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Supply Chain Vulnerabilities in Healthcare Systems Exposed by Global Health Crises

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Abstract: Healthcare supply chains have long been viewed as an overly complex, costly ecosystem. Visibility is limited due to data silos and lack of automation, and stringent regulatory certification hinders quality assurance. However, three key vulnerabilities have increasingly attracted attention: (a) dependence on single-source suppliers for critical products, (b) just-in-time inventory management without buffer stock, and (c) fragmented global logistics susceptible to border disruptions during crises. These vulnerabilities do not merely raise costs or reduce service levels; they directly affect patient safety and compromise health systems' resilience.

All supply chains are vulnerable to disruption, whether through natural disasters, infrastructure failure, geopolitical tension or, as demonstrated in the COVID-19 pandemic, global health crises. The pharmaceutical and medical device supply chains are no exceptions. These sectors, hitherto operating under a veneer of relative stability, are now reassessing strategies in order to mitigate catastrophe — and attention is shifting to solutions that go beyond individual enterprise-level adaptations.

Keywords : Healthcare supply chain resilience,Medical supply shortages,Global health crisis preparedness,Pandemic-induced supply disruptions,Critical medical logistics,Pharmaceutical supply chain risk,Medical device availability,Just-in-time inventory failures,Global sourcing dependencies,Health system operational resilience,Emergency procurement strategies,Supply chain risk management in healthcare,Vaccine and PPE distribution challenges,Health infrastructure fragility, Crisis-driven supply chain adaptation.

I. INTRODUCTION

Healthcare supply chains were designed for efficiency rather than resilience. These systems usually maintain low inventories of finished goods, with many medical devices produced in Asia, transported via global shipping routes, and distributed to various locations around the world. Crises such as the COVID-19 pandemic, Hurricane Katrina, the Fukushima disaster, the U.S.-China trade war, and the Russian invasion of Ukraine have stressed supply chain infrastructures and highlighted key vulnerabilities. The global healthcare system depends on a complex web of suppliers, many of whom manufacture medical products with little or no redundancy in alternative supply locations. Some of these products are in very short supply, leading to shutdowns of treating hospitals and conversely long wait times for surgeries, while crises are creating demand spikes for a large range of medical-devices. Data silos within supply chains are also beginning to be integrated as global end-to-end supply chains become a reality.

A large share of the medical-device market is now supplied by a very limited number of companies, some with single-source suppliers of key components and materials. These companies still perceive the cost savings associated with a widely dispersed global supply chain as outweighing the risk of stockouts, counterfeit products, or losses associated with delayed shipment for a distinct but short period of time. Investments are being made at different levels to regionalize mass manufacturing to counter the long global shipments as eco-frontier supply chains become a reality.

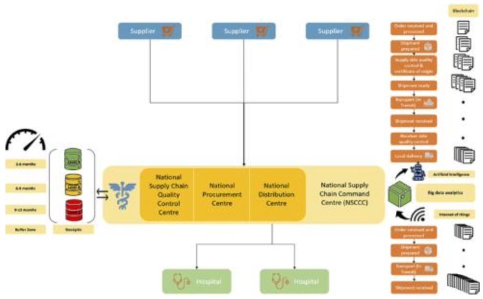

Fig 1: Supply Chain Vulnerabilities in Healthcare

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1.1. Background and Significance

The supply chains that support healthcare systems are the most complex, fragmented, and opaque in the global economy. Constrained visibility, lack of integration, tight margins, and limited investments in technology have left these systems vulnerable to disruption—an especially troubling fact in light of current global events. COVID-19, geopolitical tensions, and natural disasters have exposed these weaknesses and created significant short-term and long-term consequences for healthcare organizations. Patients are the ones who suffer the most from these weaknesses. Infrastructure failures, trade restrictions, pandemics, workforce shortages, and natural disasters that impact the supply chains of healthcare systems can lead to stockouts of critical products, delayed surgeries, increased mortality rates, and other adverse effects on patients and communities. Health systems at all levels struggle to mitigate these disruptions and their subsequent effects because healthcare supply chains remain fragmented, lack comprehensive visibility, and do not incorporate advanced supply chain management technology. Recent developments have highlighted the need to rethink and rethink supply chain strategies. In general, supply chains are designed to operationalize a business model while lowering costs. Throughout history, these systems have focused on moving products from suppliers to buyers at the lowest possible price while meeting service levels. On the healthcare side, however, service levels are expressed in health outcomes rather than units sold. Supply chain disruptions that affect these outcomes are largely outside the control of most health systems, especially those in the United States, which are not designed to carry large volumes of durable goods. As healthcare becomes increasingly influenced by economic principles, the systems supporting patients must also become more resilient, responsive, and flexible. Fortunately, while it is impossible to eliminate all supply chain vulnerabilities, proven strategies can help reduce exposure and risk at least some disruptions.

