

Healthcare Supply Chain Disruption Risks

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ABSTRACT

The healthcare sector stands as a cornerstone of every nation's economy, while playing a vital role in fostering the health and wellbeing of populations. Numerous studies have addressed the effective management of healthcare supply chains to ensure optimal healthcare provision. Implementing efficient strategies not only reduces costs but also enhances quality, efficiency, and adaptability. However, the COVID-19 pandemic has exposed significant shortcomings in Healthcare Supply Chain (HSC) risk management strategies. This pandemic has shown that the HSC was unprepared for such disruption and that the traditional supply chain risk strategies

followed are restrictive in tackling long-term global pandemic disruptions. To contribute to the current research on this topic, we introduce a framework that identifies and comprehends disruption risks, their origins, and impacts. Through a thorough literature review and interviews with HSC specialists, risks are identified and prioritized using Bayesian Belief Networks (BBN). The findings of this study seek to provide HSC decision-makers with valuable insights into the primary risks associated with HSC disruptions, paving the way for the development of effective mitigation strategies.

Keywords: *bayesian belief network COVID-19, disruptions, healthcare supply chain, risks*

1. INTRODUCTION

Following the disruptions and tragedies of the COVID-19 pandemic, the healthcare sector has emerged as one of the most indispensable, yet vulnerable, industries for societal sustenance. Beyond safeguarding our health and well-being, the healthcare sector significantly influences a nation's economy through various channels. Firstly, it commands a substantial portion of national budgets; for instance, in 2019, healthcare expenditure in the United States consumed nearly one-fifth of the country's Gross Domestic Product (GDP) (Investopedia Team, 2021). Research cited by the Organization for Economic Cooperation and Development (OECD) Observer indicates that a mere 10% increase in life expectancy correlates with an annual economic growth of approximately 0.4% (Triviron Healthcare, 2019). Furthermore, with its diverse sectors encompassing pharmaceuticals, medical equipment, and healthcare facilities, the industry generates ample employment opportunities.

Like any sector, healthcare confronts numerous hurdles, including integrating new technologies, cybersecurity, market disruptions, and shortages. Projections from the UK Center for Health Solutions anticipate that by 2024, around 68% of medical devices will be interconnected via Internet of Things (IoT) technology (Choudhary, 2019). However, this advancement poses challenges, necessitating training for healthcare personnel and raising concerns about data security as patient information becomes accessible online. Additionally, external market forces such as social media platforms and online pharmaceutical retail disrupt traditional healthcare channels. Increasingly, individuals rely on internet sources to self-diagnose, bypassing traditional medical consultations, and platforms like Amazon offer direct access to medications (Choudhary, 2019).

A critical challenge exacerbated by the COVID-19 crisis is shortages within the healthcare system. Shortfalls in personal protective equipment, hospital beds, ICU capacity, COVID-19 testing supplies, ventilators, and healthcare personnel have been starkly evident (Berlin *et al.*, 2020). These shortages seem to indicate an apparent unpreparedness and inadequate management of healthcare supply chains. In the following sections, we address the intricacies of supply chains, supply chain management, and their disruptions, both generally and in the healthcare context.

1.1 Healthcare Supply Chain Management

The Healthcare Supply Chain (HSC) plays a crucial role in acquiring resources, managing supplies, and distributing goods and services to providers and patients. This process involves various stakeholders, such as manufacturers, insurance companies, hospitals, providers, group purchasing organizations, and regulatory agencies. The primary challenge lies in aligning the supply chain with the care delivery model. Common hurdles in HSC management include provider preference items driving up costs with no discernible improvement in outcomes, limited supply chain health IT hindering price and utilization transparency, and hidden expenses. Improving the HSC entails recognizing its strategic importance to senior leadership, investing in supply chain talent, devising a comprehensive strategy, encompassing all non-labor expenditures within the supply chain scope, understanding

Total Cost of Ownership (TCO), addressing Logistics & Distribution Costs as significant opportunities, and managing across the entire continuum of care (Tang & Musa, 2011).

Within healthcare organizations, numerous departments procure and utilize medical devices, supplies, and equipment. Fragmented purchasing across departments often leads to duplicated or excessive purchases, resulting in wastage. Implementing supply management in healthcare can mitigate such inefficiencies. For instance, the Cleveland Clinic continually refines its supply chain management strategies, yielding savings of up to \$150 million in just two years (2012-2014) from operational costs (Steele, 2014). However, many healthcare organizations lack robust supply chains. Issues highlighted by (Dixit *et al.*, 2019), include deficient collaborative and strategic planning, inadequate capacity planning, and suboptimal profitability for healthcare firms. Other challenges in HSCs encompass inadequate tracking and visibility, as well as ineffective risk, waste, and inventory management (Dixit *et al.*, 2019). Nonetheless, ongoing research focuses on addressing these issues in healthcare, as effective supply chain management not only reduces waste and costs but also enhances healthcare quality, process efficiency, and service flexibility within healthcare facilities (Min, 2014).

1.2 Supply Chain Disruption

Supply chain disruptions refer to abrupt alterations in the availability and demand for materials caused by unforeseen events that could be caused by natural calamities like earthquakes, floods, or human-induced incidents such as industrial accidents (Shen & Li, 2017). These disruptions can manifest as either demand or supply-related issues. Demand disruptions occur when there is a sudden surge or decline in market demand for a specific product, while supply disruption arises when suppliers fail to meet their clients' demands due to unforeseen disasters. The onset of COVID-19 in 2020 caused severe disruptions across various industries globally, with manufacturing closures leading to supply chain disturbances and a spike in demand for medical supplies causing disruptions in the healthcare sector (Queiroz *et al.*, 2022).

Effective risk management is crucial in supply chain management to anticipate and address various risks, including disruptions. Disruptions in supply chains are typically categorized based on their probability and duration, with some posing short-term, low-risk disruptions, while others present longer-term, high-risk challenges (Shu & Mao, 2014). The COVID-19 pandemic exposed the inadequacy of traditional risk strategies in addressing prolonged global disruptions, thereby highlighting the need for more robust approaches (Queiroz *et al.*, 2022). Moreover, in healthcare, technological advances such as Artificial Intelligence (AI), machine learning, and blockchain have introduced new types of disruptions to supply chains (Shaw & Chisholm, 2020). Taken together, it has become apparent that healthcare systems and global supply chains were not prepared to handle such disruptions (Bhaskar *et al.*, 2020).

This study aims to develop a framework to identify disruption risks and their sources, particularly focusing on mitigating disruptions in Healthcare Supply Chains (HSCs). Research questions are formulated to understand the types

and sources of disruptions in HSCs and identify key factors impacting disruption mitigation. Objectives include conducting a literature review on HSC disruptions, analyzing healthcare facilities' responses, identifying critical disruption factors, and developing a comprehensive framework for understanding disruption risks.

The research will contribute by providing insights into HSC disruption sources and types, examining supply chain responses to disruptions like COVID-19, offering a comprehensive overview of risk and disruption in HSCs, and proposing a framework to guide healthcare facilities in enhancing their supply chain risk management and preparedness for disruptions.

2. LITERATURE REVIEW

The literature review commences by detailing the search strategy employed to pinpoint the knowledge gap and the objectives of this study. Subsequently, various supply chain disruption management strategies across diverse industries will be explored, followed by examining HSC disruptions. This will encompass a discussion of different strategies, failures, and complexities within the healthcare sector, along with examples of successful management responses to disruptions.

The methodology for this study involved several sequential stages. Initially, relevant keywords were

identified to guide the search process, utilizing three databases: ABI Inform, Scopus, and Proquest, focusing on publications between the years 2010 and 2021. Subsequently, search results were organized and categorized based on topic, methodology, and research domain. These findings were then analyzed and deliberated upon. Nine (9) keywords were determined for the research, and all relevant papers were retrieved from each database search. **Table 1** displays the keywords used and the corresponding number of papers found in each of the three databases. The subsequent phase involved the elimination of redundant and irrelevant articles, consolidating all relevant papers into a master list. Papers pertinent to supply chain, HSC, and disruption in the supply chain were retained, as they were deemed most pertinent to the study. Following classification, a total of 259 related papers were identified. These were further categorized based on topic, with 143 papers focusing on HSC and the remaining 116 addressing other supply chains with a focus on risk and disruption. **Figures 1 and 2** illustrate the distribution of publication years for papers within each category. Notably, there has been a surge in supply chain research in recent years, with a significant spike in publications in 2020, attributed to the disruptive impact of the COVID-19 pandemic on global supply chains.

