasts that the global economy will shrink by 5.2% in 2020 (IMF, 2020; World Bank, 2020b). Domestic demand, supply, trade, and finance have been severely affected by the pandemic. Indeed, the World Bank anticipates that economic activities among advanced economies are likely to shrink by 7% in 2020 (World Bank, 2020b). The World Bank (2020b) also claims that emerging markets and developing economies, as a group, are expected to shrink by 2.5% in 2020. Therefore, per capita income is projected to decline by 3.6%, causing millions of people to face extreme poverty in 2020. Therefore, the pandemic has caused a severe ***financial shock*** for firms. The demand shock, supply shock, and financial shock, termed as triple shocks, have impacted the manufacturing, sourcing, logistics, transportation, and SCs of manufacturers of essential items (Haren et al., 2020; Ivanov et al., 2020).

The ***supply shock*** caused by COVID-19 is widespread in the pandemic (Adam, 2020; International Labour Organization, 2020a). The restrictions placed on air-travel and maritime movement due to the pandemic have caused congestion at airports and seaports, resulting in delayed delivery and increased lead times (Rahimi and Talebi Bezmin Abadi, 2020). The quarantined suppliers have failed to deliver raw materials to manufacturers residing abroad due to sudden shutdowns and travel restrictions (Brinca et al., 2020; International Labor Organization, 2020b). The pandemic situation has severely disrupted local and international logistics and transportation systems (Bonadio et al., 2020). Therefore, manufacturers depending on global suppliers face a severe scarcity of raw materials (Shih, 2020). The manufacturers of essential items are the worst sufferers in extraordinary disruptions (Paul et al., 2020a). The supply shock caused by the COVID-19 pandemic has severely disrupted global SCs (Yaya et al., 2020; Ivanov, 2020c).

The ***demand shock*** is clear and evident during pandemics, such as COVID-19 (Elleby et al., 2020). Maiello (2020) stated that the demand shock occurs when an initial supply shock further causes an advanced supply shock, resulting in a demand-deficient recession. The current extraordinary situation has suddenly increased the demand spike for essential items and decreased the demand for some non-essential items (Nicola et al., 2020). People are panic-purchasing essential items due to restrictions on moving and being encouraged to stay at home (Nicomedes et al., 2020). Manufacturers cannot meet the ongoing demand for essential items in pandemics due to supply disruptions and the need to implement social distancing instructions at manufacturing facilities (Kilpatrick et al., 2020). The ***financial***, ***supply,*** and ***demand shocks*** have severely impacted global SCs and caused a global economic recession (Sarmah, 2020). The recovery plans for disrupted SCs should utilize technology (Parast, 2020), sustainability (Mani et al., 2020), agility, resilience, transformability, and adaptability (Ivanov, 2020). The scarcity of information regarding product demand during this extraordinary situation has led to inaccurate predictions (Wu et al., 2020).

2.3. Supply chain disruption recovery strategies

Eliminating all risks to SCs is not possible (Christopher et al., 2011). Previous studies have recommended specific recovery strategies, including several response actions that might help firms reduce the effects of SC risk events and resume operations with ease (J. Chen et al., 2016). The recovery strategies suggested in these studies are based on the seven layers of SC disruption:

Macro-level disruption recovery: Macro-level analysis considers social, political, economic, and other forces, which impact societal and individual levels. COVID-19 has turned SC disruption into a macro-level disruption. Darom et al. (2018) suggested that strategic stock management can help manufacturers reduce supply stockout risks. McKinsey and McKinsey (2020) pointed to tracking consumer behavior shifts to predict product demand during a pandemic. Chen et al. (2019) studied SC collaboration and revealed that vertical and horizontal SC collaborations contribute to a quick recovery from disruptions at the macro level. In another study, Cai et al. (2020) proposed maximizing the benefits of government policies as a recovery plan to resume operations in a pandemic.

Demand disruption recovery: During any disruptive situation, a surge or decline of demands abruptly impacts the entire SC's performance (Correia et al., 2020; Ivanov et al., 2021). Restricting purchasing by setting limit bars for single consumers purchasing specific high-demand products in retail shops can help recover from panic-buying tendencies induced by consumer hoarding behaviors (MacLeod, 2020). Rainisch et al. (2020) suggested a demand algorithm specific to the product based on recent data of the last week to the last three months to determine product demands during pandemics. PWC (2020) suggested buying ahead to procure inventory and raw materials in short supply in disrupted areas during a pandemic.

Manufacturing disruption recovery: Paul et al. (2020a) stated that production could be increased to mitigate manufacturing disruptions by utilizing more shifts, hiring more operators, and buying more machines to help recover from disruptions, such as COVID-19. Expanding the manufacturing capacity by sharing information and resources and collaborating with local manufacturers have commonly been suggested in previous studies (Hsin Chang et al., 2019). The diversification of manufacturing plants in different locations and establishing emergency operation centers also might mitigate manufacturing disruptions (S. Li et al., 2017). Paul et al. (2020a) suggested that essential product manufacturers should offer basic quality products rather than premium quality items and pack the items in a minimum standard size so the same production volume could reach more customers. This would reduce the demand for essential items during pandemics.

Supply disruption recovery: Aldrighetti et al. (2019) recommended focusing on supplier risk tiers 1 and 2 during pandemic situations to mitigate supply disruptions. These authors also suggested that manufacturers should focus on buffer strategies to overcome long-lasting SC disruptions. For example, finding and activating multiple backup suppliers with effective strategies. Several studies suggested that retail shops should convert their operations to mimic a quasi-distribution center by picking, packing, and delivering orders to end consumers to mitigate the enormous demand (Ang et al., 2017; Kilpatrick et al., 2020; Paul et al., 2017; Paul et al., 2018). Paul et al. (2020b) explained that manufacturers could use collective emergency sourcing capabilities to source more raw materials and increase production. This process could foster SC flexibility as part of humanitarian SC activities (Paul et al., 2016).

Information disruption recovery: Correct and timely information sharing is key for thriving during an extraordinary epidemic, such as COVID-19 (Moorthy et al., 2020). Wang et al. (2019) suggested introducing blockchain technology to secure information and create a path to move information from every stakeholder within SCs. Creating open channels of communication with key customers is recommended by several studies to mitigate information disruption in any disruptive event (Jüttner et al., 2007; Banerjee, 2018).

Transportation disruption recovery: Transportation disruption creates fragile delivery channels and hampers demand–supply calibration. J. Li et al. (2012) researched how to manage SCs in a demand disruption environment. The researchers found that collaborative transportation management can significantly improve firm flexibility by tackling demand disruptions (Paul et al., 2019). Several studies have suggested building backup depot facilities and inbound and outbound transportation channels for quick disruption recovery (Ivanov et al., 2017; Sayed et al., 2020).

