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Enablers of resilience in the healthcare supply chain: A case study of U.S healthcare industry during COVID-19 pandemic

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A R T I C L E I N F O

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A B S T R A C T

Healthcare is considered one basic necessity to sustaining life; thereby, assessing the character of a healthy and resilient supply chain can help a nation develop ideas to combat the healthcare crisis. COVID-19 has led to a long-term strain on the healthcare supply chain (HCSC) and has resulted in a lack of basic healthcare necessities. It has become apparent that supply chain disruptions and increased usage has led to a lack of medical supplies needed to provide the proper care to patients. Multicriteria decision-making (MCDM) will help to indicate what characteristics contribute to resilient healthcare supply chains. To assess the characteristic of a resilient supply chain, significant healthcare supply chains will help indicate significant characteristics. A case study on the *medical supplies'* supply chains is presented. A rank reversal proximity index MCDM method ranks criteria to assist with decision making. The proximity index will reduce the chances of the rank reversal phenomenon that results in incorrect rankings from occurring. Results show that *redundancy, collaboration, and robustness* are key indicators of a resilient supply chain while, *supply chain design*, *communication capabilities*, and *supply chain risk management* become comparatively less important during the COVID-19 pandemic. Furthermore, an unsupervised machine learning tecnique named "cluster analysis" is conducted to group the resilience indicators of the respective supply chain. Through this study, the best way to combat disruptions in the healthcare supply chain due to large-scale pandemics is to share information quickly, reduce reliance on the design of the supply chain, and track the usage of necessary medical supplies. Alternatively, we validated our study by comparing a Preference Selection Index (PSI) to the proposed method.

1. Introduction

A supply chain is the sequence of processes involved in the production and distribution of a commodity. A supply chain network enables a company to look over all the entities of producing or providing a product from the beginning supplies to the customers (Marques et al., 2019). The overall movement of materials and information along supply chains allows companies to see the value in each node within the network. Resilience in the supply chain is defined as the ability to respond to unpredicted interruption caused by unexpended events and recover from them by maintaining operations at the desired level of connectedness and control (Obeidat et al., 2020). Resilience can also be defined as the adaptive capability of a system to respond to disruptions in a better way or even gain an advantage during disruptive events (Bahadori et al., 2017; Polater & Demirdogen, 2018). A resilient supply chain is increasingly more critical in light of a natural disaster. However, the impact of COVID-19 on the healthcare supply chain has led to shortages of necessary protection, medication, and space to treat all infected patients.

Healthcare is vital to human life, and the supply chain must remain resilient in light of any event that could cause disruption. The healthcare supply chain deals with providing quality products and effective services to patients promptly with the lowest cost possible. In 2017, $3.5 trillion was spent on healthcare and 25.4 billion was spent on the healthcare supply chain in the United States (Daniels et al., 2018). Healthcare bills can be expensive and seem to be rising consistently. Hospitals are looking to find areas along the healthcare supply chain where the response time can be reduced, and demand can be met consistently without failure. Natural disasters such as hurricanes, storms, and terrorist attacks have also forced the government to improve funding

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and planning for healthcare supply chain resilience in the United States (Zeneli et al., 2018). Apart from the natural disaster and terrorist attack, the pandemic, COVID-19 has already increased cost across the board for healthcare and led to an unprecedented amount of spending by the world governments.

Supply chain resilience is essential considering many disruptions that can happen without much time to prepare. Natural disasters and pandemics put a high amount of strain on healthcare supply chain entities and can result in the inability to provide care. The most recent pandemic, COVID-19 has one of the most unexpected and dangerous new development in 2020 that has caused much strain on the healthcare system. The length of the disruption in supply chains puts strains on all entities to do their job effectively (Ivanov, 2020). Many hospitals are deciding on who gets the care and are operating without all the necessary materials. Additionally, more people are joining the distribution workforce, working overtime, and putting their lives are risk without proper protection. There is a need to develop a resilient healthcare supply chain structure that could withstand the effect of a pandemic like COVID-19. The objective is to find which indicator characteristics are critical for keeping a resilient medical supplies supply chain in the light of a long-term disaster such as COVID-19.

Several approaches have been adopted to address the issue of the pandemic, but till the date of submission of this manuscript, the application of MCDM is not broadly discussed in the case of COVID-19. To address this gap, this paper identifies and assesses the most influential enablers to the resilience of the healthcare supply chain against COVID-19 using the proximity indexed value (PIV) MCDM approach. This paper not only identifies the most important enablers from literature and expert opinion, but it also ranks them in order of significance using the proximity indexed value (PIV) MCDM approach. The contribution of this study is summarized as follows:

- Identification of enablers to healthcare resilience to withstand the shock stems from pandemic COVID-19.
- Ranking enablers of healthcare resilience to help decision-makers emphasize the most important ones.
- Application of proximity indexed value (PIV) MCDM approach to a medical supplies supply chain.

The PIV method for minimizing rank reversal was developed by Mufazzal and Muzakkir (2018). We employ the PIV method in our study to evaluate 12 indicators that are crucial to the medical supplies supply chain in healthcare during the pandemic. Although we are primarily focused on the medical supplies' supply chain, 3 additional significant supply chains are employed in the PIV case study. The PIV method has some benefits over other MCDM approaches. A proximity index finds the distance of each between available solutions and the worst solution. Based on the distance between alternative solution has from another alternative, a decision-maker can make a more comfortable decision on how to proceed with choosing a solution. Additionally, the rank reversal phenomenon occurs in many MCDM methods, causing the ranking to not look as expected due to the change in scaling value that occurs with normalization. Incorporation of a proximity index value into an MCDM method attempts to make the calculation values in the matrix more precise, which reduces the rank reversal phenomenon.

In decision-making problems, the situation is highly sophisticated, and the decision involves high risk as in the case of facility layout selection. The PIV method used in this study takes in various ranking values for each criterion of the medical supplies supply chain to rank each indicator characteristic. The longevity of the COVID-19 pandemics strain on the availability of medical supplies has questioned the resilient of healthcare supply chain. This study fills the gap for decision-makers aiming to find an effective way to decide what supply chain resiliency enablers create a more resilient supply chain during a long-term disaster.

The rest of the paper is organized as follows: Section 2 presents a description of previous research. Different SC characteristic enablers and indicators are described and presented in Section 3. Section 4 contains the decision problem, MCDM framework, proposed method results, and validation method. The discussion of the MCDM method and results are presented in Section 5. Section 6 concludes the study findings and suggests possible improvements.

2. Literature review

This section discusses the existing literature pertaining to the impact of healthcare supply chain resilience. It presents studies that attempt to analyze the healthcare system to enhance the resilience by understanding what indicators lead to a lean and versatile supply chain. Resiliency Indicators are characteristic of the healthcare supply chain that leads to increased ability to perform as expected. The literature review explores both new studies, on the effects of COVID-19 on supply chains, and previous studies, which analyzed the healthcare supply chain using theoretical models, analytical models, multicriteria decision making (MCDM) models, and statistical models. Exploring the indicators in the healthcare system helps to determine how each indicator improves resilience. In addition to the literature review, this section also explores the most critical supply chains in healthcare.

2.1. Related research

Healthcare has been one of the most critical industries, and the preservation of life is essential for every government, but the healthcare supply chain has only been seriously addressed within the past 20 years due to several different disasters. Developing approaches to the management of people and resources is a growing concern. Theoretical, mathematical, and MCDM approaches to healthcare and resilience are reviewed along with recent studies on COVID-19 and long-term disasters in this section. In Landry and Philippe (2004), a material logistic approach addresses the decentralization of healthcare in the United States. The objective is to develop strategies for the procurement of medical supplies through centrally located stores or distribution departments. The development of healthcare supply chain management is further researched in De Vries, Huijsman, Aronsson, et al. (2011). The purpose was to create a lean and agile flow within the healthcare industry supply chain. The authors recommend improving supply chain practices by examining the design of the supply chain.

Balcázar-Camacho et al., 2016 explores the interaction and cooperation between organizations that make the supply chain. This method suggests coordinated planning of healthcare services using a mixed-integer programming model. In the first approach, patient care is performed under the assumption of the free flow of information and cooperation to satisfy demand. The second approach assumes non-cooperation. The mathematical study shows that the supply chain improves with coordinated planning. Gunpinar and Centeno (2015), evaluate the challenges in managing the shortages and wastage of blood products. A stochastic integer programming model minimizes the total cost of shortages and wastage levels by considering the uncertainty of demand rates. The models found that wastage can be reduced by 19.9 to 2.57 on average.

A mathematical approach to decision-making is proposed by Jochmann and León-González (2004). They estimate demand for healthcare using the semiparametric Bayesian approach. The objective of the approach is to control different behavior attributes or genetic diversity across individuals that are similar and likely to influence demand for healthcare. Findings show that number of visits to the doctor's office increase to 85 and decrease thereafter. More potential outcome models could be developed upon this Bayesian approach to understanding the effects on demand. Also, communication is an essential indicator of resilience. Yee-Long Chong at el. (2015) predicts Radio frequency identification (RFID) adoption in healthcare improves communication between systems. Neural network analysis and sensitivity analysis are performed to make predictions and identify more significant variables. The finding shows that specific personalities, such as openness, extraversion, neuroticism, conscientiousness, and agreeableness, are among the most important predictors and that RFID will not fit into every aspect of the supply chain.

Multicriteria decision-making methods have a broad spectrum of applications in the field of healthcare resilience engineering. The objective is to help support decision-making with an optimization approach ranking significant variables with priority given to criteria that are seen as more significant. Ranking aspects that lead to more resilient healthcare supply chains provide healthcare agencies with information on where the supply chain could improve. In Mehralian et al. (2015), a fuzzy TOPSIS decision-making matrix is used to develop a model and plan on how to improve the agility of the healthcare pharmaceutical supply chain. Delivery method, speed, planning, reordering, and trust development, rank among the top priorities in this model. Pharmaceutical companies should learn how to manage unexpected disruptions and pay more attention to supply chain operations.