Table 1 Keywords and databases

Keywords		ABI Inform	Scopus	Pro Quest
1	Healthcare Supply Chain	43	57	64
2	Supply Chain Disruption	51	46	48
3	Healthcare Supply Chain Disruption	44	39	34
4	Healthcare Disaster Supply Chain	25	34	15
5	Healthcare Supply Chain in COVID-19	24	38	35
6	Healthcare Supply Chain in Pandemics and natural disasters	16	1	12
7	Healthcare Risk and Supply Chain	24	13	26
8	Disaster Supply Chain	12	13	33
9	Risk and Supply Chain	22	6	28

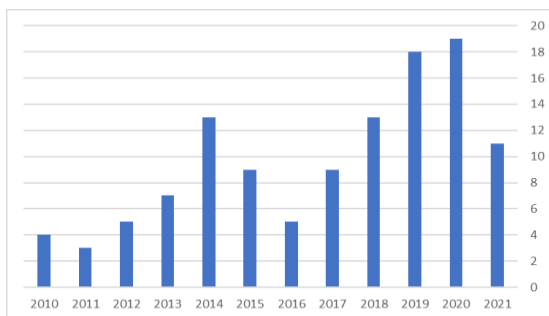


Figure 1 SC risk and disruption related papers per year

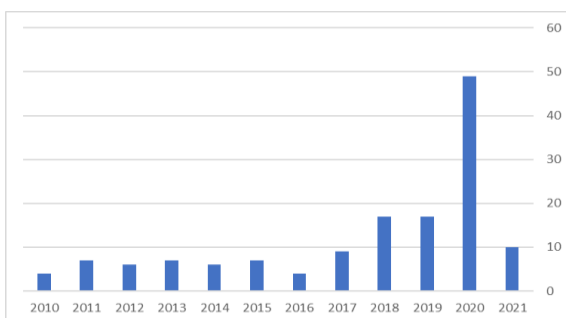


Figure 2 HCSC papers per year

Additionally, the findings were further categorized into three groups: supply chain disruption and risk, HSC, and HSC disruption and risk. The breakdown of the number of papers for each classification is detailed in **Table 2**. Within the supply chain risk and disruption classification, 8 papers were found to be irrelevant and were consequently excluded, resulting in a total of 108 papers in the supply chain disruption and risk category. Regarding healthcare supply chain papers, there were a total of 143, which were then categorized into "Healthcare Supply Chain" and "Healthcare Supply Chain Disruption and Risk." The former comprised 69 papers, while the latter consisted of 74 papers.

Table 2 Number of papers for each category

	Supply Chain Disruption and risk	Healthcare Supply Chain	Healthcare Supply Chain Disruption and risk
Number of papers	108	69	74

The documents in each category were sorted and juxtaposed annually, depicted in **Figures 3 and 4** below. It becomes apparent that research attention on HSC disruption did not escalate until the onset of the COVID-19 pandemic in 2020, evident in a significant rise in published papers. Additionally, scrutiny into the actual theme of HSC gained prominence from 2018 onward.

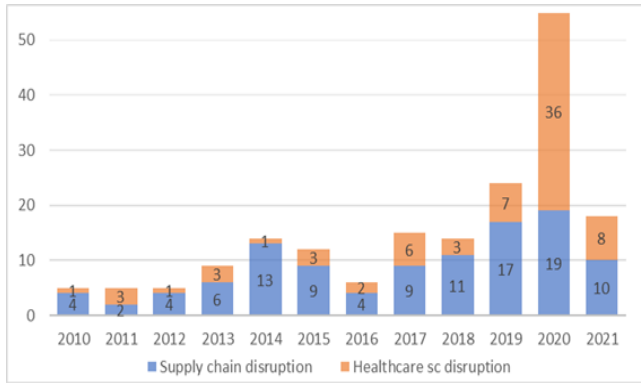


Figure 3 Healthcare SC disruption vs. supply chain disruption

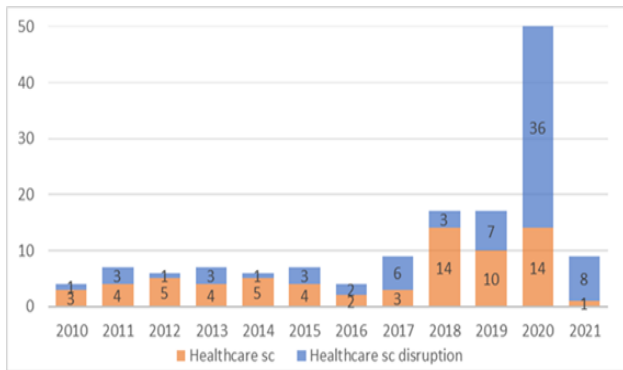


Figure 4 Healthcare SC vs. healthcare SC disruption

Additional categorization was conducted for HSC and HSC disruption and risk, with papers in these categories further classified across research areas such as equipment, material, blood, pharmaceuticals, and general/operations, as depicted in **Figure 5**. From the data presented, it can be inferred that medical equipment, material, and blood supply chains are among the least explored areas within the realm of HSC.

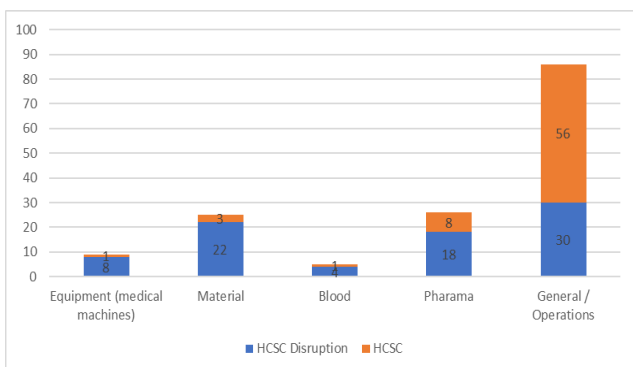


Figure 5 HCSC disruption vs. HCSC research areas

Finally, the papers within each category were sorted according to the research methodology employed, with the outcomes and paper count detailed in **Table 3**.

Table 3 Research methodologies

Research Methodology	Supply Chain Disruption and risk	Healthcare Supply Chain	Healthcare Supply Chain Disruption and risk
Modeling and Simulation	44	20	17
Data Analytics	8	7	5
Case Study	8	11	16
Conceptual	28	19	35
Framework	22	8	2
Review paper	9	8	5

In conclusion, the analysis reveals that the least utilized research approaches within the realm of HSC and HSC disruption are data analytics, review papers, and frameworks. However, focusing specifically on HSC disruption, only two papers were found to propose frameworks. The first paper, titled "Defining Roles for Pharmacy Personnel in Disaster Response and Emergency Preparedness" delineates key activities for various pharmacy personnel categories to undertake in preparation for, response to, and recovery from emergency situations (Alkhalili *et al.*, 2017). The second paper, "Risk Management in Executive Levels of Healthcare Organizations: Insights from a Scoping Review" presents a risk management framework tailored for executive levels within healthcare organizations, consisting of five primary phases. While the former concentrates on the selection and readiness of pharmacy personnel and the latter offers a general risk management approach, both lack a specific plan for addressing HSC disruptions. Consequently, this study identifies a literature gap and aims to propose a framework to outline factors crucial for effective management strategies in dealing with HSC disruptions. Additionally, **Table 4** provides an overview of all papers categorized under "Healthcare Supply Chain Disruption and risk," with highlighted papers addressing COVID-19-related issues (Ferdosi *et al.*, 2020). Notably, recent papers on COVID-19 predominantly discuss material supply chain shortages utilizing conceptual research methodologies.

2.1 Healthcare Supply Chain Disruptions

Effective supply chain management is crucial across all sectors, yet healthcare presents a unique challenge due to the lack of consumer choice in product selection. Unlike other industries, healthcare facilities cannot market or utilize products beyond their expiration dates, highlighting the intricacies of the HSC.