Financial disruption recovery: Evidence from the COVID-19 pandemic suggests that the SC is the economy's vein (Liu et al., 2020; Taqi et al., 2020). Fosso Wamba et al. (2020) suggested that blockchain technology could reduce the financial disruption of SCs. A prominent study recommended integrating the supplier, manufacturer, and retailers or distributors using enterprise resource planning software (e.g., SAP or Oracle) to decrease the financial disruption for SCs (Banerjee, 2018).

Refer to Table A1 in Appendix A for further details regarding the existing research on recovery strategies and modeling for SC risks.

2.4. Research gaps

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 extraordinary disrupted situations, such as the COVID-19 pandemic (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 be applicable for 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 Section 2 and Table A1 in Appendix A. However, limited research has been performed using simulation modeling 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 modeling (ABM) method is useful for simulating and evaluating complex SC interactions without formally developing a mathematical model for risk recovery situations (Mizgier et al., 2012). This is the present study's main contribution. Indeed, the study identifies strategies and recovery plans to mitigate the demand disruption of essential items, such as facemasks. It further analyzes improvements by implementing strategies and recovery plans during disrupted situations using an agent-based simulation model of an SC. An analysis of recovery plans in a simulation model provides us with further insight into how to recover from disruptions. It further sheds light on how the proposed strategies can improve the SCs for essential item manufacturing during demand disruptions. These contributions will expand insights on the disruption recovery of SCs. Most previous studies have offered strategies for navigating the post-disruption period. However, the present study proposed strategies and recovery plans and examined them using an SC simulation model to evaluate their effectiveness, which is where the novelty lies.

3. Problem description

The demand for essential medical items is at its peak, including facemasks and ventilators, essential food items (e.g., pasta, canned foods, canned fruits), and essential daily items (e.g., toilet paper, hand sanitizer) (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 behavior of people (Sim et al., 2020). People have been panic-purchasing and stockpiling essential items, skyrocketing the demand for such items. However, there has been a scarcity of essential items 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 boom in customers 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 (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.

4. Proposed strategies and model formulation

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

4.1. Proposed strategies and supply chain disruption recovery plans

During extraordinary pandemic situations, such as COVID-19, we propose the following strategies 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 analyzed 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 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. Maximize 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 enough supplies to help meet the high levels of 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 maximize 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.

Table 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%)

(2015).

Strategy 2: Increase the production capacity

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

A. Maximize 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 should 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. They could quickly decide to produce 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 analyzed four scenarios on production capacity increases, as shown in Table 1.

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 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 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

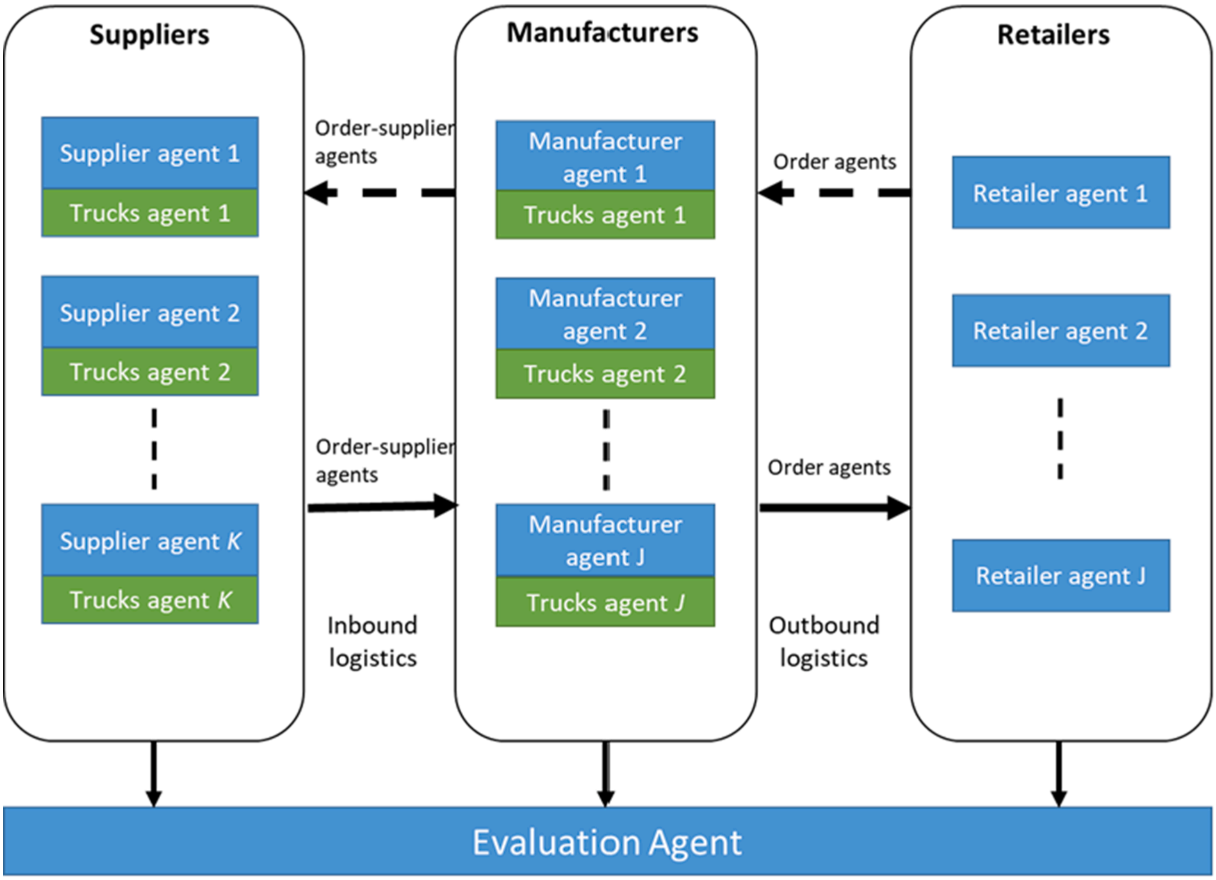

Fig. 1. Overall conceptual overview of the proposed agent-based supply chain system.