Sustainability is also evaluated in the healthcare supplies disposal industry in Chauhan and Singh (2016). A hybrid multicriteria decision-making method is used to select sustainable locations of healthcare waste disposal facilities. A TOPSIS method is used to rank locations based on variables such as distance, cost, exposure to the public, and road conditions. Less exposure to the public, farther distances, and less harm, are seen as critical conditions when considering a location. Several other works can be found in the literature that discussed the application of MCDM against backdrop healthcare-related problems. Readers are referred to works of ELECTRE (Shojaie et al., 2017; Akcan and Güldeş, 2019); AHP (Liberatore and Nydick, 2008; Yuen, 2014; Singh & Prasher, 2019 Yucesan & Gul, 2020; Alansari et al., 2017); TOPSIS (Mehralian et al, 2015; Chan, Choi, Hui, & Ng, 2015; Li & Wei, 2020); VIKOR (Chithambaranathan et al., 2015; Bahadori et al., 2017; Samanlioglu, 2019); Gray Rational Analysis (Akcan & Güldeş, 2019; Kou & Wu, 2014; Hashemi et al., 2015).

COVID-19 is a global emergency that spreading in an unprecedented rate across the world. Compared to other disease outbreaks in the past, a possible connection to the fast spread of COVID-19 is various products being traded around the world (Sohrabi et al., 2020). When SARS took place in 2003, China was only 4 percent of the global gross domestic product, and now it is 17 percent. Supply chains run across country borders, and the necessary supplies to combat pandemic is dependent upon fast-acting communication and transfer of supplies between countries. Lichtenwald (2020), states that the risk of not having the necessary supplies for healthcare workers around the world is real. In unfamiliar times, governments and industries need to relax restrictions and put measures in place to boost the availability of resources while restricting speculation and hoarding. He suggests that a robust supply chain management system helps in times such as the COVID-19 outbreak. First, there must be an increase in the management of items, tracking of supplies by all suppliers, and monitoring of everyday items that are in use. In Ivanov (2020), he evaluates a supply chain's resilience by looking at the length of the long-term disruptions, such as COVID-19, that causes ripple effects throughout a network. A discrete-event simulation methodology is created with assumptions that lead-time and backup suppliers are crucial elements, and a ripple effect usually accompanies a disruption. The findings of this study suggest that supply chain performance reaction is dependent upon the timing and scaling of the disruption.

2.2. Resilience and healthcare resilience

The term "resilience" has several different meanings and changes based on the topic or industry. The term can range in meaning from "withstanding major disruptions" to "the ability to prevent frequent failures." In the manufacturing industry, a machine is described as resilient if there is less of a need for maintenance of the machine that in turn lowers cost. While in the supply chain industry, the objective is to get past disruptions with a considerable amount of risk, additional costs, and move toward a more efficient state. Resilient supply chains provide products as expected despite unexpected disruptions. The challenge with creating a resilient supply chain is that it is impossible to predict how each disruption will affect the market and transportation of goods. Thus, depending on the industry, the supply chain must have a certain ability to be resilient through any disruption. The resilience of the healthcare supply chain was put to a new and complex test with the rise of the COVID-19 pandemic.

In literature, we find a few key definitions of resilience that relate to our healthcare supply chain resilience. Mandal (2017) define resilience as the dynamic capability that enables firms to prepare for uncertainties through adequate planning with supply chain partners. Furthermore, disaster resilience is defined by Berke et al. (2008) as the capacity to restructure, adapt, and adjust to stress. These definitions directly relate to the HSCS because during a long-term disaster such as COVID-19 a variety of different interconnected networks could be affected. The increased reliance on telecommunication and wireless networks leads to network efficiency issues. Transportation of supplies is key to successfully sustaining a steady flow of medical materials while an interdependent infrastructure between healthcare entities allows for the allocation of necessary supplies to all necessary providers. Resilience being key to many supply chains makes finding key enablers important during any disruption. Several key enablers will help HCSC during long-term disruptions such as COVID-19 to stay resilient. Stoppages in the Healthcare supply chain can result in terrible penalties for patients and additional costs to healthcare providers. The following enablers in section 3 provide more insight into how an HCSC can be resilient.

3. Supply chain characteristic enablers/indicators

In this section, we will discuss the resilience indicators of the health care supply chain (HCSC) and different types of HCSC.

3.1. Methodology of the proposed framework

The methodology for the proposed framework was conducted based on a systematic review of comprehensive literature. The search for relevant literature was guided using Google Scholar, Scopus, and Web of Science databases through relevant keywords (i.e., resilience, resilience indicators, healthcare supply chain, medical supplies) about healthcare, supply chain disruptions, and supply chain network resilience. Additionally, databases were searched for Multicriteria decision-making methods that were popular in literature. The database search included peer-reviewed papers, proceedings, and book chapters to comprehend all aspects related to healthcare, supply chain disruptions, and supply chain network resilience. Initial search results produced 100+ papers. The initial screening of the papers was achieved by reviewing the selected keywords and then filtering the papers based on the abstract to check the aptness and materiality of the work. To further narrow the search results to obtain the most relevant list of papers related only to prominent supply chains in healthcare, we excluded papers that are not directly related to the daily supply of healthcare and healthcare supply chain network resilience. A total of 56 relevant works were selected for extensive literature review for healthcare supply chain resilience indicators. The proposed framework is developed based on the mentioned systematic review process. Fig. 1 summarizes the steps used to develop the research methodology.

3.2. Resilience indicators

The important enablers $\{A_1, A_2, \ldots, A_n\}$ necessary for supply chain resilience to aid the decision towards the objective of the study are determined. Different healthcare industry supply chains are characterized by several the resiliency indicators below. Based on the industry

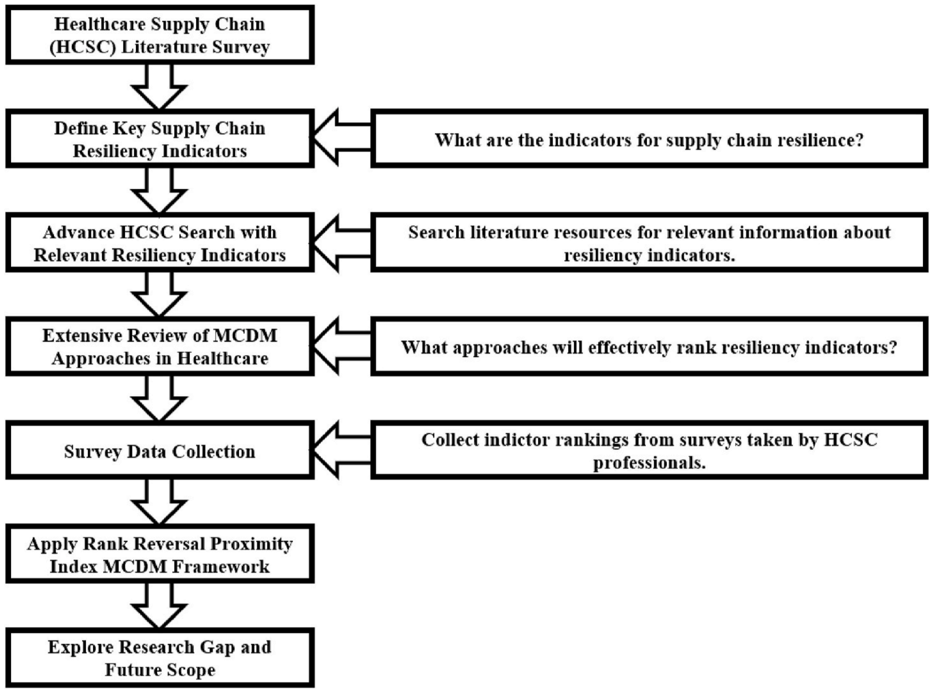

Fig. 1. Steps of research methodology.

and objective of the singular supply chain, some indicators will be seen as more important than other indicators. The objective is to identify which indicator is the most critical to healthcare medical supplies supply chains against the pandemic like COVID 19. Table 1 summarizes the main enablers of healthcare resilience to subside the effect of COVID-19.

Table 1
Supply chain indicators.

S·N	Indicators	References
1	*Agility*	Rajabzadeh Ghatari et al., 2013; De Vries, Huijsman, de Vries, & Huijsman, 2011; Kamalahmadi & Parast, 2016; Ali et al., 2017; Kilpatrick and Jim, 2020; Doyon-Plourde et al., 2019
2	*Security*	Music, 2012; Lodree & Taskin, 2009; Alansari et al., (2017); Zeneli et al., 2018; Jalali & Kaiser, 2018; Lichtenwald, 2020
3	*SC network design*	Marques et al., 2019; Lennquist & Hodgetts, 2008; Miah et al., 2013; Sinha & Kohnke, 2009; Lichtenwald, 2020
4	*IT capability*	Peng et al., 2014; Dey et al., 2013; Ratnam & Dominic, 2016; Jain et al., 2017; Rahimi & TalebiBezminAbadi, 2020
5	*Supply chain risk management*	Miah et al., 2013; Lam, 2016; Chen et al., 2013; Saedi et al., 2016; Kumar, 2012
6	*Collaboration*	Peng et al., 2014; Chakraborty et al., 2014; Arya et al., 2015; Papadopoulos et al., 2017; Conway, 2020
7	*Flexibility*	Arora et al., 2010; De Vries, Huijsman, de Vries, & Huijsman, 2011; Fayezi et al., 2016; Simwita & Helgheim, 2016; Stevenson & Spring 2007; Bakertilly, 2020
8	*Robustness*	Hartsfield, 2014; Qiang, Nagurney, & Dong, 2009; Hanne et al., 2009; Choi & Hastak, 2018; Lichtenwald, 2020
9	*Sustainability*	Hale & Moberg, 2005; Hussain et al., 2018; AlJaberi et al., 2017; Maria Jesus Saenz et al., 2015; Kaplan, 2020; Conway, 2020
10	*Velocity*	Hartsfield, 2014; Cagliano et al., 2011; Jüttner and Maklan, 2011; Stevenson & Spring 2007; Lichtenwald, 2020; Conway, 2020
11	*Redundancy*	Hartsfield, 2014; Lodree & Taskin, 2009; Ehrenhuber et al., 2015; Ali at el., 2017; Doyon-Plourde, Fakih, Tadount, Fortin, & Quach, 2019
12	*Awareness/ sensitiveness*	Fanoodi et al., 2019; Mandal, 2017; Achour et al., 2011; Conway, 2020; Sawyer, 2020

3.2.1. Agility

Agility is characterized as the capacity to react to erratic change in supply and demand quickly (Ali et al., 2017). Supply chains need to be able to survival in turbulent times, where environmental forces create additional uncertainty (Rajabzadeh Ghatari et al., 2013). Agile supply chains can compete within states of dynamic and continuous change and implement an innovative solution (Ali et al., 2017; De Vries, Huijsman, de Vries, & Huijsman, 2011). Healthcare officials in agile supply chains find and create new ways to get the necessary materials to supplement the demand for all healthcare materials. Supply chains become agile through expanding bed capacity, hiring more workers, and locating more supplies during COVID-19 (Kilpatrick et al., 2020 , May 5;).