Like any other supply chain, the HSC is susceptible to various disruptions, which are particularly critical as they directly impact human lives. According to **Figure 5**, solutions for supply chain disruptions are most readily available for operations, followed by materials, pharmaceuticals, medical equipment, and blood. Consequently, this section will explore previous solutions and proposed strategies within the healthcare industry to mitigate the impact of disruptions on each sector of the supply chain.

Table 4 Healthcare supply chain disruption and risk table of references

Research Methodology/ Area	Modeling & Simulation	Data Analytics	Case Study	Conceptual	Framework	Review Paper
Equipment	(Aldrighetti <i>et al.</i> , 2019)	(Koç & Türkoğlu, 2022)	(Gereffi, 2020)	(Belhouideg, 2020), (Choong <i>et al.</i> , 2020), (Jafarnejad <i>et al.</i> , 2019)		
Material	(Aldrighetti <i>et al.</i> , 2019), (Abedrabbah <i>et al.</i> , 2021)	(Fillat-Gomà <i>et al.</i> , 2020), (Göçmen, 2022)	(Aldrighetti <i>et al.</i> , 2019), (Gereffi, 2020), (Kwan <i>et al.</i> , 2020), (Martin-Delgado <i>et al.</i> , 2020), (Rowan & Laffey, 2020)	(Bhaskar <i>et al.</i> , 2020), (Choong <i>et al.</i> , 2020), (Hut, 2020), (Cohen & Rodgers, 2020), (J. L. Cox & Koepsell, 2020), (Fields <i>et al.</i> , 2020), (Francis, 2020), (Kunovjanek & Wankmüller, 2020), (McGarry <i>et al.</i> , 2020), (Nibudey & Vidya Baliga, 2020), (Patel <i>et al.</i> , 2017)		(Karim <i>et al.</i> , 2020)
Blood	(Fahimnia <i>et al.</i> , 2017), (Ghatreh & Seyyed-Mahdi, 2019)		(Cheraghi & Seyyed-Mahdi, 2020), (E. Lee <i>et al.</i> , 2020)			
Pharmaceuticals	(Azghandi <i>et al.</i> , 2018), (Doroudi <i>et al.</i> , 2020), (He <i>et al.</i> , 2017), (Lawrence <i>et al.</i> , 2020), (Marcão <i>et al.</i> , 2021), (Moktadir <i>et al.</i> , 2018), (Pearson <i>et al.</i> , 2020), (Tucker, 2020)	(Zavvar Sabegh <i>et al.</i> , 2017)	(Lawrence <i>et al.</i> , 2020), (Marcão <i>et al.</i> , 2021), (Bradaschia & Pereira, 2015), (Shrestha <i>et al.</i> , 2018)	(Cox, 2021), (Evenett, 2020), (Faiva <i>et al.</i> , 2021), (Kharisma & Ardi, 2020), (Morris, 2019)		(Jaberidoost <i>et al.</i> , 2013)
General/ Operations	(Abukhousa <i>et al.</i> , 2014), (Anjomshoe <i>et al.</i> , 2016), (Rastegar <i>et al.</i> , 2021), (Zeng, 2011)	(Lee <i>et al.</i> , 2012)	(Carenzo <i>et al.</i> , 2020), (Govindan <i>et al.</i> , 2020), (Ilie & Popa, 2013), (Naor & Bernardes, 2016), (Woods, 2015)	(Shaw & Chisholm, 2020), (Armani <i>et al.</i> , 2020), (Chakraborty & Dobrzykowski, 2013), (Emmett, 2019), (Jayaraman <i>et al.</i> , 2019), (Kuo <i>et al.</i> , 2021), (Rao <i>et al.</i> , 2011), (Short & Mammen, 2020), (VanVactor, 2011), (Kim & Lee, 2021)	(Alkhalili <i>et al.</i> , 2017), (Ferdosi <i>et al.</i> , 2020)	(Marbough <i>et al.</i> , 2020), (Syahrir <i>et al.</i> , 2015), (Syahrir <i>et al.</i> , 2019)

Shortages and disruptions in healthcare stem from natural disasters, production issues, and medical litigation, among other factors. (Emmett, 2019) proposed steps to prevent disruptions in the HSC. Firstly, enhancing supply chain management in healthcare by involving multiple suppliers and maintaining safety stock is recommended. Secondly, fostering better collaboration among suppliers, consumers, and government entities is crucial. Lastly, every healthcare facility should devise risk management and emergency plans. However, a significant challenge in the

HSC lies in the lack of transparency during disruptions. For example, during the Malaysian flood, a bullwhip effect was observed in the HSC, prompting the development of a mathematical model demonstrating that information sharing was more effective in mitigating this effect (Anjomshoe *et al.*, 2016). (Doroudi *et al.*, 2020). explored the impact of transparency and trust in HSC disruptions, concluding that suppliers should estimate disruption duration and severity and share this information to facilitate the design of ordering policies and risk-sharing mechanisms. Additionally, research

suggests that in the pharmaceutical supply chain, risks related to supply, such as lack of information sharing and key supplier failure, should be prioritized (Moktadir *et al.*, 2018).

Disruptions in the HSC may also arise from inadequate supply chain management and supplier issues such as product recalls influenced by globalization, technology, and operational factors. Blockchain technology offers the potential to track the product supply process from manufacturer to healthcare facility (Jayaraman *et al.*, 2019). Various mathematical models and simulations have been employed regarding pharmaceutical supply chain disruptions to identify effective mitigation strategies. For instance, for saline supply chain disruptions, simulation models recommend investing in manufacturing equipment and adopting agile inventory management techniques that respond to current and anticipated future circumstances. However, given the uncertainty of the future, specialists must identify optimal inventory management policies for different disruptions (Azghandi *et al.*, 2018).

Furthermore, simulations have been conducted to address disruptions and shortages in the HSC. (Aldrighetti *et al.*, 2019). simulated northern Italy hospitals with disruption measures, finding that for long-term disruptions, having a backup supplier is the most efficient mitigation strategy, whereas lateral trans-shipment is effective for short-term disruptions. Additionally, (Zavvar Sabegh *et al.*, 2017). developed a multi-objective optimization model considering green supply chain concepts during natural disasters, aiming to enhance HSC efficiency and effectiveness by saving time, minimizing costs, reducing environmental impact, and optimizing resource utilization.

2.2 Healthcare Supply Chain Disruptions during COVID-19

The initial occurrences of COVID-19 were recorded in December 2019, leading to its classification as a global pandemic by the World Health Organization (WHO) on 11 March 2020 due to its highly contagious nature. This global health crisis has disrupted Healthcare Supply Chains (HSCs) worldwide, a scenario reminiscent of previous instances such as the H1N1 influenza outbreak in 2009 and the Ebola virus epidemics in 2014 (Armani *et al.*, 2020). As a result of the pandemic, there were significant shortages in crucial supplies like personal protective equipment (PPE), intensive care unit (ICU) beds, disinfectants, and mechanical ventilators. This section will explore various strategies proposed or employed to address these shortages (Bhaskar *et al.*, 2020).

To begin, the utilization of 3D printing technology emerged as a viable solution to the scarcity of PPE (Belhouideg, 2020). Given the mode of transmission of COVID-19 through airborne droplets, masks, and face shields became indispensable for public safety. However, the sudden surge in demand overwhelmed existing supply chains. Leveraging 3D printing technology can facilitate the rapid production of PPE, including masks, such as the Copper3D NanoHack (Alkahtani *et al.*, 2021) and HEPA mask models (Kvaternik, 2020), as well as face shields and certain ventilator components (Belhouideg, 2020).

Alternative proposals for addressing PPE shortages include boosting national PPE reserves and deprioritizing profit motives in PPE procurement and management (Cohen

& Rodgers, 2020). Game theory models, drawing on data from healthcare systems like NHS England, underscored the efficacy of proactive stock management practices, including early stockpiling and expanding storage capacities to brace for potential future waves of infection (Abedrabboh *et al.*, 2021). Additionally, linear programming models were developed to optimize PPE inventory routing in disrupted environments, minimizing wastage and stockouts during crises like COVID-19 (Göçmen, 2022). Furthermore, effective programs incorporating administrative measures and staff education, like those developed by (Kwan *et al.*, 2020). were devised to monitor and regulate PPE consumption in clinical settings during outbreaks.