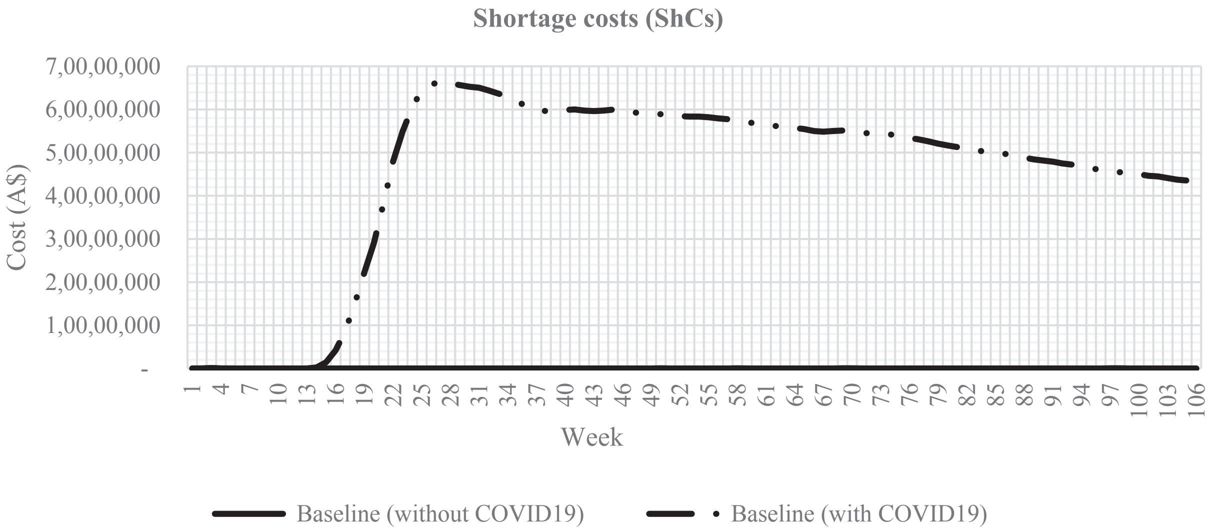

Fig. 2. Shortage costs in normal and disrupted situations.

materials over a long period 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 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.

4.2. Model formulation

This section proposes the ABM used to simulate a typical SC for facemasks to compare and analyze the set of SC risk recovery scenarios (discussed in Section 4.1). Fig. 1 offers a 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 fulfill the 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 fulfill 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 as carton, where each carton contains 100 facemasks. The costs considered in the analysis framework include:

- 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

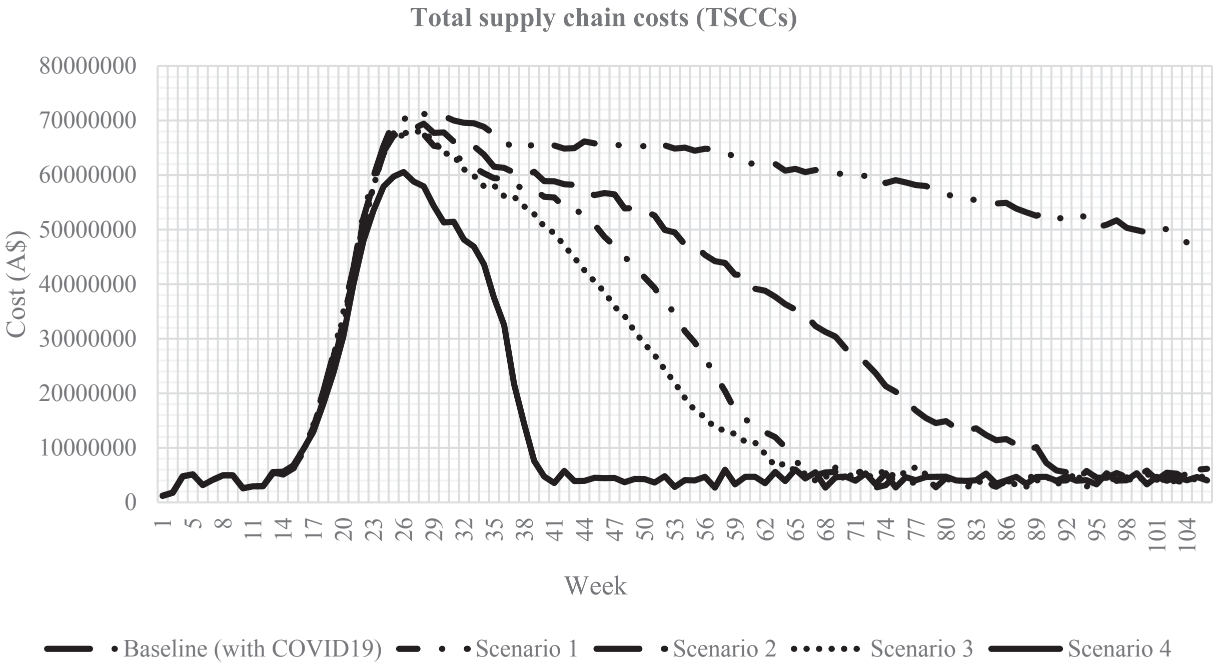

Fig. 3. Total supply chain costs for the recovery plans under different scenarios.

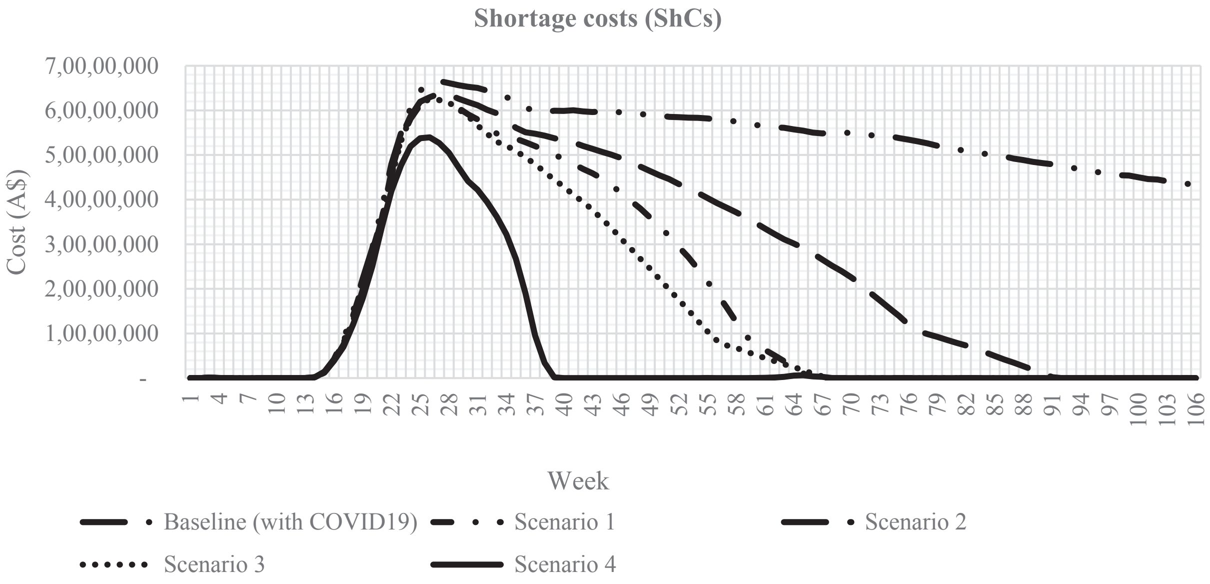

Fig. 4. Shortage costs for the recovery plans under different scenarios.

incoming product orders from retailers while meeting various performance objectives (e.g., lead time and total SC costs). Appendix A shows the model parameters (Table A2), the agent details (Table A3), and the cost metric equations evaluated by the agents for each period.