3.2.2. Security

Security is characterized as the ability to plan and secure the safety of different entities and products. Security also involves the wellbeing of different stockholders within the company and how they cared for in stressful situations. During an influenza outbreak, the practices go into protecting patients and workers (Music, 2012). Security against environmental events such as natural disasters, cyberattacks, and terrorism are some of the many security concerns of a supply chain (Lodree & Taskin, 2009; Jalali & Kaiser, 2018; Zeneli et al., 2018). Unnecessary security restrictions can lead to a less effective healthcare network during COVID-19 (Lichtenwald, 2020).

3.2.3. Supply chain network design

Supply chain network design is characterized as how the design of the supply network contributes to the healthcare supply chain resilience. The design of a network determines how to transport materials and how to treat different entities along the supply chain. The essential supply chains are thoughtfully designed to respond to natural disasters and adaptive supply chain network design could create a more resilient network (Lennquist & Hodgetts, 2008; Marques et al., 2019). Additionally, entity selection such as supplier selection is pivotal in ensuring the proper materials for different entities in the healthcare supply chain

(Miah et al., 2013). The network must account for growing demand and be able to supply high-quality, cost-effective, and timely healthcare (Sinha & Kohnke, 2009). Design of a network is often altered and changed during long-term disasters such as COVID-19 (Lichtenwald, 2020).

3.2.4. IT communication capability

The IT communication capability is characterized as having the technology and resources to communicate along the supply chain and prevent disaster. Supply chains must have the ability to communicate and to carry out specific functions. Keeping communication during natural disasters improves preparation efforts and increases the ability supplement demand (Peng et al., 2014). Evaluating weaknesses in technology and communication are essential to a resilient supply chain (Dey et al., 2013; Ratnam & Dominic, 2016). Globalization of communication and essential technologies has improved healthcare practices (Jain et al., 2017). Improved video chats capabilities and increased information sharing capabilities will allow the world to work together to find ways to fight COVID-19. Transparency and information sharing could help abate the COVID-19 pandemic (Rahimi & TalebiBezminAbadi, 2020).

3.2.5. Supply chain risk management

Supply chain risk management is characterized as the strength of the management teams to effectively contribute to the healthcare supply chain resilience. Effectively evaluating the risks within the supply chain and decision support models improve supply chain management (Miah et al., 2013). Supply chain risk and disruption have been a concern for many stakeholders and risk assessment is necessary due to the growing complexity of markets (Lam, 2016; Cagliano et al., 2011; Sakib et al., 2021). Inventory management approaches mitigate shortages at a healthcare facilities to improve resiliency (Saedi et al., 2016). Decisions were made by hospitals and their workers to manage the risk associated with the spread of COVID-19. Management is looking at what entities can hurt the medical supplies supply chain's ability to provide care. Detailed and well-communicated plans to manage the risk of COVID-19 are necessary for healthcare supply chain resiliency (Kumar, 2012).

3.2.6. Collaboration

Collaboration is characterized as sharing the correct information and working together effectively in the healthcare supply chain. False, slow, or different levels of communication can affect the timely response needed in healthcare during a natural disaster (Peng et al., 2014). The effects of increased technology collaboration and impact of supply chain collaboration improves resiliency (Arya et al., 2015; Chakraborty et al., 2014). The role of sharing data is to create a more resilient supply chain and collaboration can only improve understanding of disruptions (Papadopoulos et al., 2017). Sharing information on how to slow the spread and documenting findings of research for a cure can help supply chains return to normal. Increased collaboration has allowed entire states to plan and function as one system during COVID-19. Sharing data or methods for solving a particular bottleneck or disruption can save time and money down as the disruption continues to be in effect long-term (Conway, 2020).

3.2.7. Flexibility

Flexibility is characterized as the capacity of a supply chain to adjust according to the required necessities of its network partners and environmental condition in the smallest amount of time. A necessary requirement for flexible supply chains is resource allocation for demand surges (Arora et al., 2010). A lean and agile supply chain creates a flexible supply chain (De Vries, Huijsman, de Vries, & Huijsman, 2011; Fayezi et al., 2016). It is important to implement resource flexibility on different stages of the patient treatment process to cope with uncertainty (Simwita & Helgheim, 2016; Stevenson & Spring 2007). Flexible models for new COVID-19 medical supplies supply chains supply routes save time and allow for a broad approach to managing a disruption. New ways of conducting business, serving customers, and reducing costs are helpful to the whole healthcare supply chain network (Bakertilly, 2020).

3.2.8. Robustness

Robustness is characterized as how the supply chain handles large volumes and does not change standards. A robust supply chain can work despite a few unsettling influences and evaluate all uncertainties that contribute to disruptions (Qiang et al, 2009). Employing methods of bringing robustness to patient flow management in hospitals is necessary for supply chain resiliency (Hanne et al., 2009). Post-disaster coordination of healthcare functions is needed to effectively provide patients with care (Choi & Hastak, 2018). Removing restricting during COVID-19 improves robustness but standards of care should remain the same (Lichtenwald, 2020). The process of obtaining medical supplies during COVID-19 will inevitably change.

3.2.9. Sustainability

Sustainability is characterized as how the supply chain utilizes resources and mitigates the present problems without using all available resources. Improving preparedness and stocking emergency supplies in disaster situations is necessary to supplement demand (Hossain et al., 2020; Hale & Moberg, 2005). Lack of necessary supplies in health care can lead to unfortunate circumstances and the growing need for social practices in the supply chain (Hussain et al., 2018)). Measuring sustainability in the healthcare system and developing a framework for prioritizing the importance of sustainability factors is necessary to remain resilient (AlJaberi et al., 2017). Proactive and reactive strategies for sustainability are both necessary qualities of a supply chain (Maria Jesus Saenz et al., 2015). Mitigating shortages should be part of the healthcare system plan and previous disasters should provide insight into how to use medical supplies during COVID-19 (Conway, 2020; Kaplan, 2020).

3.2.10. Velocity

Velocity is characterized as a supply chain network that has reduced waste by having necessary supplies, treatments, and personnel in the shortest amount of time. Developing a systematic approach to detecting waste and errors is suggested for improved adjustments to disruptions (Cagliano et al., 2011). Knowledge management to improves velocity and flexibility contributes to improved velocity ((Jüttner & Maklan, 2011; Stevenson & Spring 2007). Changes in who is making, distributing, and regulating the supplies and adjusting methods of obtaining supplies improves resiliency during COVID-19 (Conway, 2020; Lichtenwald, 2020).

3.2.11. Redundancy

Redundancy is characterized as the severe and vital utilization of extra stock can be conjured in an emergency. Natural disaster causes a massive demand in stock and usage of stock results in new problems for healthcare (Lodree & Taskin, 2009). Volatile and unpredictable market conditions that occur frequently can cause any level of issues along the supply chain (Ehrenhuber et al., 2015). A framework for analyzing concepts of supply chain resilience is necessary before disruptions occur (Ali et al., 2017). Usage of available hospital beds and protection supplies at an alarmingly fast rate during COVID-19 puts the medical supplies supply chain at risk of not being able to provide necessary material because of the alarming usage and depleting storage (Dentzer et al., 2020).

3.2.12. Awareness and sensitiveness

Awareness and sensitiveness are characterized as anticipating the actual demand and the capacity to perceive a conceivable disturbance by detecting and translating occasions through early cautioning systems. A sensitivity analysis shows the impact of different variables on supply chains (Muñoz-Villamizar et al., 2019, p. 101844). Importance of knowing an organization's needs and informing the organization about the types of supplies that various disasters may require (Achour et al., 2011). Market sensitiveness is dependent upon the amount of collaboration, small changes in one entity can lead to big changes in another entity. Each entity in the medical supplies supply chain is reliant on each other during long-term disasters such as COVID-19. Early detection of threats to the healthcare supply chain can support decision-making and help calculate the severity of a COVID-19 infected group (Conway, 2020). Many countries are reliant on the global supply chain to receive necessary and sensitive medical supplies (Sawyer, 2020).

3.3. Medical supplies supply chains

Each supply chain contributes to a different aspect of healthcare. *Medical supplies, healthcare services, medicines, and blood* are the four significant supply chains in healthcare (Marques et al., 2019). These supply chains have different networks and are connected in different ways. Each primary node within each of these supply chains has a variety of different inner networks with varying complexity. In this study, the medical supply chain is examined. The medical supplies supply chain is primarily focused on everyday hospital necessities. These supplies include materials such as gloves, masks, and gauze. It is necessary to compare and implement data from the medical supplies supply chain to other significant supply chains in healthcare to perform an effective cluster analysis and implement a multi-criteria decision-making methodology. The data from each supply chain is incorporated into the analysis.