Innovative approaches, such as the global supply chain model proposed by (Bhaskar *et al.*, 2020), advocate for integrating blockchain, Internet of Things (IoT), and Artificial Intelligence (AI) technologies into healthcare supply chains. Similarly, recommendations emphasize leveraging information technology, analytics, and fostering an agile and innovative culture within supply chains (Francis, 2020). Suggestions also include diversifying suppliers and capacities, striking a balance between price and availability, and implementing comprehensive sourcing strategies and distribution models. Finally, building robust governmental and regulatory relationships is emphasized to facilitate swift responses to crises like COVID-19 and ensure timely updates and resolutions on a national scale.

3. METHODOLOGY

This section, we outline and explain the chosen approach to address the research inquiries and achieve the objectives of this study. We also provide a comprehensive explanation of interview formats, survey methodologies, and statistical analysis techniques, alongside an acknowledgment of the research limitations and constraints.

3.1 Research Philosophy and Approach

This research will adopt a pragmatic philosophy, incorporating both qualitative and quantitative data collection methods. Qualitatively, semi-structured interviews and a literature review will be employed, while quantitatively, responses will be gathered through a survey. Regarding the research approach, a combination of inductive and deductive approaches will be utilized. Initially, data will be gathered from HSC (Health and Social Care) experts through semi-structured interviews to form a foundation for theory development, necessitating an inductive research approach. Subsequently, the theory will be tested and validated using a deductive approach through a survey.

3.2 Research Methodology and Data Collection

The research methodology comprises three key phases. Initially, information will be collated from existing literature to establish an initial framework. Subsequently, interviews with HSC experts will be conducted to validate this framework using their expertise. Following the analysis of these interviews, surveys will be administered to HSC professionals to assess the proposed framework. The final phase involves collecting and analyzing survey data to conclude the research. These stages align with the research questions and objectives outlined in **Table 5**.

Table 5 Data collection methods

Research Questions	Objectives	Data Collection		
		Qualitative		Quantitative
		Literature Review	Interviews	Surveys
1. What are the different types and sources of disruptions in the HSC?	To review the HSC disruptions literature and provide a reliable literature review for future research. To provide an overview of HSC disruptions and healthcare facilities' response to them.	X		
2. What are the most significant factors that impact mitigating disruption in HSCs?	To identify the most critical factors with respect to the disruption in HSCs. Develop a framework that identifies disruption risks, disruption risks, their sources, and significance.	X	X	X

3.2.1 Interviews

In this research, interviews represent the second data collection approach following the literature review. Semi-structured interviews were selected due to their adaptability, allowing researchers to incorporate questions as discussions unfold. This approach was favored over alternatives like focus groups because it facilitates in-depth, one-on-one interactions between the researcher and the interviewee, fostering a conducive environment for the expression of individual opinions without external influence. Additionally, scheduling with professionals is more feasible, given their demanding schedules. The interview phase served to validate the initial framework and elucidate the state of HSC in the United Arab Emirates (UAE).

3.2.2 Surveys and Statistical Analysis

Since surveys allow capturing required data from a larger population, a structured survey was formed using an online platform. The goal of the survey was to evaluate the validated framework risks based on impact and probability. Therefore, the survey sampling technique will be purposive; only people with relevant experience and expertise will participate. All the survey participants were chosen based on their backgrounds and experience. The structured survey consisted of 3 sections: the respondents' background, evaluating the framework risks based on impact, and evaluating the framework based on probability of occurrence using a Likert scale for both categories. The respondents' background was essential to make sure the collected information came from experienced HSC professionals. Nonetheless, the reliability of the survey answers was also tested using Cronbach's alpha coefficient. Cronbach's alpha measures the internal consistency of a set of items; it ranges between 0 and 1. The closer the α is to 1, the more reliable the survey answers are; it's preferable that Cronbach's alpha is always above 0.8 to have a reliable set of data (Leontitsis & Page, 2007). The survey results will be analyzed using the Relative Importance Index and the Bayesian Belief Network.

3.2.2.1 Relative Importance Index

The results of the survey will be analyzed using the Relative Importance Index (RII). This method of analysis is based on equation 1 (Kassem *et al.*, 2020). It can show a score for impact, probability, and risk score for each risk, and the highest impact, highest probability, and highest risk score can then be ranked. The higher the RII, the higher the rank of the risk. This method directly depends on participants' responses in the survey, which will give us the independent rank of the risk.

$$RII = \frac{\sum W}{A \times N} \tag{1}$$

Where,

RII = Relative Importance Index

W = Weightage given to each factor by each participant

A = Highest weight

N = The total number of participants

3.2.2.2 Bayesian Belief Network

In addition to the RII, Bayesian Belief Networks (BBNs) will be used to show the interdependencies between risks and rank them accordingly. Bayesian Networks (BNs), also known as Bayesian Belief Networks (BBNs) and Belief Networks, are probabilistic graphical models representing a set of random variables with a possible mutual causal relationship. They are graphed in a network by a Directed Acyclic Graph (DAG). The network consists of nodes representing random variables, edges between pairs of nodes to show the relationship between them, and conditional probability distribution in each node (Horný, 2014). The BBNs can be solved manually or automatically by using appropriate software using the Bayes' Rule shown in equation 2 below. Where P(A) is the preceding distribution of parameter A; P(A|B) is the subsequent distribution, the probability of A given new data B; and P(B|A) the likelihood function, the probability of B given existing data A.

$$P(A|B) = \frac{P(A|B) P(A)}{P(B)} \tag{2}$$

Bayesian networks have been used in many different situations to compile different data from various sources and generate probabilistic predictions. They summarize and combine both qualitative and quantitative information (Borsuk *et al.*, 2004). For instance, for risk management, the usual evaluation of risks would be based on risk score and mapped into a risk matrix without considering the interdependence between risks. When introducing BBNs, the risk will be connected to its risk network, and the risk's effect will be measured without ignoring the holistic impact of the risk across the risk network (Qazi & Dikmen, 2021). The methodology used to calculate the interdependence of the risks is as follows: first, the risk exposure of each risk is calculated using equation 3 below. Then, the risks exposures were mapped to a risk matrix into three zones; high, medium and low, as shown in **Figure 6** below. Risk matrices' main uses are for decision-making purposes and to prioritize

which risk needs to be addressed first (Duijm, 2015). While the risks are healthcare-related, the risk matrix was highly conservative by having a high score to be from [10,25], medium [5,10], and low [1,5].

$$r_{ij} = \alpha_{ij}\beta_{ij} \tag{3}$$

Where,

r_{ij} is the risk exposure assessed by respondent j for risk i ;

i is the ordinal number of risk, $i \in (1, \dots, 38)$;

j is the ordinal number of valid feedback to risk i , $j \in (1, \dots, 39)$;

α_{ij} is the ordinal number representing the likelihood occurrence of risk i , assessed by respondent j , $\alpha_{ij} \in (1, \dots, 5)$;

β_{ij} is the ordinal number representing the level of impact of risk i assessed by respondent j , $\beta_{ij} \in (1, \dots, 5)$