Equation 1: A simple quantitative "risk" equation for the vulnerabilities in the paper

Let:

- P = probability (likelihood) of a disruptive event or failure mode
- I = impact severity if it happens (e.g., patient-care disruption severity)

Definition

$$R = P \times I$$

Step-by-step derivation (why multiplication?)

Consider a failure event E that happens with probability $P(E) = P$.
Suppose the consequence magnitude is I if E happens, and 0 otherwise.
Define a random variable for loss:

$$L = \begin{cases} I, & \text{if } E \text{ occurs} \\ 0, & \text{otherwise} \end{cases}$$

The expected loss:

$$\mathbb{E}[L] = I \cdot P(E) + 0 \cdot \big(1 - P(E)\big) = IP$$

So, the expected-risk score is $R = P \times I$.

II. HISTORICAL CONTEXT OF HEALTHCARE SUPPLY CHAINS

Healthcare supply chains have historically been characterized by limited visibility into upstream and downstream participants. Thus, the effects of disruptions have typically remained obscured until a global health crisis plunged the world into sickness and economic chaos. The rapid transition of healthcare delivery to telehealth models relieved some supply chain stressors, but shortages of essential drugs, personal protective equipment, test kits, imaging services, and blood products persisted. Recent analysis of the global healthcare supply chain revealed vulnerabilities that threaten remaining quality and patient safety—three key exposures emerge:

1. Disruption or closure of single-source suppliers—especially in China—An unnecessary or unacceptable risk
2. Just-in-Time inventory policies—now viewed as a head-scratching point of failure
3. Fragmented global logjams exposed by border closings and COVID travel restrictions

Key take-aways from supply chain management experts and the practitioners enabled by digital tools include the encouragement to regionalize supply chains as much as possible, particularly for Essential Medical Supplies (EMS). Recent studies by the European Commission and the Organisation for Economic Co-operation and Development (OECD)

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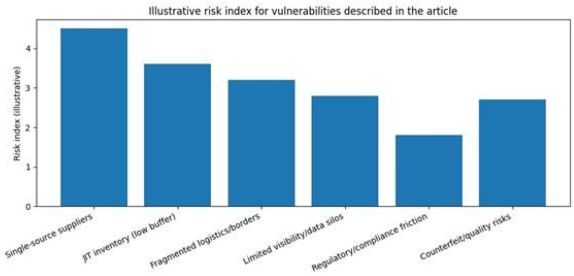
argue eloquently for a supply chain quality mindset to complement the visible-cost focus that has dominated for decades. Other supply chain experts point to the need for smart inventory planning—modeled after just-in-time production—and digital twins that optimize movement through a complex mesh of stockpiles, manufacturers, warehouses, medical facilities, and customers.



2.1. Limited Visibility and Data Silos

Numerous interconnected organizations, including manufacturers, distributors, healthcare providers, testing facilities, and payers, collaborate throughout a healthcare supply chain both to gain value from the supply chain and its products and to provide quality patient care. Medical devices must satisfy local, national, and international regulatory and compliance requirements prior to entering the market; however, distribution processes that ensure that the most up-to-date devices reach the marketplace quickly are also critical. Nevertheless, limited visibility across the healthcare supply chain can hinder companies' efforts for quality enhancement and product development. In addition, lack of data sharing across the healthcare supply chain is an inhibitor to increasing integration and collaboration levels among supply chain partners. Data silos can occur when industry-wide monitoring becomes difficult, as monitoring providers cannot access the full set of information necessary for risk and crisis prediction across the supply chain. An inability to draw upon strong communications with local suppliers has also been shown to hinder resilience during crises.