To effectively evaluate healthcare supply chain resilience, one must understand the different networks within the healthcare supply chain. Healthcare has a variety of different suppliers, distributors, hospitals, and intermediaries. Fig. 2 shows the medical supplies supply network perspectives that are necessary for providing healthcare (Marques et al., 2019). The network was adapted to include medical supplies categories and delivery frequency. The broad categories of hospital supplies, and frequency of delivery, are found in Matopoulos and Michailidou (2013). The solid line boxes represent network actions and dashed line boxes represent delivery frequency. Arrows represent the flow of services and resources to patients with different types of lines that represent different types of linkages. The number within each box represents the number of network actions within a single entity. Solid lines represent the traditional flow of resources. Fig. 2 shows that if a vital entity were delayed or stopped, it would cause damage to other entities along the supply chain. Distributors are the main choke point in the medical supplies supply chain, and if operations for distributors become abruptly stopped, disaster would likely happen.

4. Research framework methodology

4.1. Decision problem description (case study)

The healthcare supply chain is pivotal in providing proper healthcare and providing treatment in the wake of a disaster. Due to the healthcare supply chain becoming increasingly more complex which often leads to a downfall in inefficiency. As the COVID-19 epidemic spreads throughout the country, understanding what characteristics contribute to an effective supply chain helps medical professionals nationwide to make informed decisions. Many decisions on how to improve a healthcare supply chain are made on each chain separately, and some healthcare entities do not focus on all areas of possible improvement. The objective of this decision problem is to indicate which characteristics contribute to more resilient supply chains in healthcare during the COVID-19 pandemic. Supplies across the country are more depleted than many would expect during a pandemic. Unlike many other disasters, COVID-19 has affected every community in the United States. Affective use of all supplies and personal, while keeping in mind everyone's safety is the top priority for the healthcare supply chain industry.

During the COVID-19 pandemic, cases were significantly higher in places with shortages of personal protective equipment (Press, 2020). The availability of supplies is the first and sometimes only way to combat the disease for many people. Many deaths could have been prevented if adequate supply chains were in place before the pandemic. The medical supply chain starts with raw materials that are determined by the needs of healthcare provider at the end of the network. Larry Glassock, a global logistics professional of the global medical supply chain, stressed the need for many suppliers in wake of unpredictable demand (National Academies of Sciences, 2018).

The connection from suppliers to manufactures is fragile even before

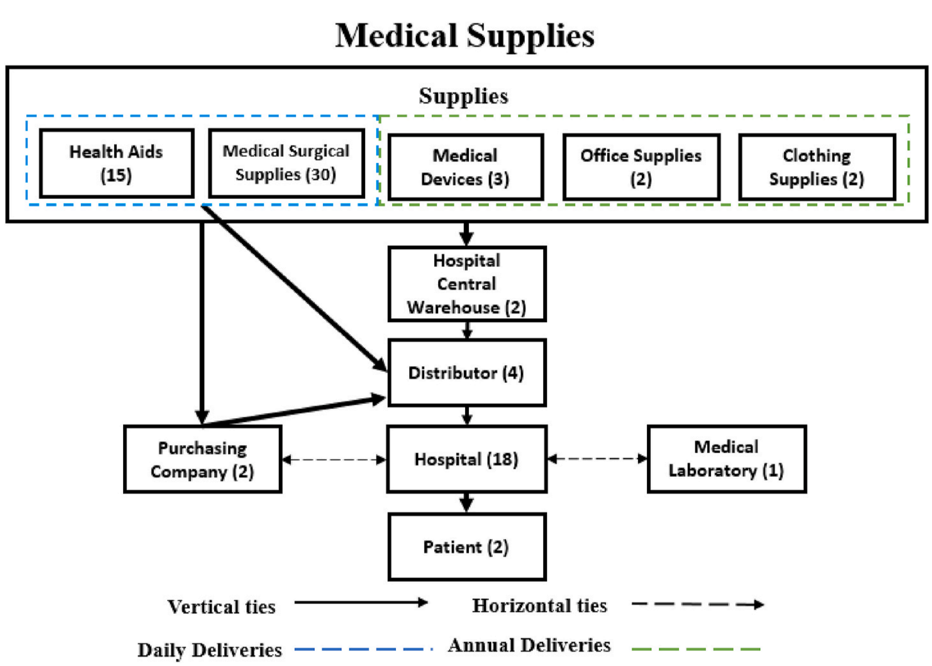

Fig. 2. Medical supplies supply chains in healthcare network.

the pressure of emergency events (National Academies of Sciences, 2018). Manufacturers prioritize certain products based on the need of society. Without constant supply the network resiliency is in imitate danger. Then the products flow into purchasing companies and warehouses (National Academies of Sciences, 2018). This is unique to the medical supply chain because the purchasing companies determine the strategic initiatives of the supply chain to providers and stores products in warehouses around the United States. These entities determine what areas need more supplies and predict where the next threat to network flow is likely to occur. Yet, a pandemic disrupts many different locations at the same time and there could be a new epicenter in the following months. Purchasing companies have a difficult time determining how to distribute medical supplies. Warehouses store these materials to distribute to several medical providers and retail companies. The need for cold storage warehouses increased during the pandemic because cold temperatures are necessary for vaccine preservation. How they distribute, and the number of different entities they can, cover must be calculated. After healthcare providers receive medical supplies, the moral and ethical use of these supplies must be evaluated during an emergency. How much supply can be used for one patient? Where does the provider draw the line? These questions often do not have straightforward answers, but the supply must last until the next available shipment arrives (National Academies of Sciences, 2018).

Many supply chains are prioritizing lean inventories for reduced holding costs. A 15-day reserve for fast-moving products and up to 60 days for slow-moving ones is common and could be a push for even thinner margins (National Academies of Sciences, 2018). As the medical supplies move closer to just-in-time inventory, the elasticity of the supply chain diminishes, creating a threat during a disaster. During a disaster, the steady state of supply moves to a surge. These surges are based on a temporary increase in demand. Medical supplies are difficult to predict, and many healthcare providers would rather use more supplies, if necessary, when treating a patient. During the pandemic, the need for personal protection equipment creates demand curves that were out of sight. Lean inventories put pressure on the providers to be aware of their use of certain materials. The life cycle of that equipment could be reduced rapidly. This would likely reduce the time of slow-moving materials in warehouses. The medical supplies supply chain flows materials downstream and information upstream is the first step to combating disruption by being aware of changes in supply and demand.

The multicriteria decision-making evaluates the 12 indicators and medical supplies supply chain. The alternative values are the indicators listed vertically. The rank values were obtained from five surveys taken by healthcare professionals—the average of the four surveys provides the data for exploring the use of the PIV method. The objective is to find which indicator's characteristics are the best for keeping a resilient supply chain in light of a long-term disaster such as COVID-19. Every indicator is important to the medical supplies supply chain in some shape or form. During COVID-19, demand stain on supply chains is greater than ever seen before. Management must make a tough decision on what indicators are more important to maintaining a resilient supply chain. The multicriteria decision-making aims to help support decision-making in the supply chain industry.

Each healthcare SC expert works in the medical supplies supply chain. The interconnectedness of the HCSC makes employees, along with the network, familiar with other nodes and entities. Like other supply chains, the HCSC is disrupted by any changes or bottlenecks in the natural flow from raw material to patient services. Long-term employees of the HCSC can effectively understand what enables a healthy supply chain to remain resilient and where improvements are needed. A variety of disruptions affect the HCSC each year, creating the need to be prepared for many different issues. Experts in Table 2 are effectively able to determine the enablers that are important to their node, and surrounding nodes along the HCSC, through experience with disruptions and changes to the flow of products.

Table 2
Healthcare supply chain experts profiles.

Healthcare SC Expert	Education Level	Management Experience (Years)	Industry Experience (Years)
Expert 1 (Ex1)	Masters	10	14
Expert 2 (Ex2)	Masters	0	2
Expert 3 (Ex3)	Masters	7	12
Expert 4 (Ex4)	Bachelors	0	1
Expert 5 (Ex5)	Bachelors	1	5

For data collection, a survey was sent to participants who were working in the Healthcare SC problem domains. The entities and interconnectedness of various industries in SC can be vastly different; the target group was chosen specifically to reflect the healthcare supply chain industry. This target group consisted of healthcare professionals and SC engineering managers in the healthcare supply chain management industry. Upon indicating their willingness to participate in the study (i.e., written consent), a PDF document containing instructions asked participants to complete a 5-min questionnaire. The survey, which was conducted from April 2020 to May 2020, had a response rate of 30%. Participants were asked to specify their education, management, and industry experience. Participants ranked each HCSC resilience indicator 1–9 based on the definitions of indicators provided in section 3.2. The various years of experience provided different perspectives on HCSC resilience. There was no identifying information asked of any participant, and the results of the analysis were kept anonymous without traceability to any participant.

Multicriteria decision-making is a technique used to compare different options with a variety of different variables to decide on the best option for the given study. The decision matrix ranks each decision from 1 to the last possible decision. In our study, governments and hospitals want to determine whether a supply chain should be more flexible, have a better supply chain design, and several different factors during COVID-19. The medical supplies supply chain has a percentage value that sums to 100 percent. The percentage value ranks their importance to the healthcare system based on complexity and necessity. Asking medical professionals to rank the importance of flexibility, supply chain design, and many different indicators from 1 to 9 for the medical supplies supply chains during COVID-19 helps to develop a unified approach toward maintaining a resilient supply chain. The Multicriteria decision matrix rank reversal method will rank each indicator. When in a long-term disaster, all indicators are essential to the medical supplies supply chain, but some indicators should take precedence over other indicators.