The list of parameters used in each agent (see Table A4, Table A5, and Table A6 in Appendix A) and the assumed changes in demand, production, and supply of facemasks (Fig. A1) are also shown in Appendix A.

5. Scenario analysis and outcomes

5.1. 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, respectively. 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 with no disruption (i.e., simulating "business-as-usual"). The results from the simulation model indicated that no ShCs were incurred (Fig. 2). Therefore, the existing SC for facemasks could effectively fulfill the market demand.

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 Fig. A1 in Appendix A. 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 stabilized 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

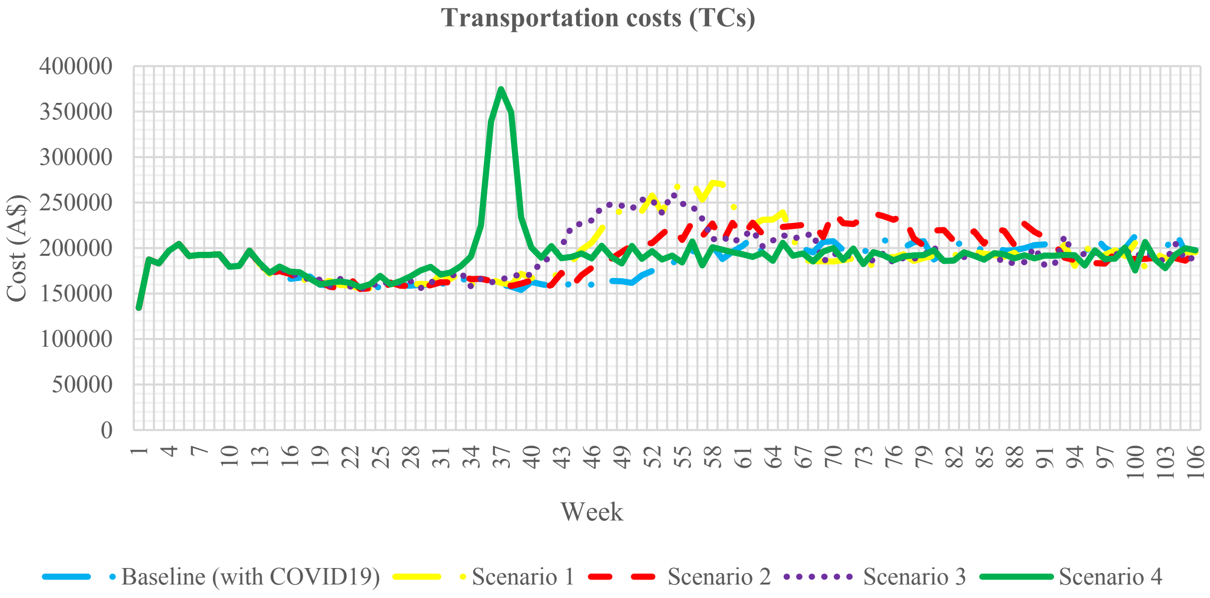

Fig. 5. Transportation costs for the recovery plan under different scenarios.

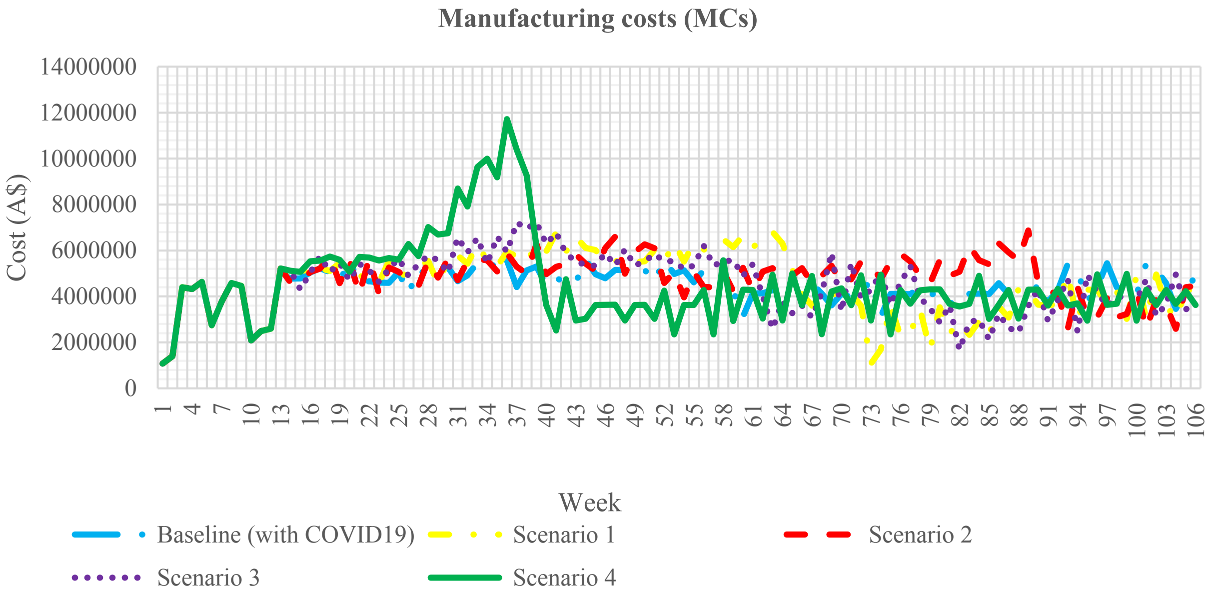

Fig. 6. Manufacturing costs for the recovery plans under different scenarios.