Data sharing and transparency are indeed affected by the extent to which the industry's product lifecycle phase adheres to a well-defined and coordinated flow within the supply chain. Although it is crucial that all participants supply relevant information, a focus on these trusted collaborations appears to be more important than the extent of data-sharing capabilities in improving supply chain performance. The ability to quickly respond to changing customer demands is vital in fast-moving industries such as consumer goods and high-tech; however, understanding customer demand for medical devices can take a relatively long time. Given that medical devices are often affordable for hospitals only when multiple units are produced, suppliers are generally not able to anticipate future orders for many devices without very close communication with the hospitals. Unfortunately, horizontally and vertically segregated information systems limit data sharing.

2.2. Regulatory and Compliance Constraints

Overcoming the inherent limits on supply chain visibility necessitates overcoming unquestionable regulatory and compliance constraints. Supply chain visibility in healthcare is of paramount importance for effective risk management, yet achieving it remains a significant challenge for companies in pharmaceutical manufacturing and distribution. Healthcare supply chains have distinct characteristics: long lead times, complex regulatory requirements, a high degree of segmentation, strict quality assurance policies, and the potential for the emergence of counterfeit products. These characteristics create silos of information that limit data sharing within the supply chain. The discrete nature of these silos creates multi-tier supply networks whose levels bend, twist, and branch according to the product under investigation, leading to many blind spots in the overall supply network, making traditional top-down strategies of risk monitoring ineffective.

Regulatory compliance results in loss of visibility within the supply chain. Supply chains supported by highly constrained environments such as food and pharmaceutical logistics are subjected to tighter control and regulation than those of many other industries, undermining attempts to achieve end-to-end visibility. For food and pharmaceutical cargoes, government agencies require shippers and shipping companies to supply additional information covering the physical and chemical make-up of these sensitive products. Additional government licences and permits are also required to load, store, pack, and discharge these cargoes. Meeting such strict compliance requirements along each leg of an intricate supply chain imposes a heavy operating burden and is a major contributor to the persistent data silos throughout the supply chain.

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Vulnerability (from article)	Likelihood (1–5)	Impact on patient care (1–5)	Risk index = $(L \times I)/5$
Single-source suppliers	4.5	5.0	4.5
JIT inventory / low buffers	4.0	4.5	3.6
Fragmented logistics & borders	4.0	4.0	3.2
Limited visibility / data silos	3.5	4.0	2.8
Regulatory/compliance friction	3.0	3.0	1.8
Counterfeit/quality risks	3.0	4.5	2.7

Table: Vulnerabilities in the paper, expressed as an *illustrative* risk index

2.3. Quality Assurance and Counterfeit Risks

Healthcare supply chains often lack adequate visibility, making it difficult for hospitals and care networks to monitor the quality of products supplied throughout the entire chain. Many make-or-buy decisions are based on pricing. But the market for low-cost imitatives that lack approval or quality testing—including medicines, surgical products, PPE, and radiopharmaceuticals—continues to grow. Because there are no official trade barriers, European Union assessments have documented that many resemble original products but are often either of inferior quality or entirely different products. Control of the quality of these products is so weak that there is even evidence of counterfeit controls being counterfeited. The production of counterfeit medicines exposed by "Operation Pangea V," the largest-ever joint-interpol policing operation targeting counterfeit medicines, revealed that the Internet is posing increased challenges for quality assurance. The use of counterfeit medicines is a significant risk in reach and treatment of rare diseases with self-injectable therapies. Some hospitals may face financial problems because hospitals have relied on fewer suppliers, particularly manufacturers based outside the jurisdiction of the Food and Drug Administration. Counterfeit medicines may enter by computer-controlled instruments or devices used for long-term treatment. The current supply chain mismanagement at many organizations originates in the failure to realize that security and supply chain continuity—for any component, device, system, or service entering healthcare facilities—must be the first consideration in the analysis of any expenditure. Counterfeit medical products are dangerous because they may contain toxic substances or no active ingredients, be sub-potent or super-potent, be distributed in non-sterile conditions, or interact with either the pathogenesis or treatment of the condition being treated by the patient.

III. KEY VULNERABILITIES REVEALED BY GLOBAL HEALTH CRISES

Recent global health crises have exposed three critical vulnerabilities in healthcare supply chains. These include a heavy dependence on single-source suppliers, particularly for essential products; just-in-time delivery that is too lean and has little margin for risk; and a fragmented global logistics structure that cannot easily accommodate sudden border disruptions. Together these factors have contributed to sporadic but severe stockouts of the supplies necessary for patient care.