4.2. Cluster analysis

We employ cluster analysis to better understand the relationship between HSCS resilience indicators and survey rank values. Cluster and MCDM approaches can be seen in Büyüközkan, Feyzioğlu, and Gocer (2016) where countries are combined into groups for data analysis and an MCDM approach is used to rank countries based on prosperity levels. This data analysis tool will help us to organize the indicators into related categories that explain how the survey participants utilized the definition provided in section 3.2 to determine the ranks for each supply chain. K-means cluster method was employed to cluster the resilience indicator into 4 clusters. By employing the K-means unsupervised machine learning technique, we aim to organize the indicators into 4 groups of equal variances, minimizing the sum of squares. We must have data from at least two columns to visualize the cluster analysis. In the K-mean algorithm, four centroids are placed randomly in the data. The objective is to move the centroids to the location where each observation can belong to a cluster and the Euclidean distance between observations and centroid is minimized (Büyüközkan and Çifçi, 2010). The normalized rank values are used to determine the proper cluster without having larger outliers affecting the position of the centroid in the K-mean algorithm. Fig. 3 shows the four clusters of HCSC resilience indicators.

Through this cluster analysis, we can hypothesize how HCSC resilience indicators were used to evaluate each healthcare supply chain. First, the recognition indicators are SC risk management and awareness/sensitiveness. Both factors are directly related to preemptive awareness of threats and risks within the supply chain. A medical supplies supply chain professional needs to be able to identify risk situations before they happen and plan accordingly. Second, we have the reporting indicators communication capability, collaboration, and velocity. This has to do with the flow of information between entities and the effectiveness of communication. Knowledge management information upstream and materials downstream can help to better adjust supply and find alternative ways to solve distribution problems. Third, we have the elasticity indicators agility and flexibility. These indicators directly correlate to how the supply chain handles change and how flexible some of the entities are at finding solutions. The speed at which these changes are made is crucial to getting the proper materials in the hands of healthcare providers during the COVID-19 pandemic. Lastly, we have the SC operation attributes. Security, SC network design, robustness, sustainability, and redundancy are all Indicators that are calculated ahead of a disruption in the SC. Effective distribution is balanced with a safe network by the strategic implementation of security and SC network design. Careful calculations can take place between robustness, sustainability, and redundancy to know how operations should continue to take place during many types of disruption. The indicators and survey results are better explained through the cluster analysis to show how we suspect they are used in the Healthcare system. A simplistic view of the cluster analysis is depicted in Fig. 4.

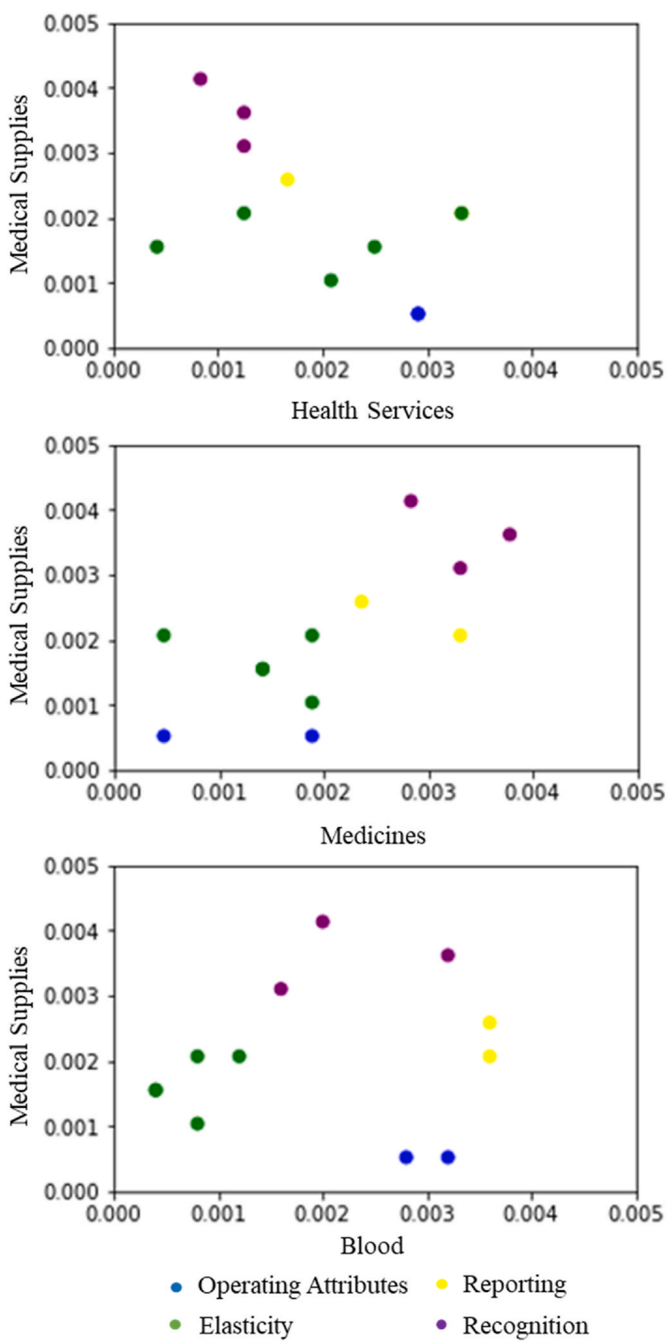

Fig. 3. K-mean clustering of healthcare supply chain resilience indicators.

4.3. Proposed rank reversal proximity index method

The rank reversal method is when alternatives are reverse ranked when new alternatives are added, or existing alternatives are deleted. This method first appeared in Belton and Gear study in 1980 (Büyüközkan, Feyzioğlu, & Gocer, 2016). The best alternative is ranked as one while the worst alternative is ranked as the highest possible value. Rank reversal then began to be used more uniformly in many MCDM methods, and normalization became part of the process to link the relationship between values.

The phenomenon surrounding the rank reversal method often causes the ranking to look different than expected when adding or deleting alternatives from the decision problem. This has to do with the expansion or condensation of the range and thus changes the relative distribution of alternative values. The values are dependent upon each other, and the relationship of values can produce disproportional shifts in the location of alternatives. This is mainly due to the normalization of values, which distorts the original data. Often, to determine the overall weighted normalized distance of alternative from the best, the Mikowski distance was used to calculate the absolute dispersion (Mufazzal & Muzakkir, 2018). The PIV method reduces the rank reversal phenomenon if the criterion is properly defined by weight-ratio index, and a proximity index is employed. Thus, the PIV model in this study uses a weight-ratio index and rank reversal method. This method considers both the aspects of reliability (Logically correct ranking) as well as robustness (stable relative ranking) as an evaluation technique (Mufazzal & Muzakkir, 2018).

The applied PIV MCDM approach considers multiple criteria and multiple alternatives to find the ideal solution. This MCDM approach makes a significant change to the TOPSIS decision matrix method by employing a proximity index value to find the difference of the normalized value of each alternative from the worst available alternative. Normalizing the data allows all features to be scaled equally given the data is normally distributed. The PIV method reduces the worst available alternative to 0 and every successive indicator afterward is larger than 0. This process effectively reverses the rank, making the value farthest from 0 the preferred indicator of healthcare supply chain resilience. The rank reversal method's objective is to find the value closest to a rank score of 1, the best possible value. The best-normalized distance is the value furthest possible location from the largest normalized value in each criterion. It is also important to note that this method only considers positive values so the range for any criterion is all the same. In other rank reversal methods, the ranking can negatively affect values changing the distance between observations. The PIV method is preferred due to its ability to keep the distance information between alternatives solutions. This method is robust and provides adequate reliable rankings. The flowchart of the PIV method is depicted in Fig. 5, followed by the description of each step.

Step 1: **Establish the Decision Problem**

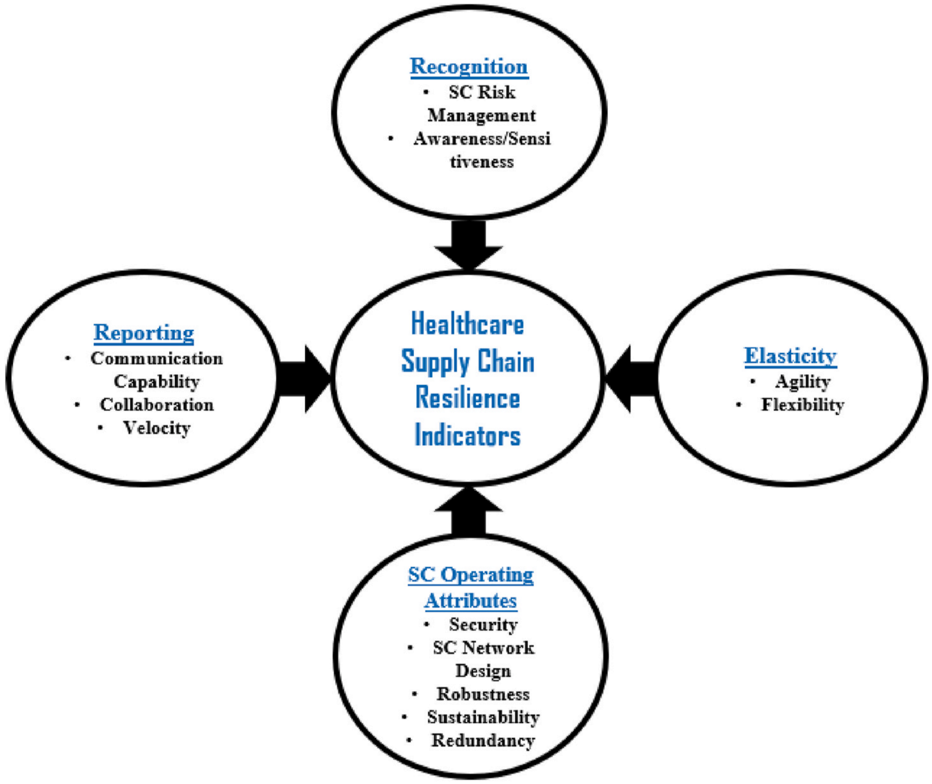

Fig. 4. Organization of indicators into four K-mean Clusters.