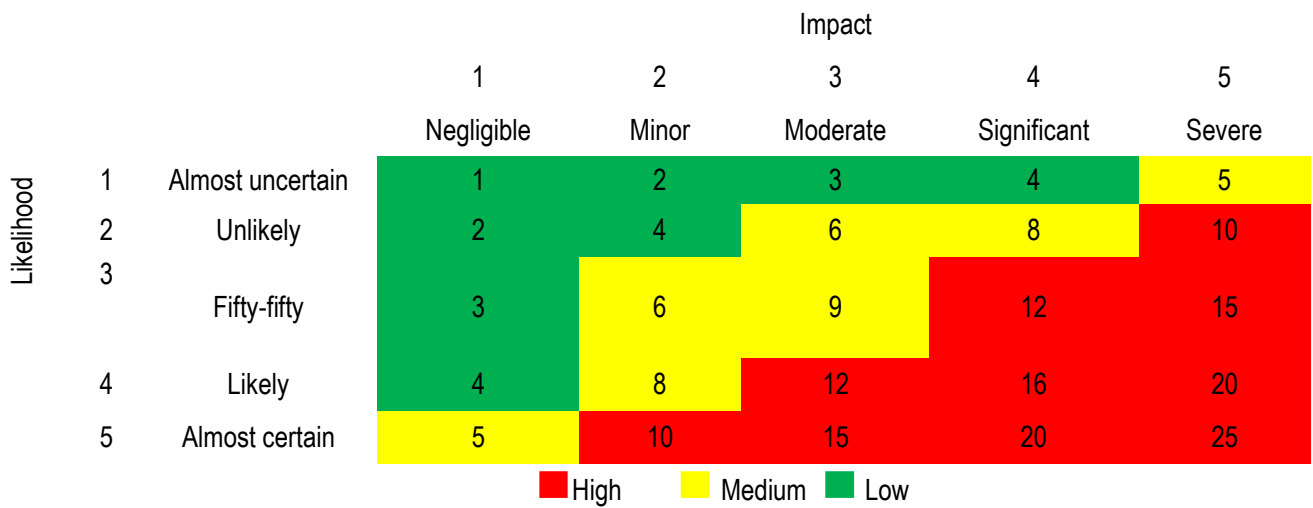


Figure 6 Risk matrix

Afterward, a Bayesian network would be modeled by using the risk exposure data. This paper used the Bayes server software to model and predict the data. Therefore, discretizing the risk exposure data was done, and then the PC algorithm was applied to the network to predict the interdependencies between the different risks. When risks are connected in a network, they will have a different risk exposure score than before. The risk exposure for a network is shown in equation 4 below. Since each risk in a network will affect the whole network's risk exposure score, to prioritize risks accordingly, each risk was shifted to both extremes (high and low). Then, by using equation 5, Network Propagation Impact (NPI) will be calculated for each risk which will be the basis for ranking the risks afterward. The higher the NPI the higher the effect of the risk on the network (Qazi & Dikmen, 2021).

$$RE = \frac{\sum_i^n (Ri = high)}{n} \tag{4}$$

$$NPI_{Ri} = RE|(Ri = high) - RE|(Ri = low) \tag{5}$$

4. RESULTS AND ANALYSIS

This section will encompass the outcomes of the interviews along with the refined framework shaped by the interviewees' feedback. Following this, the survey findings will be outlined, providing a snapshot of the participants'

demographic data. Finally, the data will undergo analysis utilizing both the relative importance index and Bayesian Belief Networks methodologies to yield distinct rankings of the risks.

4.1 Interview Results

Three seasoned professionals with extensive experience spanning over two decades in various emirates of the United Arab Emirates (UAE) were interviewed. The interviews were structured into three segments: delving into the experts' backgrounds, posing open-ended inquiries concerning the UAE HSC, and evaluating the existing framework. These experts previously encountered disruptions in their workplaces, attributed to factors including COVID-19, political unrest, and inflation. Among these, the prolonged duration of the COVID-19 pandemic had the most pronounced impact. Primary challenges faced by the UAE HSC encompassed issues with procurement, limited resources, the absence of a competitive vendor landscape due to single distributors for most supplies, and exorbitant costs for medical equipment and materials. Despite these challenges, the experts perceived the UAE HSC's response to the COVID-19 disruption as effective. Mitigation strategies included proactively engaging local manufacturers to ensure stable material supply through pre-established contracts. However, suggestions were made to

enhance future response capabilities. These included implementing an advanced Enterprise Resource Planning (ERP) system linked to sensors for automatic procurement, installing 3D printers within hospitals for on-demand production during shortages, fostering collaborations with universities for research and development initiatives, particularly in sterilization techniques and integrating AI in healthcare supply chains, and continual improvement of supply chain methodologies to streamline processes and enhance efficiency, crucial for safeguarding lives in healthcare settings.

4.2 Finalized Proposed Framework

After conducting interviews, experts evaluated the initial draft of the framework, incorporating their feedback, suggestions, and additional insights, resulting in the finalization of the framework presented in Table 6. Comprising 38 risks identified through interviews and literature review, the framework was unanimously recognized by experts as impacting the HSC. These risks

were further categorized based on their sources, external or internal and subsequently organized into risk categories and subcategories, as illustrated in **Table 6**. These classifications drew upon an existing risk management framework for the HSC within hospital settings (Wang, 2018). Furthermore, each risk was individually assessed with respect to the triple bottom line principle focusing on People, Planet, and Profit which encapsulates dimensions of sustainable development: environmental quality, social equity, and economic benefits (Correia, 2019). Subsequent categorization was based on the areas of the HSC that were affected, namely material, operations, and others. The material encompasses a range from medical devices to daily medical and non-medical consumables and Personal Protective Equipment (PPE), while operations encompass risks affecting general processes within the HSC. The category of "others" encompasses labor, as it differs from materials in terms of procurement. Finally, the framework also considers the broader impacts on the healthcare facility, such as financial implications, quality of service delivery, and overall operational functionality.

Table 6 Healthcare supply chain risks framework

Supply Chain Disruption Source	Risk Categories	Subcategories	#	Risks Leading to Disruptions	Reference	Triple Bottom Line	Supply Chains impacted in the Healthcare Facility				Areas impacted internally				
						Social	Environmental	Economical	Materials	General/Operations	Others (Labor, etc.)	Financial	Quality	Operations	
External Source of Disruption	Supply Chain Risks	Capacity Risks	1	Low demand of existing products	(Pearson <i>et al.</i> , 2020)		X	X	X			X	X	X	
			2	Higher demand than supply capacity	(Alkahtani <i>et al.</i> , 2021)			X	X	X		X	X	X	
		Forecast Risks	3	Inaccurate demand forecasting	(Duijm, 2015)			X	X	X		X	X	X	
			4	Demand uncertainty	(Duijm, 2015)			X	X			X	X	X	
		Quality Risks	5	Increased Product Recalls	(Jayaraman <i>et al.</i> , 2019)			X	X	X		X	X	X	
			6	Increased probability of purchasing poor quality products	(Duijm, 2015)		X	X	X	X		X	X	X	
			7	Increased levels of counterfeiting	(Duijm, 2015)	X	X	X	X	X		X	X	X	
			8	Low shelf life of products increasing waste	(Pearson <i>et al.</i> , 2020)		X	X	X	X		X	X	X	
		Supplier Risks	9	Unavailability of products from supplier/Shortage in the market	(Moktadir <i>et al.</i> , 2018), (Duijm, 2015)			X	X						X
			10	Lack of information transparency from suppliers	(Doroudi <i>et al.</i> , 2020), (Moktadir <i>et al.</i> , 2018), (Anjomshoae <i>et al.</i> , 2016)				X	X	X		X	X	X
			11	Unavailability of raw material	(Duijm, 2015)			X	X				X	X	
			12	Cash flow/ cash management threat associated with small companies and hospitals	(Duijm, 2015)			X		X		X		X	
			13	Shipping delays negatively impacting performance	(Gereffi, 2020), (Duijm, 2015)			X	X			X	X	X	
			14	Lack of backup suppliers negatively impacting supply	(Aldrighetti <i>et al.</i> , 2019)			X	X	X		X	X	X	

Table 7 Healthcare supply chain risks framework (con't)