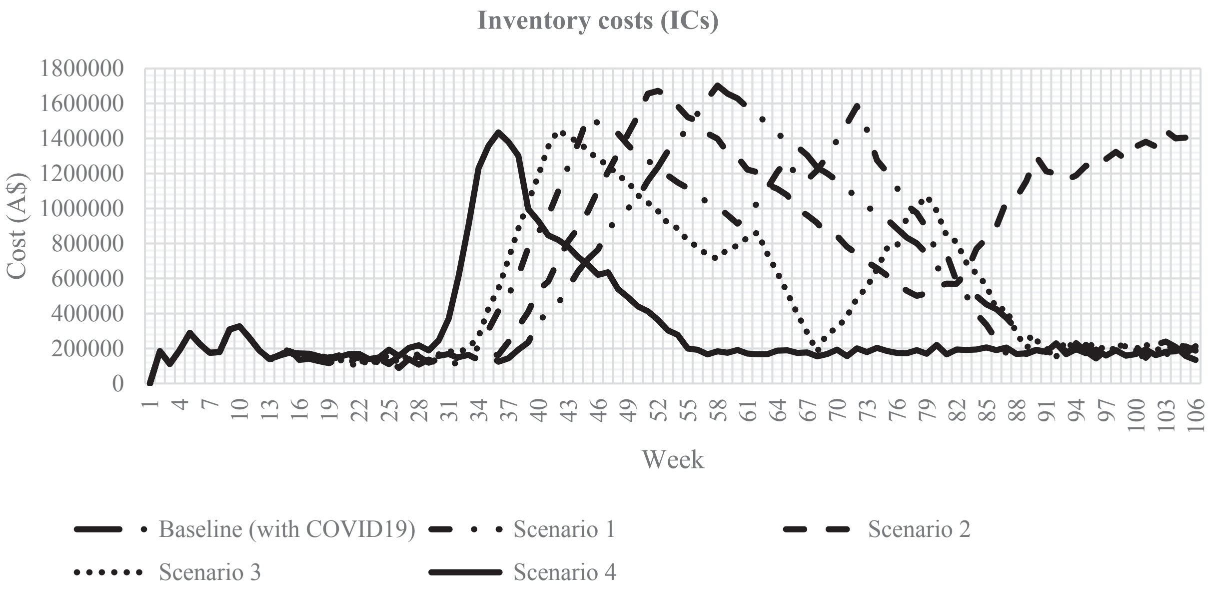

Fig. 7. Inventory costs for the recovery plans under different scenarios.

and physical distancing (see Fig. A1 in Appendix A).

We included changes in the demand, manufacturing capacity, and supplier capacity in the SC model. The ShCs from the simulation are shown in Fig. 2. If the manufacturing production capacity was not increased, supply and demand disruptions could lead to high ShCs. Fig. 2 shows that the ShCs started to increase from week 15 and peaked at week 28, with ShCs of A$66 million (approx.). Therefore, demand disruption during the pandemic had a significant impact on 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.

5.2. Impact of disruption on supply chains

The performances of the SCs in a baseline scenario with the COVID-19 pandemic are shown in Figs. 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 to increase at 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 Fig. 3.

Shortage costs (ShCs): The ShCs started to increase at 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 Fig. 4.

Transportation costs (TCs): The TCs remained between A$0.15 and A$0.22 million (approx.) as seen for **BS1** in Fig. 5.

Manufacturing costs (MCs): The MCs remained between A$4 and A$5 million (approx.) in the disrupted situations depicted for **BS1** in Fig. 6.

Inventory costs (ICs): The ICs started to increase at week 36 and peaked during that week before decreasing until week 92. After week

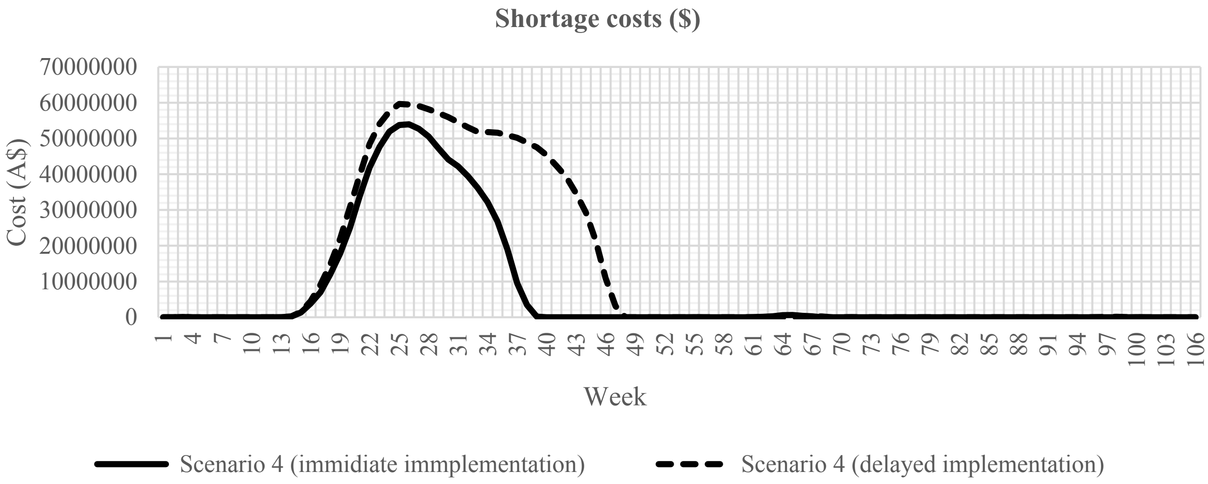

Fig. 8. Shortage costs of immediate and delayed implementation for Scenario 4.

Table 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%

92, the IC was normalized with A$0.2 million (approx.) as depicted for **BS1** in Fig. 7.

5.3. Immediate recovery plans and outcomes

We tested four recovery plans to improve the SC of facemask manufacturing firms, including increases in production capacity 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 Figs. 3–7, describing the TSCCs (**TSCC1**), ShCs (**ShC1**), TCs (**TC1**), MCs (**MC1**), and ICs (**IC1**).