The main objectives of the decision problem are to define the criteria, alternative values, weight-ratio for each criterion, and to input the values for setting the feasible alternatives. This step is the building block for every step forward in the rank reversal method. The 12 indicators and 4 supply chains are the alternatives and criteria, respectively. The primary focus of our study is on medical supplies, but the healthcare services, medicines, and blood supply chains are considered in this case study. Each assigned value can affect the overall outcome due to the rank reversal phenomenon. Assigning values needs to be given considerable care.

The w_n value is the weight put on each criterion. The criteria that are more vital to the supply chain are weighted higher. The supply chain with more networks and connections is weighted higher in this study. The x_{mn} value is the rank value response from each expert of the indicators from 1 to 9.1 being alternative indicator being very important to the decision and 9 being not a very important alternative indicator to the decision. The A_m values are the alternatives choices in which the decision matrix rank. The alternatives with the values closest to 0 are ranked as the worst possible choice. The supply chain indicators are the different alternatives to be ranked in the decision matrix. The c_n value is the decision criteria. The criteria are the different supply chains that are essential to healthcare resilience.

Step 2: **Build the Decision Matrix**

The columns in the decision matrix are the criteria for each decision. The rows are the different choices at which to make a decision. The matrix is filled with different rank values for each alternative. A weighted value is placed on each criterion of the decision. A demonstartaion is provided at Table 3.

Step 3: **Determine the Normalized Decision Matrix**

Each x_{mn} value is normalized because each value may be spread on different scales. A common scale is necessary to aggregate data and to make a comparison. Equation (1) uses a normalizing value function for each value in the matrix. The choice of x value will govern the overall spread of the data in the normal distribution. If irrelevant alternatives are determined, the ranking of alternatives can be improperly distributed causing incorrect rankings.

$$r_t = \frac{x_{mn}}{\sqrt{\sum_{t=1}^{m} x_{mn}^2}} \quad (1)$$

Step 4: **Calculate the Weighted Normalized Decision Matrix**

The w_n weight value is multiplied by each normalized value in the matrix. The weight value corresponds to each criterion value. Each weight value is multiplied down the criterion column to which it corresponds in the matrix. The weight value will give more decision power to criteria with a larger weight. The sum of weight values for all criteria is equal to 1. Without the addition of a weight value, all criteria would be given the same decision power in the ranking of alternative values.

$$v_t = w_n * r_t \quad (2)$$

Equation (2) multiples each weighted value by the normalized value.

Step 5: **Approximate the proximity values for each indicator value from the worst indicator value**

The objective of proximity value is to find the proximity of each alternative from the worst available in the range of each decision criterion. The distance of each alternative from the worst alternative measures the deviation and helps to prevent the rank-reversal phenomenon. The proximity index calculation is a unique step and helps to produce more precise rankings compared to other existing methods. The x_{mn} values farther from the worst possible x_{mn} value are rank higher in the decision matrix. Equation (3) is calculated by taking a difference of the weighted normalized value v_t from the worst value in the range.

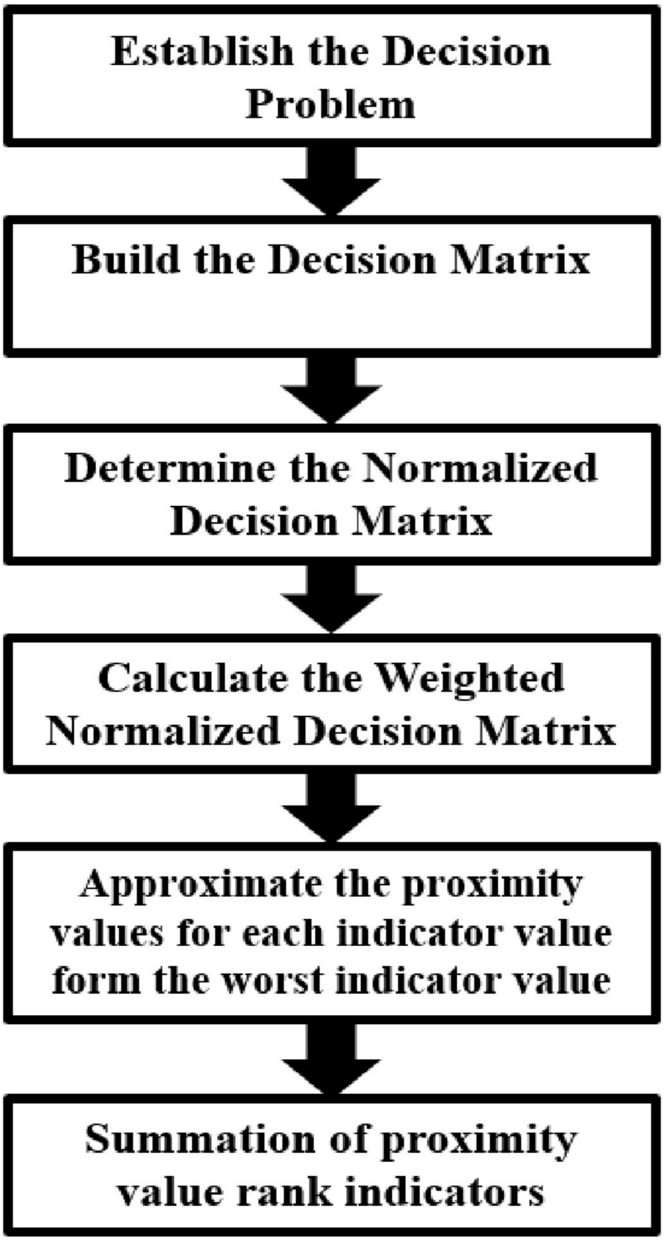

Fig. 5. Flowchart of the PIV method.

Table 3
Decision matrix.

	w_1 / c_1	w_2 / c_2	… / …	w_n / c_n
A_1	x_{11}	x_{12}	…	x_{1n}
A_2	x_{21}	x_{22}	…	x_{2n}
…	…	…	…	…
A_m	x_{m1}	x_{m2}	…	x_{mn}

$$u_t = v_{max} - v_t \quad (3)$$

v_{max} is the max weighted normalized value.

Step 6: **Summation of proximity value and rank indicators**

The values across each row for each alternative value are summed to determine the rank. The largest overall proximity value will be the best feasible option. The smallest value is ranked the worst, while the largest value is ranked the best. Overall proximity values are very precise and a small difference in rank value can be seen in this proposed method.

$$d_t = \sum_{t=1}^{n} u_t \quad (4)$$

Rank d_t values from the smallest proximity to the largest proximity value.

4.4. The proposed method

The rank reversal proximity index decision matrix will be applied to the healthcare supply chain framework proposed in Tables 4–8. The average x values from healthcare professionals are the input data for each column. The weight value, W_j, is listed in the first row of Table 4. W_j in this study is the complexity of each supply chain. From the healthcare supply chain networks discussed in Marques et al. (2019), *medicine* has the highest number of nodes (actors) making it the most complex supply chain. We divided the number of nodes in each supply chain by the total number of nodes in all the supply chains to obtain the weight value W_j. To obtain the weight, we must have at least two columns in this MCDM approach.

Next, the data is normalized to spread values on a different scale, making the values dependent upon each other. All features within the data are put on a common scale without distorting the distance between values.

The weights of each criterion are then multiplied by every value in the column. Criterion with Larger weight values gives the criterion a higher decision value because some healthcare supply chains are more important to the overall decision during the COVID-19 pandemic.

The proximity distance from the largest weighted value in each column is calculated. The largest weight value is the worst attribute for each criterion.

4.5. Validation

To show how the proposed method compares to other popular methods, we demonstrate the results of a Preference Selection Index Method (PSI). The PSI multicriteria decision-making method was first developed by Mandal (2017). This method is known for not including

Table 4
Starting decision matrix table with the average input values from survey.

	Wj:	0.31	0.36	0.24	0.09
		Health Services (HS)	Medicines (M)	Medical Supplies (MS)	Blood (B)
Indicators	Agility (A)	2.80	3.60	4.40	3.40
	Security (S)	5.33	3.40	4.00	3.33
	SC network design (SCND)	5.67	3.20	4.00	3.80
	Comm. Capability (CC)	4.00	4.20	4.40	3.80
	SC risk management (SCRM)	3.67	4.60	4.80	4.33
	Collaboration (C)	1.67	3.20	3.20	2.80
	Flexibility (F)	4.33	3.80	4.00	3.00
	Robustness (RB)	3.00	3.60	4.60	2.33
	Sustainability (SA)	4.33	4.00	3.60	3.67
	Velocity (V)	3.67	4.40	4.60	2.67
	Redundancy (R)	3.00	2.60	2.80	1.67
	Awareness/ sensitiveness (A/S)	2.50	3.67	4.67	3.67

Table 5
Normalized data.

$$r_t = \frac{x_{mn}}{\sqrt{\sum_{t=1}^{m} x_{mn}^2}}$$

	Supply Chains	Health Services (HS)	Medicines (M)	Medical Supplies (MS)	Blood (B)
Indicators	Agility (A)	0.0017	0.0022	0.0022	0.0028
	Security (S)	0.0031	0.0021	0.0020	0.0027
	SC network design (SCND)	0.0033	0.0019	0.0020	0.0031
	Comm. Capability (CC)	0.0024	0.0025	0.0022	0.0031
	SC risk management (SCRM)	0.0022	0.0028	0.0024	0.0035
	Collaboration (C)	0.0010	0.0019	0.0016	0.0023
	Flexibility (F)	0.0026	0.0023	0.0020	0.0024
	Robustness (RB)	0.0018	0.0022	0.0023	0.0019
	Sustainability (SA)	0.0026	0.0024	0.0018	0.0030
	Velocity (V)	0.0022	0.0027	0.0023	0.0022
	Redundancy (R)	0.0018	0.0016	0.0014	0.0014
	Awareness/ sensitiveness (A/S)	0.0015	0.0022	0.0023	0.0030