When just-in-time inventory systems work smoothly, they minimize waste and help keep costs under control. Many healthcare organizations have come to rely on this approach, a cost-saving measure that nevertheless carries risk. Unforeseen problems—flooding in Thailand, earthquakes in Japan, border closures due to disease or geopolitical tensions—can disrupt supply. So too can the failure of a single-source supplier. Demand for a specialized product may surge to many times normal levels; reliance on a limited supplier base can amplify scarcity in such cases. When a production surge causes a favored supplier's quality controls to slip, counterfeit products become a danger. The industry also faces challenges that extend beyond supply and demand. Natural disasters, manmade accidents, terrorism, geopolitical conflicts, and even labor strikes can damage distribution routes.

Fig 2: Healthcare Supply Chain Resilience

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3.1. Dependence on Single-Source Suppliers

An overreliance on single-source suppliers is the most evident weakness in healthcare supply chains, as highlighted by COVID-19. Such suppliers are acutely vulnerable to disruption. Lockdown measures forced many such manufacturers to close temporarily, creating backlogs that would take many months and, in some cases, years to rectify. Factories that remained open could not keep pace with global demand. Exponential growth in demand from one sector—medical devices and PPE for COVID-19—was not matched by an equal contraction in less essential, more discretionary sectors, where production capacity was switched to meet COVID-19 needs.

The issue of single suppliers is exacerbated by the growing practice of outsourcing. The pharmaceutical industry is highly dependent on a small number of overseas manufacturers for the key ingredients—especially from China—used in the complex formulas for medicines. Product recalls for contamination of medicines manufactured in India highlight the hidden risk that such concentration poses. Such incidents may seem to be isolated quality control failures, but these hidden risks multiply exponentially through the network of connected supply chains across the globe.

The just-in-time (JIT) philosophy that underpins modern supply chains has long-since made visible the impact of travel restrictions. Many large pharmaceutical companies had moved to JIT supply chains with limited raw materials; such a strategy has often been regarded as a contributing factor to the rapid coronavirus vaccine rollout. However, JIT with single-source suppliers is also accompanied by limited stockpiling. Any sudden surge in demand will soon use up the clean or infected stock. When the US Government activated the Defense Production Act to enable the emergency stockpiling of FFP3 masks and respirators, concern that these stockpiles might dwindle accelerated an industry push—to little avail, as stockouts soon became evident.

Equation 2: Single-source dependence → Supplier concentration equation (HHI)

Let there be n suppliers, and supplier i provides share s_i of total supply, where:

$$\sum_{i=1}^{n} s_i = 1, \quad 0 \leq s_i \leq 1$$

Definition

$$HHI = \sum_{i=1}^{n} s_i^2$$

Step-by-step reasoning (why squares?)

If supply is evenly split across n suppliers: $s_i = \frac{1}{n}$

Then:

$$HHI = \sum_{i=1}^{n} \left(\frac{1}{n}\right)^2 = n \cdot \frac{1}{n^2} = \frac{1}{n}$$

So, **more suppliers → lower HHI**.

If there is a single supplier: $s_1 = 1$, others 0

$$HHI = 1^2 + 0 + \cdots + 0 = 1$$

So **single-source → HHI = 1 (maximum concentration)**.

Squaring penalizes dominance: a jump from 0.5 to 0.8 share increases s^2 sharply.

3.2. Just-in-Time Inventory and Stockout Risks

Healthcare supply chains have increasingly relied on a Just-in-Time (JIT) inventory strategy to minimize costs associated with storing expensive inventory. Although JIT inventory management has merits, such as lowering inventory-holding costs, maintaining a low-cost health logistics solution, and incentivising closer working relationships between distributors and manufacturers, it has a dark side. Such supply chains are susceptible to stockouts when unanticipated demand surges arise. Capability development, which refers to establishing sufficient inventory to address demand surges, is an essential aspect of a highly resilient healthcare system. Capabilities provide a level of healthcare support that may be required but not needed on a continual basis. The lack of any buffer to accommodate spikes in demand was especially stark during the COVID-19 pandemic. For example, national stockpiles were depleted rapidly, and additional stock was not available

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because vital health products were manufactured on a JIT basis and global suppliers had been relied on by the health system.