Supply Chain Disruption Source	Risk Categories	Subcategories	#	Risks Leading to Disruptions	Reference	Triple Bottom Line	Supply Chains impacted in the Healthcare Facility					Areas impacted internally			
						Social	Environmental	Economical	Materials	General/Operations	Others (Labor, etc.)	Financial	Quality	Operations	
External Source of Disruption	Environmental Risks	Natural Risks	15	Occurance of natural disasters	(Zavvar Sabegh <i>et al.</i> , 2017), (Duijm, 2015)	X	X	X	X	X	X	X	X	X	
			16	Unexpected changes in environment conditions	(Duijm, 2015)	X	X	X	X	X	X	X	X	X	
			17	Unexpected disease outbreaks (Pandemics/Epidemics)	(Bhaskar <i>et al.</i> , 2020), (AbuKhoua <i>et al.</i> , 2014)	X	X	X	X	X	X	X	X	X	
External Source of Disruption	Supply Chain Risks	Logistics Risks	18	Insufficient safety stock- Lack of JIT/Lean in logistics	(Duijm, 2015)			X							
			19	Lack of stock visibility	(Duijm, 2015)			X							
			20	Weak logistics service infrastructure	(Duijm, 2015)			X							
			21	Fragmentation of the drug distribution process	(Duijm, 2015)			X							
			22	Errors in packing and dispensing & picking products	(Duijm, 2015)		X	X							
		Procurement Risks	23	Lack of streamlined procurement process	(AbuKhoua <i>et al.</i> , 2014)			X							
			24	Working with numerous different suppliers complicating operations	(Duijm, 2015)			X							
			25	Conflicting clinician's preferences	(Duijm, 2015)	X		X							
		26	Contractual issues with suppliers negatively impacting performance	(Govindan <i>et al.</i> , 2020)			X								
Internal Source of Disruption	Operational Risks	Strategic Risks	27	Insufficient capacity planning increasing waste	(Dixit <i>et al.</i> , 2019)		X	X							
			28	Lengthy planning horizon negatively impacting decision-making process	(Duijm, 2015)			X							
			29	Inadequate profit margins negatively impacting profitability	(Dixit <i>et al.</i> , 2019)			X							
		Labor Risks	30	Inavailability of workforce	(Alkhalili <i>et al.</i> , 2017), (Kim & Lee, 2021), (Duijm, 2015)	X		X							
			31	Lack of incentive mechanism	(Duijm, 2015)	X									
		Technological Risks	32	Insufficient use of data in the organization	(Marbough <i>et al.</i> , 2020)			X							
			33	Lack of using advanced technology to analyze data	(Prasad & Singh, 2019)			X							
			34	Irregularity of collecting data	(Duijm, 2015)			X							
		Financial Risks	35	Lack of funds from governments and investors to the hospital	(Duijm, 2015)	X		X							
		Legal and Compliance Risks	36	Changes in Regulatory requirements - manufacturing using licensing/change of standards	(Duijm, 2015)	X		X							

4.3 Survey Results and Analysis

The survey was distributed amongst HSC professionals in the UAE; 39 responses were collected in total. The experience profiles of the respondents were 36% with 16+ years of experience, 18% with 11-15 years of experience, 33% with 6-10 years of experience, and the rest with less than 5 years of experience. Also, about 15% of the respondents have 16+ years of experience in HSC, 18% with

11-15 years, 38% with 6-10 years, and 28% with less than 5 years. About 90% of the respondents experience moderate to severe disruption in their workplace due to COVID-19. The HSC professionals were mostly located in Abu Dhabi and Dubai, with a percentage of 46% and 59%, respectively. Moreover, 82% of the respondents dealt with disruptions during their work experience and the effect of COVID-19 disruption in their workplace.

Next, the HSC professionals were asked to evaluate each risk based on impact and probability using a Likert scale with a range from 1 to 5. For likelihood, 1 is "Almost uncertain" and 5 is "Almost certain". For risk severity, 1 is "Negligible" and 5 is "Severe".

4.3.1 Relative Importance Index

Before analyzing the survey results, Cronbach's alpha was calculated, and the value was 0.96, which means the responses were considered reliable. The first method used to analyze the results was the Relative Importance Index. The RII has been calculated based on equation 1 for the impact, probability, and risk score and ranked accordingly. The calculation results are shown in **Table 7** below.

Table 7 RII analysis results

RISK	Impact RII	Rank	Probability RII	Rank	Overall Risk Score RII	Overall Rank
R1	0.5590	19	0.5538	10	0.3096	17
R2	0.7026	4	0.5949	5	0.4179	5
R3	0.6718	6	0.6256	2	0.4203	4
R4	0.6667	8	0.5538	10	0.3692	9
R5	0.4718	38	0.4615	37	0.2178	38
R6	0.5436	23	0.4923	29	0.2676	26
R7	0.5231	31	0.4821	31	0.2521	34
R8	0.5231	31	0.5026	26	0.2629	28
R9	0.7487	1	0.6462	1	0.4838	1
R10	0.6103	11	0.5641	8	0.3442	11
R11	0.6718	6	0.5487	14	0.3686	10
R12	0.6462	9	0.5795	6	0.3744	6
R13	0.7282	3	0.6256	3	0.4556	2
R14	0.6769	5	0.5487	14	0.3714	7
R15	0.6103	11	0.4359	38	0.2660	27
R16	0.5641	18	0.4872	30	0.2748	24
R17	0.7385	2	0.5692	7	0.4204	3
R18	0.5077	34	0.4718	36	0.2395	37
R19	0.4974	36	0.5179	21	0.2576	33
R20	0.4769	37	0.5026	26	0.2397	36
R21	0.5692	17	0.5538	10	0.3153	15
R22	0.5026	35	0.5179	21	0.2603	30
R23	0.5282	30	0.5077	25	0.2682	25
R24	0.5385	26	0.4821	31	0.2596	31
R25	0.6051	14	0.5487	14	0.3320	13
R26	0.6410	10	0.5282	19	0.3386	12
R27	0.5795	16	0.4974	28	0.2883	21
R28	0.5436	23	0.4821	31	0.2620	29
R29	0.5385	26	0.4821	31	0.2596	31
R30	0.6000	15	0.5385	18	0.3231	14
R31	0.5590	19	0.5538	10	0.3096	17
R32	0.5538	21	0.5641	8	0.3124	16
R33	0.5487	22	0.5282	19	0.2898	20
R34	0.5436	23	0.5128	24	0.2788	22
R35	0.5179	33	0.4821	31	0.2497	35
R36	0.5333	28	0.5179	21	0.2762	23
R37	0.6103	11	0.6051	4	0.3693	8
R38	0.5333	28	0.5487	14	0.2926	19

4.3.2 Bayesian Belief Network

BBN was used to get the interdependence score of risks. The risk exposures of all risks were calculated using equation 3 for each survey response, and then the results were imported into the Bayes server. Using the PC algorithm, the network shown in **Figure 7** was developed. The network shows interdependencies between some risks within the network, where other risks are independent and

not affected by other risks. An example is shown below in **Figure 8** of an interdependent network that consists of 3 risks (R5, R6, and R7) and how the NPI was calculated for an R5 in the network. **Figures 9** and **10** show the result of mitigation and realization of R5 by setting the node to low and high, respectively.