Table 6
Weighted normalized data.

$$v_t = w_n * r_t$$

	Supply Chains	Health Services (HS)	Medicines (M)	Medical Supplies (MS)	Blood (B)
Indicators	Agility (A)	0.0005	0.0008	0.0005	0.0002
	Security (S)	0.0010	0.0007	0.0005	0.0002
	SC network design (SCND)	0.0010	0.0007	0.0005	0.0003
	Comm. Capability (CC)	0.0007	0.0009	0.0005	0.0003
	SC risk management (SCRM)	0.0007	0.0010	0.0006	0.0003
	Collaboration (C)	0.0003	0.0007	0.0004	0.0002
	Flexibility (F)	0.0008	0.0008	0.0005	0.0002
	Robustness (RB)	0.0005	0.0008	0.0006	0.0002
	Sustainability (SA)	0.0008	0.0009	0.0004	0.0003
	Velocity (V)	0.0007	0.0010	0.0006	0.0002
	Redundancy (R)	0.0005	0.0006	0.0003	0.0001
	Awareness/ sensitiveness (A/S)	0.0005	0.0008	0.0006	0.0003

any relative weight values in the criteria values (Attri and Grover, 2015). While the proposed method provided the opportunity to choose the weight according to the application, the PSI method obtains the weight value from the input values. This method is commonly used when there is conflict in deciding the relative importance among attributes (Mufazzal & Muzakkir, 2018). The PIV method of selecting the weight values is strategically better for ranking the healthcare supply chain resilience indicators due to the weights being selected based on the number of entities in each supply chain network. The complexity of the network information is variable to overall ranking to determine the best rank of indicators. Like the proposed method, the data is normalized, and the weights get changed depending on the normalized values.

Table 7
Weighted proximity index.

$$u_t = v_{max} - v_t$$

	Supply Chains	Health Services (HS)	Medicines (M)	Medical Supplies (MS)	Blood (B)
Indicators	Agility (A)	5.2E-04	2.2E-04	4.8E-05	6.8E-05
	Security (S)	6.1E-05	2.6E-04	9.6E-05	7.3E-05
	SC network design (SCND)	0.0	3.1E-04	9.6E-05	3.9E-05
	Comm. Capability (CC)	3.0E-04	8.7E-05	4.8E-05	3.9E-05
	SC risk management (SCRM)	3.6E-04	0.0	0.0	0.0
	Collaboration (C)	7.3E-04	3.1E-04	1.9E-04	1.1E-04
	Flexibility (F)	2.4E-04	1.7E-04	9.6E-05	9.8E-05
	Robustness (RB)	4.9E-04	2.2E-04	2.4E-05	1.5E-04
	Sustainability (SA)	2.4E-04	1.3E-04	1.4E-04	4.9E-05
	Velocity (V)	3.6E-04	4.4E-05	2.4E-05	1.2E-04
	Redundancy (R)	4.9E-04	4.4E-04	2.4E-04	2.0E-04
	Awareness/ sensitiveness (A/S)	5.8E-04	2.0E-04	1.6E-05	4.9E-05

Table 8
Sum of Weighted Proximity values and Rank.

$$d_t = \sum_{t=1}^{n} u_t$$

		Sum Weighted Proximity indicators	Rank
Indicators	Agility (A)	8.56E-04	4
	Security (S)	4.92E-04	9
	SC network design (SCND)	4.41E-04	11
	Comm. Capability (CC)	4.78E-04	10
	SC risk management (SCRM)	3.64E-04	12
	Collaboration (C)	1.34E-03	2
	Flexibility (F)	6.11E-04	6
	Robustness (RB)	8.74E-04	3
	Sustainability (SA)	5.67E-04	7
	Velocity (V)	5.54E-04	8
	Redundancy (R)	1.36E-03	1
	Awareness/sensitiveness (A/S)	8.45E-04	5

The ranking is solved after the weight values are determined. Since this method does not have a proximity index, the decision matrix is more prone to rank reversal. There are not many uses of PSI in healthcare, but it does appear in Chan, Choi, Hui, and Ng (2015). Patient safety is evaluated with financial penalties criteria and hospital performance attributes to better provide healthcare to veterans. Furthermore, PSI is utilized for SC management in human resource management to better supplement production processes with adequate employees (Bahadori et al. (2017). There are few other works that uses PSI in a different domain. The interested reader may direct their attention to the following works. PSI is employed for the analysis of energy-saving sustainable materials (Arukala et al., 2020), assembly job scheduling (Paul et al., 2016), and a systematic approach to selection cleaning methods for solar panels (Obeidat et al., 2020). Table 9 shows the PSI normalized matrix for our case study.

The ranked values in Table 10 came out very similar in both

Table 9
PSI normalized matrix.

	Supply Chains	Health Services (HS)	Medicines (M)	Medical Supplies (MS)	Blood (B)
Indicators	Agility (A)	1.65E-03	2.18E-03	2.21E-03	2.76E-03
	Security (S)	3.15E-03	2.06E-03	2.00E-03	2.71E-03
	SC network design (SCND)	3.34E-03	1.93E-03	2.00E-03	3.09E-03
	Comm. Capability (CC)	2.36E-03	2.54E-03	2.21E-03	3.09E-03
	SC risk management (SCRM)	2.16E-03	2.78E-03	2.41E-03	3.52E-03
	Collaboration (C)	9.83E-04	1.93E-03	1.60E-03	2.28E-03
	Flexibility (F)	2.56E-03	2.30E-03	2.00E-03	2.44E-03
	Robustness (RB)	1.77E-03	2.18E-03	2.31E-03	1.90E-03
	Sustainability (SA)	2.56E-03	2.42E-03	1.80E-03	2.98E-03
	Velocity (V)	2.16E-03	2.66E-03	2.31E-03	2.17E-03
	Redundancy (R)	1.77E-03	1.57E-03	1.40E-03	1.36E-03
	Awareness/sensitiveness (A/S)	1.48E-03	2.22E-03	2.34E-03	2.98E-03
	Mean	2.16E-03	2.23E-03	2.05E-03	2.61E-03
	PV	5.15E-06	1.27E-06	1.07E-06	4.02E-06
	Omega	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	w	2.50E-01	2.50E-01	2.50E-01	2.50E-01

Table 10
PSI weighted normalized matrix and rank.

	Supply Chains	Health Services (HS)	Medicines (M)	Medical Supplies (MS)	Blood (B)	Average	Rank
Indicators	(A)	4.13E-04	5.44E-04	5.51E-04	6.91E-04	5.50E-04	4
	(S)	7.87E-04	5.14E-04	5.01E-04	6.78E-04	6.20E-04	9
	(SCND)	8.36E-04	4.84E-04	5.01E-04	7.73E-04	6.48E-04	11
	(CC)	5.90E-04	6.35E-04	5.51E-04	7.73E-04	6.37E-04	10
	(SCRM)	5.41E-04	6.95E-04	6.01E-04	8.81E-04	6.80E-04	12
	(C)	2.46E-04	4.84E-04	4.01E-04	5.69E-04	4.25E-04	2
	(F)	6.39E-04	5.74E-04	5.01E-04	6.10E-04	5.81E-04	7
	(RB)	4.43E-04	5.44E-04	5.76E-04	4.74E-04	5.09E-04	3
	(SA)	6.39E-04	6.05E-04	4.51E-04	7.45E-04	6.10E-04	8
	(V)	5.41E-04	6.65E-04	5.76E-04	5.42E-04	5.81E-04	6
	(R)	4.43E-04	3.93E-04	3.51E-04	3.39E-04	3.81E-04	1
	(A/S)	3.69E-04	5.54E-04	5.85E-04	7.45E-04	5.63E-04	5

methods, with one small change between sustainability and velocity. The ranked values for the Preference Selection Method and the rank-reversal Proximity Index Method are very similar, except the ranks for sustainability and velocity are flipped. This could be due to the weighted values being different for the PSI method or the rank-reversal phenomenon that occurs more commonly without the use of a proximity index.

5. Discussion

In our study, we compared healthcare supply chain resilience indicators for medical supplies supply chain with a rank reversal proximity index methodology. Rankings with the largest overall proximity value will be the most feasible option. The objective of ranking these alternatives is aimed at helping to prioritize options that produce a more resilient medical supplies supply chain. From the PIV, method we get the preference in order of redundancy > collaboration > robustness > agility > awareness/sensitiveness > flexibility > sustainability > velocity > security > communication capability > SC network design > SC risk management. This ranking is an ideal solution because we are ranking very comparable alternatives.

Removing alternatives from the decision matrix could cause a small change in the overall ranking values due to the proximity index and normalization of values. Thus, after careful consideration, all alternatives must be provided because they all are significant to the resilience of the medical supplies supply chain during COVID-19. Considering multiple indicators for improved supply chain resilience is a challenge. The top 6 indicators are ranked the same by the PIV method and validation PSI method and should be given significantly more consideration. However, this methodology could be adapted to include criteria about specific nodes along a single chain and include a large number of inputs. The limitation of this study is that we are comparing multiple supply chains within healthcare but additional details about nodes within the supply chain could prove to be more practical.

Since many of the indicators are comparable, the cluster analysis helps researchers and practitioners better understand the relationship between indicators and ranking. We found that indicators in SC operation attribute ranked higher than indicators in other clusters, but the top 6 indicators were spread out among clusters. SC operation attributes cluster involves characteristics related to a disciplined SC. The top-ranked redundancy indictor being part of the SC operation attributes cluster shows the value of being prepared ahead of disruptions. Furthermore, both elasticity cluster indictors were found in the top 6. The elasticity cluster shows the value of not only being prepared but being able to implement necessary changes promptly is of high value to SC resilience.