Fragility and risk in supply chains around the world exist as demonstrated convincingly by recent crises such as the COVID-19 pandemic, hurricane damage to the Gulf Coast of the United States, geopolitical conflicts such as the war in Ukraine, and the trade embargo by the United States against China and many others. In each of these cases, a lack of available materials halted manufacturing and thus the provision of important services in the production of products needed by people worldwide and tested the level of preparedness in health systems around the world. In the case of hurricanes in the Gulf of Mexico, the destruction of distribution facilities led to shortages of many basic necessities in the surrounding areas for short periods of time.

3.3. Fragmented Global Logistics and Border Disruptions

The emergence of the COVID-19 pandemic highlighted the effects of border and port disruptions on healthcare supply chains. The resulting chaos exemplified that while supply chains are often viewed as extended logistical networks — encompassing transport, customs inspections, ports, warehousing, distribution, and delivery — healthcare supply chains rely heavily on a transport infrastructure that is both congested and fragmented and on borders that can suddenly close or impose new restrictions. In the face of such shocks, healthcare supply chains necessarily act locally, with the potential consequences of gridlock or meltdown.

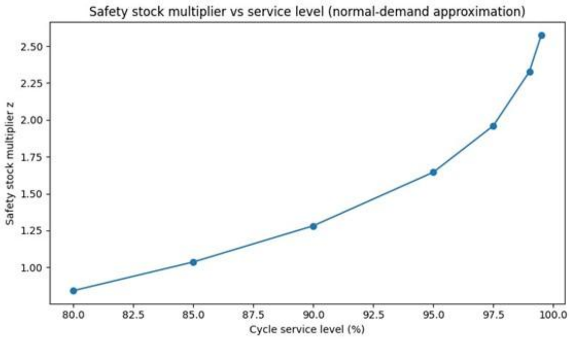
The pandemic nevertheless illustrated the interconnectedness of global supply chains across production, transport, and storage, which has led some healthcare suppliers to adopt "contract logistics" strategies that engage specialist third-party logistics providers. Implementation also raises distinct challenges. For example, some contract logistics providers are experiencing rapid degradation in service quality while the demand for vaccines, treatments, and diagnostics continues to expand; however, a lack of visibility into much of the logistics process can make it difficult for healthcare supply-chain managers to ascertain which logistics providers remain equipped to fulfil the immediate needs of their supply chains.

IV. IMPACTS ON PATIENT CARE AND HEALTH SYSTEM RESILIENCE

Well-documented supply chain vulnerabilities highlighted by global health crises are reflected in the careful research of supply chain and public health experts, who outline the substantial effects on patient care and healthcare system resilience. The consequences of modern supply chain vulnerabilities have thus far been explored primarily by examining patient care disruptions linked to COVID-19, natural disasters, infrastructure failures, and geopolitical tensions.

Effects of the COVID-19 pandemic on patient health, risk perception, and healthcare-seeking behaviour were documented in the early months of the crisis, and the WHO projected that over 80 million children would miss routine immunizations in the last months of 2020, with reductions of over 50% reported for prevention and treatment of neglected tropical diseases. Chemical shortages triggered by the pandemic caused over 7% of drug shortages in the USA in 2020 alone, and shortages of critical care drugs in European countries, including problems with water purification systems, were also noted. Delayed access to surgery, either because of post-operative complications or restrictions on elective surgery, was also reported. A supply chain assessment of hospital sterilisation and decontamination services in England during the pandemic highlighted reduced staffing and greater service fragility.

Considering these findings, experts report that supply chain disruptions and mitigation strategies adopted during the COVID-19 pandemic not only affected SARS-CoV-2 transmission trends but also future resilience to eye disease and advanced cancer in other parts of the world, with important implications for loss of life. However, efforts to enhance resilience might simply delay excess mortality rather than reduce it, with natural disasters potentially contributing to such delays.



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V. CASE STUDIES FROM RECENT CRISES

The impact of global health crises on healthcare supply chains can be observed through a series of real-life case studies. The COVID-19 pandemic was remarkable in the extent to which it undermined the ability of healthcare supply chains to serve patient needs. Hospitals could not access essential COVID-19 supplies such as N95 masks and personal protective equipment (PPE) in the necessary volumes, and even commonplace products such as syringes, oxygen, and blood bags became scarce.