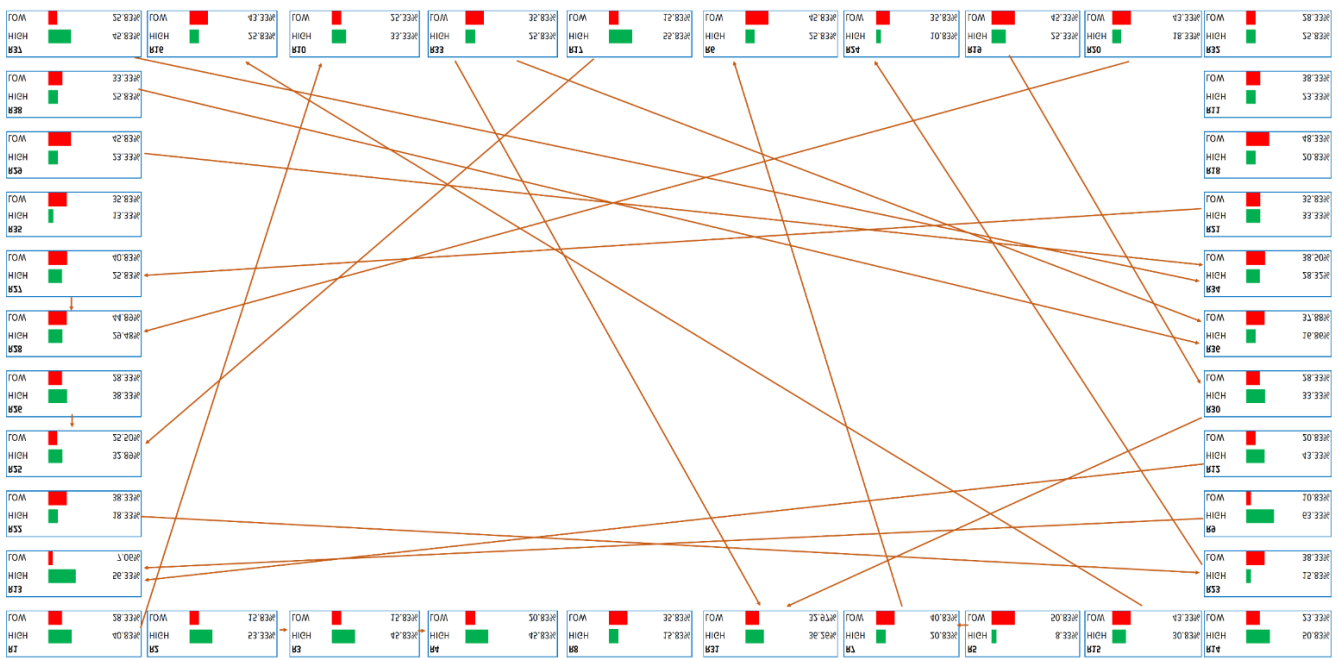


Figure 7 Bayesian belief network for framework risks

Table 8 shows the calculations done using equations 4 and 5 to get the NPI for R5. The NPI calculation results for all risks are shown in Table 9. The overall comparisons

between independent and interdependent rankings are shown in Table 10 below.



Figure 8 Interdependent risk network

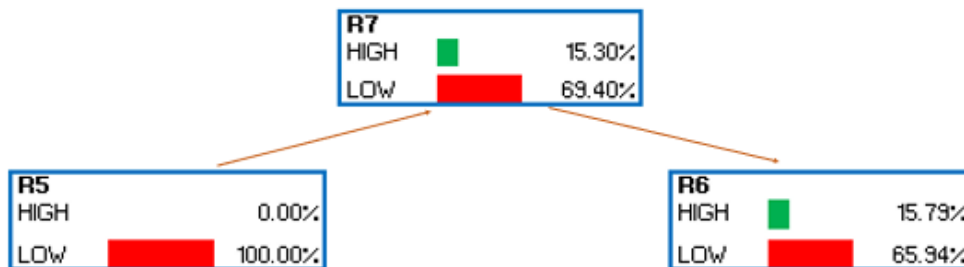


Figure 9 Mitigation of R5 in risk network

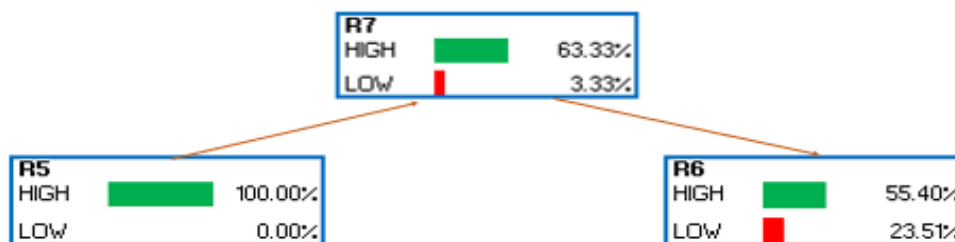


Figure 10 Realization of R5 in risk network

Table 8 NPI calculation for R5

Risk Network	High R5	Low R5
R5	100.00%	0.00%
R6	55.40%	15.79%
R7	63.33%	15.30%
Risk Exposure	72.91%	10.36%
NPI R5	72.91% - 10.36% = 62.55%	

Table 9 NPI results and rankings

Risk	NPI	Rank
R1	0.8239	3
R2	0.5603	16
R3	0.7841	4
R4	0.7743	5
R5	0.6255	12
R6	0.5374	18
R7	0.6577	11
R8	0.1583	37
R9	0.5183	22
R10	0.7447	6
R11	0.2333	34
R12	0.4758	24
R13	0.7005	7
R14	0.5083	23
R15	0.8257	2
R16	0.8604	1
R17	0.3954	26
R18	0.2083	35
R19	0.2356	33
R20	0.2449	32
R21	0.5220	20
R22	0.6097	14
R23	0.6869	9
R24	0.6724	10
R25	0.6116	13
R26	0.5187	21
R27	0.5951	15
R28	0.5499	17
R29	0.5230	19
R30	0.2918	30
R31	0.3608	27
R32	0.2583	31
R33	0.3152	29
R34	0.6871	8
R35	0.1333	38
R36	0.3229	28
R37	0.4441	25
R38	0.1926	36

Table 10 Independent and interdependent comparison

	Risks	RII	Rank	NPI	Rank
R1	Low demand of existing products	0.3096	17	0.8239	3
R2	Higher demand than supply capacity	0.4179	5	0.5603	16
R3	Inaccurate demand forecasting	0.4203	4	0.7841	4
R4	Demand uncertainty	0.3692	9	0.7743	5
R5	Increased Product Recalls	0.2178	38	0.6255	12
R6	Increased probability of purchasing poor quality products	0.2676	26	0.5374	18

Table 10 Independent and interdependent comparison (con't)

	Risks	RII	Rank	NPI	Rank
R7	Increased levels of counterfeiting	0.2521	34	0.6577	11
R8	Low shelf life of products increasing waste	0.2629	28	0.1583	37
R9	Unavailability of products from supplier/Shortage in the market	0.4838	1	0.5183	22
R10	Lack of information transparency from suppliers	0.3442	11	0.7447	6
R11	Unavailability of raw material	0.3686	10	0.2333	34
R12	Cash flow/ cash management threat associated with small companies and hospitals	0.3744	6	0.4758	24
R13	Shipping delays negatively impacting performance	0.4556	2	0.7005	7
R14	Lack of backup suppliers negatively impacting supply	0.3714	7	0.5083	23
R15	Occurance of natural disasters	0.2660	27	0.8257	2
R16	Unexpected changes in environment conditions	0.2748	24	0.8604	1
R17	Unexpected disease outbreaks (Pandemics/Epidemics)	0.4204	3	0.3954	26
R18	Lack of funds from governments and investors to the hospital	0.2395	37	0.2083	35
R19	Changes in Regulatory requirements - manufacturing using licensing/change of standards	0.2576	33	0.2356	33
R20	Environment protection requirements	0.2397	36	0.2449	32
R21	Change in governmental regulations	0.3153	15	0.5220	20
R22	Insufficient use of data in the organization	0.2603	30	0.6097	14
R23	Lack of using advanced technology to analyze data	0.2682	25	0.6869	9
R24	Irregularity of collecting data	0.2596	31	0.6724	10
R25	Insufficient safety stock- Lack of JIT/Lean in logistics	0.3320	13	0.6116	13
R26	Lack of stock visibility	0.3386	12	0.5187	21
R27	Weak logistics service infrastructure	0.2883	21	0.5951	15
R28	Fragmentation of the drug distribution process	0.2620	29	0.5499	17
R29	Errors in packing and dispensing & picking products	0.2596	31	0.5230	19
R30	Lack of streamlined procurement process	0.3231	14	0.2918	30
R31	Working with numerous different suppliers complicating operations	0.3096	17	0.3608	27
R32	Conflicting clinician's preferences	0.3124	16	0.2583	31
R33	Contractual issues with suppliers negatively impacting performance	0.2898	20	0.3152	29
R34	Insufficient capacity planning increasing waste	0.2788	22	0.6871	8
R35	Lengthy planning horizon negatively impacting decision-making process	0.2497	35	0.1333	38
R36	Inadequate profit margins negatively impacting profitability	0.2762	23	0.3229	28
R37	Inavailability of workforce	0.3693	8	0.4441	25
R38	Lack of incentive mechanism	0.2926	19	0.1926	36

5. DISCUSSION

The interview results underscore the pressing need for technological advancements in the UAE's healthcare supply chain (HSC) field, highlighting the transformative potential of Artificial Intelligence (AI) and the Internet of Things (IoT). The integration of AI and IoT in supply chain processes can provide accurate and timely data, significantly easing the forecasting and procurement of materials. Studies such as (Ivanov & Dolgui, 2021) have emphasized the role of digital technologies in enhancing supply chain resilience, particularly in the context of disruptions like the COVID-19 pandemic. Furthermore, the use of 3D printing technology is proposed as an agile and resilient solution to address shortages, especially for personal protective equipment (PPE). Literature by (Zijm *et al.*, 2018) corroborates the potential of 3D printing to mitigate supply chain disruptions by enabling on-demand production of critical supplies.