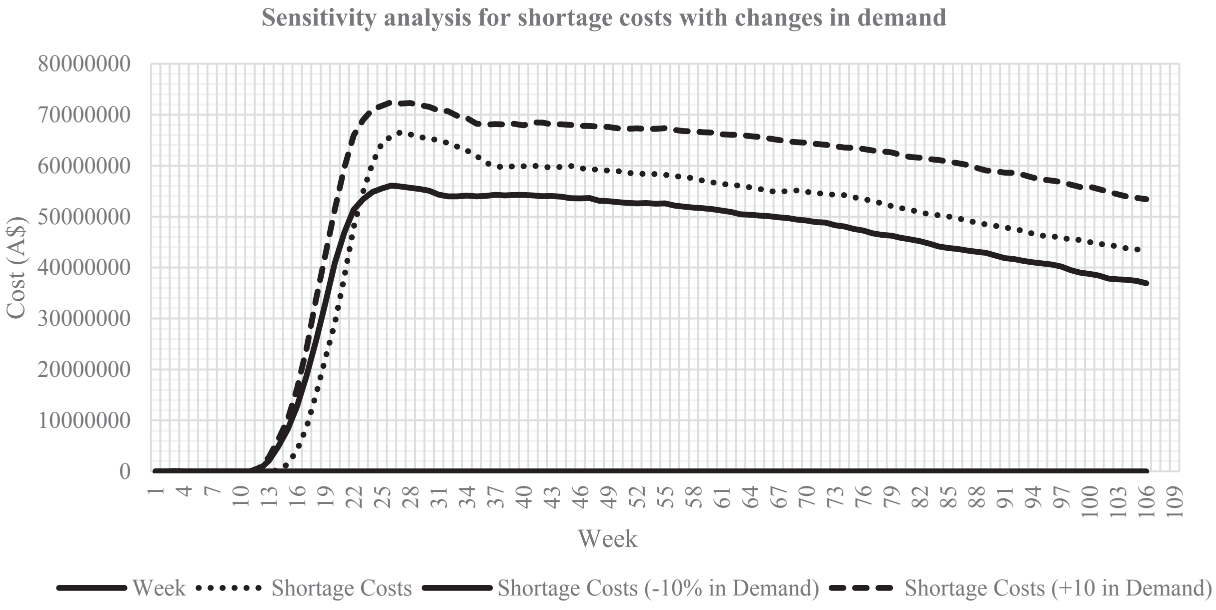

Fig. 9. Sensitivity analysis for shortage costs with changes in demand.

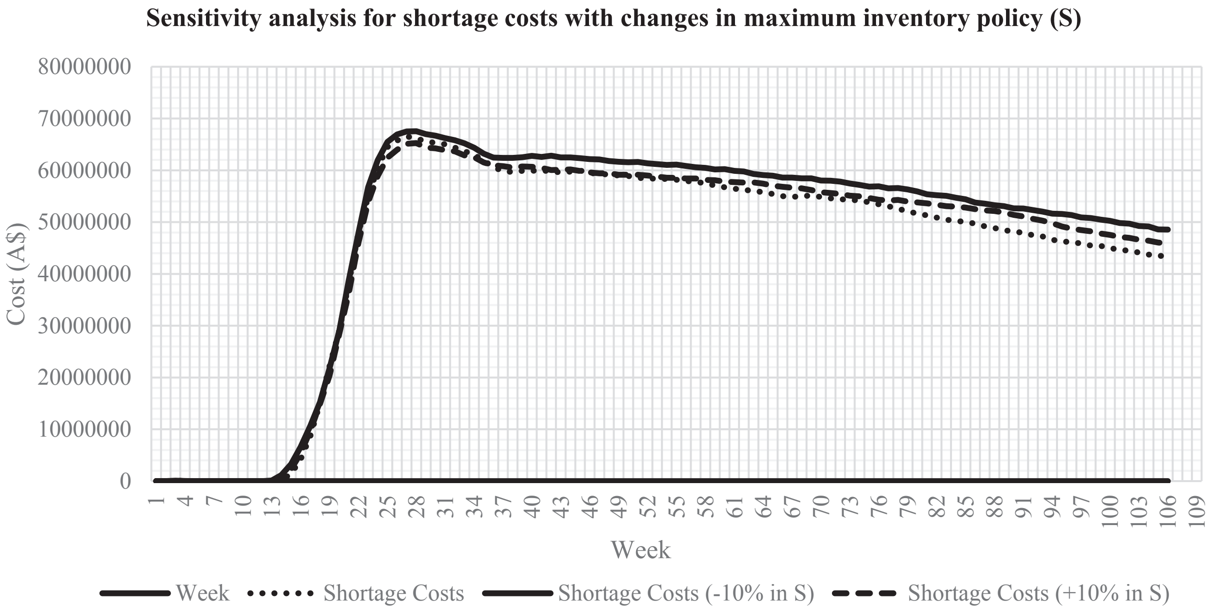

Fig. 10. Sensitivity analysis for shortage costs with changes in the maximum inventory policy (S).

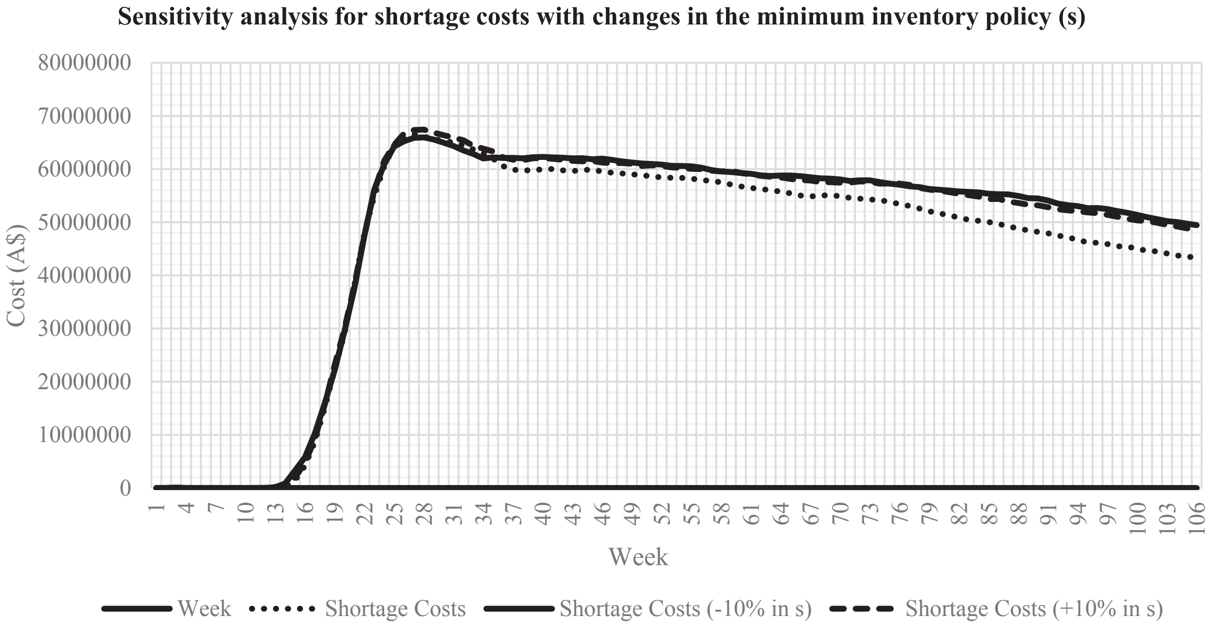

Fig. 11. Sensitivity analysis for shortage costs with changes in the minimum inventory policy (s).