Other types of crises have drawn attention to similar vulnerabilities in healthcare supply chains. Natural disasters, such as hurricanes and wildfires, have caused local product shortages and redirected deliveries out of affected regions. Disruptions in the global transportation network, such as the grounding of the Ever Given, a container ship lodged in the Suez Canal, have made it difficult to supply goods that were in demand elsewhere. Over the last decade, trade relations among many nations have soured, leading to an increased risk of protectionist policies, such as increased tariffs or outright bans on imports from specific countries, that further hinder the free flow of goods and services.

Equation 3: JIT and stockouts → Reorder Point and Safety Stock (step-by-step)

Let:

- Daily (or weekly) demands be random: D
- Lead time be L days (assume constant for the base case)
- Demand during lead time:

$$D_L = \sum_{t=1}^{L} D_t$$

Assume D_t are i.i.d with mean μ and standard deviation σ.

Mean of lead-time demand

$$\mathbb{E}[D_L] = \sum_{t=1}^{L} \mathbb{E}\,[D_t] = \sum_{t=1}^{L} \mu = L\mu$$

Variance of lead-time demand

$$\mathrm{Var}(D_L) = \sum_{t=1}^{L} \mathrm{Var}\,(D_t) = \sum_{t=1}^{L} \sigma^2 = L\sigma^2$$

Standard deviation

$$\sigma_L = \sqrt{\mathrm{Var}(D_L)} = \sqrt{L\sigma^2} = \sigma\sqrt{L}$$

A reorder point is chosen so that the probability of stockout during lead time stays below a target.

Let z be the normal "safety factor" corresponding to the desired service level.

Reorder point

$$ROP = \mu_L + z\sigma_L = (L\mu) + z\big(\sigma\sqrt{L}\big)$$

Safety stock is:

$$SS = ROP - \mu_L = z\sigma\sqrt{L}$$

Interpretation tied to the paper

- aims to push $SS \to 0$.
- Crises increase σ (demand uncertainty) and often increase L (transport/border disruption).
- Since $SS = z\sigma\sqrt{L}$, buffers must rise *nonlinearly* with disruption.

5.1. Pandemic-Driven Disruptions

A detailed assessment of the effects of the COVID-19 pandemic at a global level provides several real-world examples of patient care or healthcare system resilience problems arising from supply chain vulnerabilities. Within a year of the onset of the COVID-19 pandemic, research had already identified overburdened healthcare facilities and supply chains, and even when COVID-19 was declared a pandemic, epidemiologists emphasized the need to replace "business as usual" with "business unusual" (DDA 2020).

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In March 2020, the Global Radiology Community released a virtual consensus statement to address urgent clinical needs during the COVID-19 pandemic. The situation involved severe shortages of imaging facilities and radiologists across the world, and radiology was at a turning point in the pandemic. Superprioritization and ultradecanting across continents were expected, and these emergency procedures affected almost everything in radiology, from education to supplies; intellectual property; and licensing of imaging, equipment, algorithms, software, and examinations of all kinds. These fragile supply chains had become absolutely silenced by the global pandemic. If there was a time when infectious disease-related research received a significant boost of interest and funding, it had now reached another plateau where there was little fluctuation in research output other than changes of specific pathogens.

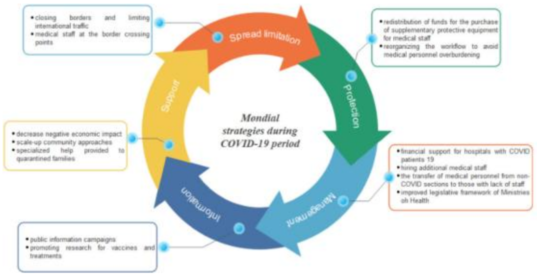

Fig 3: Public Health Care Systems during the COVID-19 Pandemic

5.2. Natural Disasters and Infrastructure Failures

Extreme weather events and natural disasters disrupt healthcare supply chains and compromise patient care. Hurricanes and floods can damage local facilities, while simultaneous events in different parts of the world challenge access to spare parts. Disaster recovery requires access to specialist equipment such as clothing and generators, which may not be readily available. The concomitant occurrence of several disasters in one region hampers the transport of goods to areas in urgent need. In Australia, for instance, the COVID pandemic coincided with floods and bushfires, paralleling occurrences in other countries and significantly disrupting supply chains.