It is important to note that the weighted proximity values in Table 8 show insight into the importance of each alternative indicator. Redundancy and collaboration are very close in proximity, and both should be taken into consideration by healthcare professionals. Awareness and robustness are also very close in proximity, and there is not much significant difference between the two indicators. The 5 worst-ranked indicators are close in proximity, with the largest distance being 0.00008 from rank 8 to rank 11.

It is to be expected that security and supply chain network design would rank as some of the least preferred characteristics during the COVID-19 crisis. Regulation tends to decrease during long-term disasters to get the necessary supplies and testing done rapidly. Many stops along a supply chain network would be passed, or new suppliers would come into support (Lichtenwald, 2020). Less regulation would lead to a more robust network that could get the necessary supplies in the hands of consumers and healthcare providers. Awareness of the treat of COVID-19 would make people more aware of their safety (Ivanov, 2021). Healthcare providers would likely increase the number of suppliers, and workers along the supply chain leading to lower risk management needed to keep the supply chain healthy. More risk analysis would be allocated to protecting workers and evaluating treatment options to increase the robustness of treatment through shorter fever periods and faster viral clearances (Yildirim et al., 2021). Collaboration between all entities within a supply chain would need to increase. Redundancy of COVID-19 cases and usage of medical supplies would also increase. We have seen through the COVID-19 crisis that products are used at alarming rates, and not having the proper medical materials can slow healthcare services.

6. Implications

The importance of our findings and subsequent research suggestions for supply chain resilience during long-term disasters such as COVID-19 is brought into consideration in this section. The resilience of the medical supplies supply chain during a long-term disaster puts strain on networks in waves. Supply chain resilience relies on the top preferences because of the following instances.

1. Redundant use of the same materials can lead to a lack of supplies and a significant amount of strain on doctors and nurses.
2. Collaboration between governments and entities along the supply chain can get more workers and materials together to combat disruptions.
3. Awareness of the threats of a healthcare crisis to the supply chain is a useful characteristic to keep people united in their efforts to support the healthcare supply chain.
4. Relaxing security constraints during a crisis can help make the healthcare supply chain more robust.

This study shows finding ways to prepare for increased usage of materials, improved collaboration, and robustness of communication and supply networks is vital to handling disruptions. The United States healthcare system can remain resilient by moderating material usage and by implementing procedures for reduced supplies in certain cases. Ivanov (2021) suggests a low-certainty-need supply chain that maintains efficient and agile "ready to change" supply chain states in dynamics rather than pre-designing some static and costly redundant supply chains. Planned and organized yet flexible decision-making procedural changes allow for increased *sustainability* that can directly plan for *redundant* use of materials. Additionally, skipping some of the intermediaries along the supply chain can get many of the materials in the hands of providers in less time. Lichtenwald (2020) suggests that *robustness* can increase if SC has fewer dimensions because the speed of movement of the necessary materials from supplier to a healthcare provider can improve. Improved networking through various communication software (Microsoft Teams, Zoom, message boards) can effectively increase collaboration and organize the flow of information. Lastly, communicating threats to connected entities along the supply chain can help each entity strategically plan the delivery of materials during disruptions. Ivanov (2020) emphasizes that the ripple effect after disruption of an entity along the supply chain can be very damaging to the entire supply chain. *Collaboration* improves the relay of information that can significantly reduce the damages of disruption through effective *awareness* of threats. The suggestions made in this paragraph will effectively improve resilience along the medical supplies supply chain.

7. Conclusion

Ranking the indicators that lead to a resilient medical supplies supply chain during COVID-19 aims to support decision-making for healthcare management professionals. The benefits of this decision-making methodology help to determine what indicators should be given more consideration in the wake of the second wave of COVID-19 or future long-term pandemics. This study has proposed 12 indicators that are significant to a resilient healthcare supply chain and ranked each indicator based on the medical supplies supply chain. Medical supplies are seen as a crucial in healthcare to maintain a resilient and effective healthcare supply chain. The rank reversal proximity index method rescales the values in the decision matrix, applies a weight to the criteria based on the complexity of each supply chain, and determines the proximity of each alternative based on the distance from the worst alternative in the column. The benefits of the proposed method are listed below.

- This method is both simple and easy to automate for a variety of problems.
- Attempts to minimize the rank reversal phenomenon that causes ranks not to appear as expected. The PIV methodology provides a more precise ranking by implementing a proximity index when rescaling the values.
- This method is quick to calculate and can be applied to several different decision matrix methods

This rank reversal proximity index method could be applied to specific material in the medical supplies supply chain, to identify the most important indicators. For example, ventilators are in high demand during COVID-19. Identifying what indicators leads to getting most of the limited supply, could help benefit decision making for hospitals across the country. Additionally, gloves, eyewear, and masks were in short supply during COVID-19. Improving factors like security, supply chain design, and collaboration could create a more robust supply chain which would prove to be beneficial. In many healthcare supply chains before the pandemic, the design of the supply chain leads to the most efficient and organized transport of materials (Singh, Soni, & Badhotiya, 2019 atmosphere of a pandemic can give healthcare management professionals a reason to prioritize other indicators that rely on rapid collaboration and the availability of supplies indicated by the PIV decision matrix. The COVID-19 crisis implies the need for supply chains to change and move quickly to support demand increases.

Before the use of a proximity index, the rank reversal method could sometimes lead to inaccurate rankings which would lead to big issues in decision-making. The proposed method's shortcoming is due to healthcare supply chains across the United States are often different and care for drastically different populations. Rural and urban populations have different strategies for handling the COVID-19 pandemic and could lead to changes in the rank of each indicator in this study. While all indicators are important, some indicators take more precedence based on the location of the healthcare supply chain. In future studies, the decision matrix could be applied to a more specific population making the results more suited for local healthcare supply chains.

The multicriteria decision matrix analysis has provided a guild line to what characteristics the medical supplies supply chain should pursue during a long-term crisis such as COVID-19. Healthcare is the most significant supply chain to sustaining life during a crisis. The following recommendation is for the medical supply chains to become more active during a crisis and keep supply chains resilient.

1. Broad backup storage of supplies in a central location helps supply chains stay sustainable and support healthcare facilities that are using many of the same materials. Redundant use of medical supplies due to exceeding maximum capacity at healthcare centers requires the storage of supplies.
2. Governments and healthcare entities should collaborate more closely during the healthcare crisis to find a way to combat COVID-19.
3. Designated individuals should provide information on healthcare processes during a crisis that will present honest facts and only present useful information. The robustness of reliable information creates a strong foot forward into finding a variety of solutions to improve the medical supplies supply chain in the wake of a disaster.

Healthcare is a necessity for all individuals. Having an effective supply chain minimizes error while increasing efficiency. The money allocated to support healthcare should help to make a resilient supply chain that is aware of threats and can combat many different disasters. The prioritized indicators are essential for the medical supplies supply chain and healthcare overall can help minimize the threats of a disaster during the COVID-19 pandemic.

CRediT authorship contribution statement

Christian Zamiela: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Niamat Ullah Ibne Hossain:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – review & editing. **Raed Jaradat:** Project administration, Resources, Supervision, Writing – review & editing.

Appendix

Healthcare Supply Chain Resilience Survey

This study is evaluating what indicators listed are most significant in healthcare supply chain resilience in the 4 most important supply chains in healthcare. Research studies in healthcare find that the four most important healthcare supply chains are health services, medicines, medical supplies, and blood. The purpose of this survey is to obtain information from individuals in healthcare or supply chain management. This information will be used to create a to rank each Indicators' importance to the healthcare supply chain using a multi-criterion decision-making methodology. *The individual taking this survey will be ranking each indicator from 1-9 for the four healthcare supply chains, 1 being the most important and 9 being the least important.*

Indicators	Health Services	Medicines	Medical Supplies	Blood
Agility				
Security				
SC network design				
Communication capability/technology				
Supply chain risk management				
Collaboration				
Flexibility				
Robustness				
Sustainability				
Velocity				
Redundancy				
Awareness/sensitiveness				

Any comments or recommendations for the study:

Operational definitions Healthcare Supply Chain Resilience Enablers

The supply chain indicators that describe the capacity to prepare properly and recover quickly from difficulties in the healthcare supply chain.

1. Agility- Characterized as the capacity to react to erratic changes in supply and demand quickly.
2. Security- How effectively the healthcare supply chain can effectively plan and secure the safety of different entities and products.
3. SC network design- How the design of the supply network contributes to healthcare supply chain resilience. The network of transportation for materials and treatments between different entities along the supply chain.
4. Communication capability- The technology and resources used to communicate along the supply chain and prevent disaster. Importance of the ability to be able to communicate and to carry out specific functions. The ability to always keep communication.
5. Supply chain risk management - The strength of the management teams to effectively contribute to healthcare supply chain resilience. Evaluating the risk within the supply chain.
6. Collaboration- Sharing the right information and working together effectively in the healthcare supply chain.
7. Flexibility- Characterized as the capacity of a supply chain to adjust according to the required necessities of its network partners and environmental condition in the smallest amount of time.
8. Robustness- How the supply chain handles large volumes and does not change standards. A robust supply chain can work despite a few unsettling influences.
9. Sustainability- How the supply chain utilizes resources and mitigates the present problems without using all available resources.
10. Velocity- A supply chain network that has reduced waste by having necessary supplies, treatments, and personnel in the shortest amount of time.
11. Redundancy- The vital and serious utilization of extra stock that can be conjured in an emergency.
12. Awareness/sensitiveness- Anticipating the actual demand and the capacity to perceive a conceivable disturbance by detecting and translating occasions through early cautioning systems.

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