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 Figs. 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 Figs. 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 Figs. 3–7, describing TSCCs (**TSCC4**), ShCs (**ShC4**), TCs (**TC4**), MCs (**MC4**), and ICs (**IC4**).

Comparative discussion of the outcomes:

Total supply chain costs (Fig. 3): In the disrupted situation, the TSCCs started increasing at week 13, peaked in week 28, and remained at high levels, as seen for **BS1** in Fig. 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 at week 28 and remained high until week 67, when it became normalized. 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 normalized. **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 normalized at week 41. **RP4** produced better results because **TSCC4** was lower than that in the other recovery plans.

Table 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**

Shortage costs (Fig. 4): The ShCs started to increase at week 15, peaked in week 28, and stayed very high in the disrupted situation, as seen for **BS1** in Fig. 4. When **RP1** was implemented under **S1**, **ShC1** peaked in week 28 before starting to improve and becoming normalized at week 67. However, when **RP2** was implemented under **S2**, **ShC2** peaked in week 28 and stayed high until week 92 before becoming normalized. **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 normalized. Finally, when **RP4** was implemented under **S4**, **ShC4** peaked in week 26 before starting to improve and becoming normalized from week 39. Thus, **RP4** lowered the ShCs better than the other recovery plans.

Transportation costs (Fig. 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 normalizing. Although the initial TCs for **RP4** were higher than that of the other recovery plans, Figs. 3 and 4 show that **TSCC4** and **ShC4** of **RP4** were lower than the other recovery plans, respectively.

Manufacturing costs (Fig. 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 normalizing. Although the initial MCs for **RP4** were higher than that of the other recovery plans, Figs. 3 and 4 show that **TSCC4** and **ShC4** of **RP4** were lower than the other recovery plans, respectively.

Inventory costs (Fig. 7)**:** ICs started to increase at week 36, peaked in week 58, and stayed high during the disrupted situation, as seen for **BS1** in Fig. 7. When **RP1** was implemented under **S1**, **IC1** peaked in week 45 and again in week 72 before starting to improve and becoming normalized at week 87. When **RP2** was implemented under **S2**, **IC2** peaked in week 52 and stayed high up to week 78 before starting to increase 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 that of **RP1** and **RP2** but higher than **RP4** up to week 92. Finally, when **RP4** was implemented under **S4**, **IC4** peaked in week 37 before starting to improve and becoming normalized at week 57. **RP4** lowered the ICs better than that of the other recovery plans.

5.4. *Delayed recovery plans and outcomes*

We tested the immediate and delayed plans for **RP4** under **Scenario 4** (immediate and delayed implementation). Following this, we analyzed the impact of the recovery plan implementation time on overall SC costs, as presented in Fig. 8.

In **RP4**, the production capacity gradually increased to 100% within six months. The ShCs remained normal up to week 14 for the immediate implementation of the recovery plan (Fig. 8). From week 15, the ShCs started to increase 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 to become normalized until week 105 in **Scenario 4 (immediate implementation)** of Fig. 8.

After delaying the implementation of **RP4** by two months, we noticed that the ShCs of **Scenario 4 (delayed implementation)** remained normal up to week 14 before starting to increase at week 15. The ShCs in the delayed implementation peaked in week 25, with increased ShCs of A$60 million (approx.), much higher than that of the immediate implementation in **Scenario 4 (immediate implementation).** In the delayed implementation, the ShCs started to decrease at 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

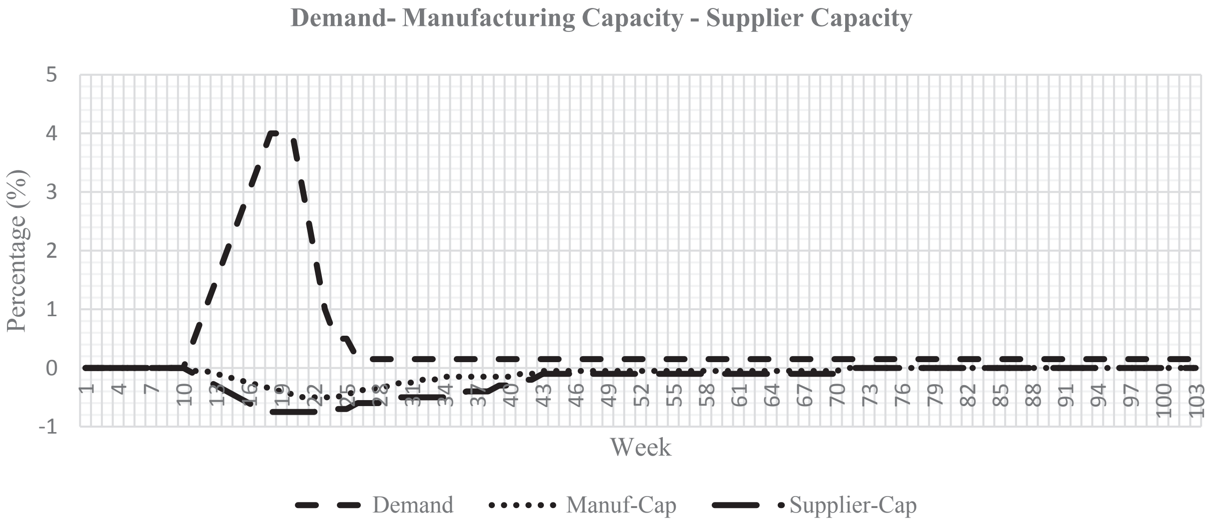

Fig. A1. Changes in demand, production, and supply caused by COVID-19 pandemic situation.

implementation started to become normalized 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.

5.5. 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 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 the 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's lockdown. The leftover variances in TSCCs are reported in Table 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 remain high compared to the baseline condition with no disruption, even when the demand is decreased by 10%. When the maximum inventory policy (S) increased, the average ShCs correspondingly increased since they did not have enough capacity to fill the required inventory level to meet increasing demands. Therefore, when the maximum inventory policy (S) decreased, the ShCs are observed as 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 2. Figs. 9–11 offers details on the sensitivity analysis for ShCs with changes in the parameters.