However, the primary challenge for the UAE's HSC remains the lack of diverse suppliers and local manufacturers. This issue is exacerbated by the reliance on

international suppliers, as demonstrated during the COVID-19 pandemic, leading to significant disruptions in the supply chain (Alicke *et al.*, 2020). Increasing local manufacturing capabilities and diversifying supplier bases are crucial strategies for building a more resilient HSC, as suggested by (Chopra & Sodhi, 2004).

The proposed framework presented in **Table 6** classifies risks based on the Triple Bottom Line (TBL) approach, assessing the impacts on economic, social, and environmental dimensions. The importance of healthcare to community well-being implies that any risks affecting hospitals also impact the broader community (Elkington & Rowlands, 1999). For instance, disruptions in healthcare supply chains can significantly affect the economic sector, given that healthcare expenditures account for a substantial portion of GDP in many countries. Socially, shortages and disruptions in healthcare services, particularly in public hospitals, can severely impact public access to essential medical care. Environmentally, inadequate supply chain planning can lead to the improper disposal of medical

supplies, contributing to pollution and the release of harmful substances (Daughton, 2003).

The framework also categorizes risks affecting internal supply chains: materials, operations, and labor. Material supply chains, encompassing medical consumables, pharmaceuticals, and devices, are particularly vulnerable due to their critical role in healthcare delivery (Sharma *et al.*, 2020). Operational risks stem from supply chain procedures, while labor supply chain risks include factors such as funding shortages. These internal risks cumulatively impact the hospital's overall functionality, affecting financial performance, service quality, and operational continuity.

Survey data from 39 HSC experts revealed that a majority had extensive experience in the healthcare field, with 71.8% having over six (6) years of experience as shown in **Figure 11**. The surveys, analyzed using the Relative Importance Index (RII) and Bayesian Belief Networks (BBN), identified the unavailability of products from suppliers and market shortages (R9) as the highest-ranked risk. Moreover, 82% of them dealt with disruptions during their work experience and, especially recently due to COVID-19, 46% of them assessed COVID-19's disruption in their workplace to be severe and significant. This finding aligns with global trends observed during the COVID-19 pandemic, where supply chain disruptions were prevalent (Ivanov, 2020).

To get the overall Bayesian Belief Network shown in **Figure 7**, the Bayes Server and PC algorithm was used and the input was the risk exposure calculated using the survey results. Then, NPI was calculated for all risks; the NPI values, along with risk rankings, are shown in **Table 8**. However, not all risks were connected to one network, there were several networks formed and some risks stayed independent of others. In total, there was 10 networks connecting 32 risks and 6 risks were independent and were not affected by other risks. The independent risks were R8, R11, R14, R18, R32, and R35. Even though, those risks were independent they still had different rankings compared to the RII since they depend on the bigger network of risks to be assessed. Moreover, the 10 networks differ in size since some were only 2 risks connected and others had up to 6 risks connected into one network. It can be observed that networks with less risks connected had a higher NPI value such R15 & R16, as well as R1 & R10 and that's due to the direct effect each risk has on the other when mitigated or realized.

Therefore, the first 2 ranked risks based on the NPI, were R16 (unexpected change in environmental conditions) and R15 (natural disasters), with values 0.8604 and 0.8257 respectively, which in fact causes very critical disruptions if they happen whilst they were ranked as 24 and 27 respectively using the RII method. Nevertheless, some risks were ranked the same in RII and NPI such as R3 (inaccurate demand forecasting) which was ranked 4 in both analysis methods. Similarly, R19 (regulatory issues) and R25 (insufficient safety stock) were ranked 33 and 13 for both RII and NPI analysis. The last 2 ranked risks were R35 (planning horizon) and R8 (low shelf life) with NPI values 0.1333 and 0.1583, respectively. Compared to RII, those risk were also at the very bottom of the prioritization but not with the same ranking. This indicates that the BBN and using interdependencies with risks will result in a more accurate prioritization than only focusing on risks independently.

Therefore, the Bayesian Belief Network analysis further refined the risk prioritization by considering interdependencies among risks. Risks such as unexpected environmental changes (R16) and natural disasters (R15) were ranked higher in the BBN analysis compared to the RII method, highlighting the critical impact of these external factors. The comparison between independent and interdependent risk rankings underscores the necessity of considering risk interdependencies for more accurate prioritization (Heckerman, 1995).

Table 10 shows a direct comparison between the independent and interdependent results. It can be observed that independent and interdependent risk rankings differ and since independent rankings do not consider other risks, interdependent rankings are more reliable. Therefore, HSC managers should take into consideration interdependencies and the network effect to plan their risk management strategies. However, it can also be observed that all the top 7 ranked risks using independent or interdependent rankings are all due to external disruption sources, which shows that the focus for mitigation planning should also consider external factors. Nevertheless, all the 38 risks should be monitored with planned mitigation strategies with paying closer attention to the top ranked risks. Based on the risk rankings, advanced mitigation strategies with appropriate costs allocated to decrease their impact and probability of occurrence should be taken into consideration. This approach aligns with the broader literature on supply chain risk management, emphasizing the need for comprehensive, data-driven strategies to enhance resilience and ensure continuity in healthcare delivery (Sheffi & Jr., 2005).

6. CONCLUSIONS

Disruptions within the HSC can arise from various factors, but their impact can be significantly reduced through a thorough understanding of risks and the implementation of suitable mitigation measures. Our study offers a comprehensive risk framework derived from the related literature, input from HSC experts, and data collected through interviews and surveys in the UAE. Our analysis employs two methods, namely the Relative Importance Index and Bayesian Belief Networks (BBNs), which are deemed the most reliable due to their consideration of interconnected risks. This integration enhances the predictive and preparative capabilities of healthcare facilities against disruptions, ensuring they are better equipped to handle unforeseen challenges. Our study offers a nuanced understanding of the interdependencies and complexities of disruption risks, thus meeting our goal to enhance decision-making capabilities in HSC management. This approach effectively bridged theoretical research with practical application, confirming the efficacy of the proposed framework in a real-world setting.

For HSC managers, our findings emphasize the pressing need to adopt a proactive risk management approach, as well as the importance of diversifying supply sources. In this paper, we also advocate for the incorporation of advanced technological innovations such as AI and blockchain technology to enhance visibility, traceability, and efficiency within the supply chain. This would augment the firm's forecasting, real-time monitoring, and supply chain responsiveness, thereby reducing vulnerability to

disruptions. As a starting point, HSC managers are encouraged to invest in training and development programs to upskill their workforce in the use of these advanced technologies to ensure their readiness and enhance their absorptive capacity (Daghfous *et al.*, 2018). Moreover, enhanced collaboration among various stakeholders, including suppliers, healthcare providers, and regulatory bodies, would create a more cohesive and agile supply chain network. In effect, the adoption of such changes could lead to significant improvements in cost management, reduction in supply chain bottlenecks, and ultimately, more reliable healthcare delivery.

Like any research, our study has limitations, primarily its narrow geographic focus and the potential biases inherent in expert interviews, which might limit the generalizability of the findings. Future research should address these limitations in various ways. For instance, expanding the geographic scope of the study would help validate the framework's effectiveness across different regulatory and economic contexts, thereby enhancing its global applicability. Another way would be through a quantitative validation of the BBN model's predictions. This could be undertaken using sophisticated statistical methods to solidify the framework's empirical foundation. Moreover, deeper explorations into the integration of emerging technologies like the IoT and advanced analytics could provide much needed insights into real-time risk monitoring and management in HSCs. Future research should also consider conducting longitudinal studies that assess the long-term impacts of implemented strategies, in order to shed light on the sustainability and efficacy of risk mitigation measures over time. Finally, examining the impact of different levels of stakeholder engagement would offer valuable insights into the mechanisms by which collaborative efforts could enhance the likelihood of success of supply chain disruption strategies, especially in context of complex and multi-tiered supply chain structures.

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