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, ICs) did not drastically increase due to the shutdown of manufacturing sites, slowed delivery, and supply failure during the lockdown. Table 2 provides a synopsis of the sensitivity analysis.

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 4), are necessary to tackle such extraordinary demand and supply disruptions in any global pandemic situation.

6. Results, analysis, and discussion

6.1. Impact of increasing emergency raw materials

The raw materials for facemask manufacturers can be increased by maximizing 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. Fig. 3 and Table 3 show a huge improvement in TSCCs when the production capacity increased quickly using the increased raw materials in demand disruption.

6.2. Impact of increasing production capacity

Facemask manufacturers can increase their production capacity by maximizing 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 timeframes from the short- to long-term. 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 Figs. 3–7 and Table 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)

For **TSCC4, ShC4,** and **IC4**, **RP4** was the most efficient of all plans since 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 in the third-ranked position**. TSCC1, ShC1,** and **IC1** of **RP1** were higher than **RP3** and **RP4**; however, **RP1** reduced the SC costs better than **RP2. RP2** was in the fourth-ranked position 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 that of the other recovery plans for **RP4.** Indeed, production capacity increased by 100% in a short period in the first six months in **RP4** to mitigate the skyrocketing demands. Later, the higher initial TCs and MCs of **RP4** became normalized very quickly, reducing the TSCCs, as depicted in Figs. 3–7 and Table 3.

6.3. 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 a maximum of 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 50% less than that of **RP4.**

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 minimize the financial shock.

Managerial insight 2:

When we compared **RP1** and **RP3's** recovery periods, **RP3** performed better than **RP1** over the long term. In **RP3**, the production capacity gradually maximized 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**.

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 minimize the financial shock.

Managerial insight 3:

RP4 had the highest production capacity increase since the capacity increased gradually to a maximum of 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 a maximum of 100%, similar to **RP4** but in the long term.

Suppose that the maximum raw material was available and managed per the supply–demand shock in a disruptive situation. In this case, findings suggest we should use the production's maximum capacity quickly in the short term to maximize 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 what was needed per the supply–demand shock in a disruptive situation. In this case, findings suggest it is better to utilize the production capacity for a long time to maximize the benefits. 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 utilize less 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 since the production capacity was maximized 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 maximized 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 a 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 (Fig. 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 disrupted situation to reduce financial shock and make their SCs more agile, resilient, and responsive (Ivanov, 2020).

Managerial insight 7:

Essential item manufacturers must immediately determine the demand increase of products and synchronize 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.

7. Conclusions

7.1. Contributions and practical implications

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. 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,*" "*maximizing 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 "*maximizing 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 proposed 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 disrupted situations through a literature review and case study. The strategies can serve as 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 contributed 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 maximize 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 any disruption. 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.

7.2. Limitations and further research directions

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. 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 setup cost impacts long-term SC improvement. More mathematical analysis of other supply chain dynamics such as the impact of disruptions on the sustainability performance of supply chains and the recovery strategies to improve them in a multiple-stage supply chain 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 in evaluating the present global extraordinary disruption caused by COVID-19 pandemic.

CRediT authorship contribution statement

Towfique Rahman: Conceptualization, Methodology, Software, Investigation, Visualization, Writing - original draft. **Firouzeh Taghikhah:** Conceptualization, Methodology, Software, Supervision, Writing - review & editing. **Sanjoy Kumar Paul:** Conceptualization, Resources, Supervision, Visualization, Writing - review & editing. **Nagesh Shukla:** Conceptualization, Resources, Supervision, Methodology, Visualization, Writing - review & editing. **Renu Agarwal:** Conceptualization, Resources, Supervision, Writing - review & editing.

Appendix A

Table A1
Studies on recovery strategies and modeling for supply chain risks.

Authors	Nature of contributions	Methodology used
Munir, Jajja, Chatha, and Farooq (2020)	Provided the framework on how to predict the consequences of pandemic on SCs	AnyLogistix simulation and optimization software
Paul et al. (2020b)	Proposed strategies to mitigate the impacts of disruptions on SCs during COVID-19	Mathematical modeling
Siva Kumar et al. (2020)	Proposed a framework called SAP-LAP to analyze the SC resilience building and improvement	Theory building
Alix, Benama, and Perry (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, Garrido-Vega, and Cruz Torres (2020)	Contributed to determining how reconfigurable technology is effective to achieve 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 pandemic on the SCs together with managerial insights	Simulation by AnyLogistix simulation and optimization software
Hobbs (2020)	The consequences of demand side shocks on food SCs are discussed, which included a study of consumer panic-buying behaviors with respect to 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 scrutinize 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 modeling
Voldrich, Wieser, and Zufferey (2020)	Proposed numerically how to decrease the processing time and cost by a minor increase in operational risk of a food manufacturing industry	Optimization by CPLEX (Linear Programming)
Kittipanya-ngam et al. (2020)	Discussed a framework for food SC digitalization in the context of Thailand food manufacturing	Case study by triangulation of data collection through semi-structured interviews, direct observations
Kamble, Gunasekaran, and Gawankar (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 A2
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 material 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^t_j	Number of products manufactured by the j^{th} manufacturer
α^t_{ijl}	Transportation time taken by truck l to transport products x^t_{jk} from j^{th} manufacturer to i^{th} retailer in time window$t$
β^t_{jkm}	Transportation time taken by supplier truck m to transport products y^t_{jk} from k^{th} supplier to j^{th} manufacturer in time window$t$
x^t_{ij}	Products transported from j^{th} manufacturer to i^{th} retailer in time window$t$
y^t_{jk}	Products transported from k^{th} supplier to j^{th} manufacturer in time window$t$
τ	Time window
Q^t_j	Average inventory level at j^{th} manufacturer in time window$t$
R^t_i	Average inventory level at i^{th} retailer in time window$t$
d^t_j	Number of products that were not delivered to the retailer within a week at j^{th} manufacturer in time window t
$\sum_j x^t_{jk}$	Number of products supplied to the i^{th} customer
$\sum_j y^t_{jk}$	Number of products supplied by the k^{th} supplier

Table A3
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 fulfill 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 which represents the demand from the set of 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 fulfillment.
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 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 needed to ship the components/raw materials to the respective 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 manufacturing and supplier stage, ICs at supplier, manufacturer, and retail, ShCs, products/components produced/shipped/received.

Table A4
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 A5
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 A6
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

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

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

$$\text{Manufacturing Inventory Cost in time window } t = \sum_j IM_j.Q_j^t$$

$$\text{Customer Inventory Cost in time window } t = \sum_i IR_i.R_i^t$$

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

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

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

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

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