Natural disasters can also disrupt supporting infrastructure. Ice storms in North America and flooding in southern Texas brought areas to a sudden standstill, sending consolidation rates to unprecedented levels. Windstorms, heavy snow, icy roads, and rains closed sea, rail, and road connections, affecting imports and domestic deliveries. The consequent delays and increased costs delayed resumption of full operations and cut freight capacity. Access to warehousing capacity also deteriorated. A shortage of available trailers aggravated the issue, as many trucks on long-distance delivery failed to return to origin. In Germany, flooding disrupted wholesale storage and distribution for several weeks, with water and electricity supply outages heavily affecting hospitals.

5.3. Geopolitical Tensions and Trade Restrictions Geopolitical tensions, such as the prolonged trade war between the United States and China, have accentuated the political and economic risks inherent in international supply chains. Medical wards in U.S. hospitals are equipped with supplies produced predominantly in China. During 2019 and 2020, patients and policymakers in the United States, Canada, and Europe expressed deep concerns about reliance on China as a source of active pharmaceutical ingredients. During the 2019 U.S.-China trade negotiations, tariffs were imposed on certain drugs imported from China. Patients receiving highly specialized medicines not produced anywhere else were especially apprehensive. This anxiety proved well-grounded. U.S. and Chinese trade tensions were matched by rising conflict over Taiwan, and by 2021 the risk of a Taiwan Strait crisis was escalating. With the largest market share of runner-up Taiwan, China has a superior position in cross-Strait relations. Health care is vulnerable to disruption of bilateral trade relations and Taiwan Straits trade. High-performance healthcare supply chains incorporate digital twins—ideally, industry consortia can help enable the creation of shared regional supply-chain twins.

Equation 4: Fragmented logistics/border disruption → Lead time shock equation

Safety stock change:

$$SS' - SS = z\sigma\left(\sqrt{L + \Delta L} - \sqrt{L}\right)$$

Step-by-step

Base: $SS = z\sigma\sqrt{L}$

Shock: $SS' = z\sigma\sqrt{L + \Delta L}$

Subtract:

$$SS' - SS = z\sigma\left(\sqrt{L + \Delta L} - \sqrt{L}\right)$$

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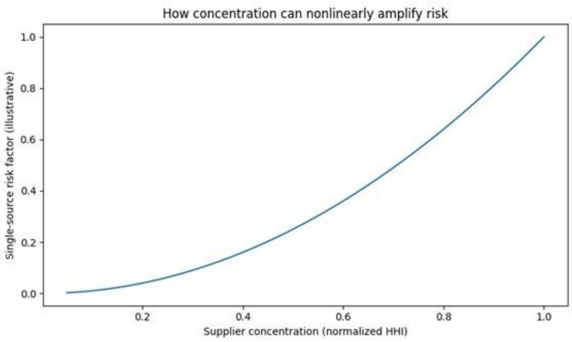
Meaning

- Even if demand variability σ stays the same, **longer lead time forces more buffer**.
- If both σ and L rise (typical crisis), the effect compounds.

VI. MITIGATION STRATEGIES AND BEST PRACTICES

Recent experiences have highlighted strategies that mitigate supply chain disruptions and their consequences. Broadening the supplier base for critical items—leveraging local production ecosystems and clustering suppliers in key regions—can reduce reliance on individual suppliers while offsetting the impact of regional disruptions. Selective strategic stockpiling and warehousing enhance resilience, albeit at an added cost. Incorporating seasonality further informs holding requirements when global weather and climate patterns indicate elevated risk. Increasing overall supply chain visibility, enabled by data-sharing across borders and among multiple partners, enables proactive decision-making. The potential benefits of investing in supply chain digital twin technologies are now clearer. Digital twins are virtual replicas of the physical parts of the supply chain that allow a healthcare organization to run simulations and analyze the implications of various "what if?" scenarios.

Control towers and digital twins are similar by allowing end-to-end visibility on supply chain flows and open supply chain collaboration among ecosystem partners. Unlike traditional control towers, however, digital twins also allow organizations to anticipate future flow behavior and conditions. For example, healthcare organizations can see not just where inventory levels are low or expiring, but also where demand is projected to spike or fall and act to prevent downstream shortages and wastage, or where there is a high risk of late delivery and alter plans accordingly. Digital twins do this by enabling organizations to track global weather patterns or political tensions, including routes that get shut down and shipments that have to be rerouted.



6.1. Diversification of Suppliers and Regionalization

In healthcare supply chains, dependence on supplies and equipment from single-source suppliers presents significant risks. Diversification across multiple suppliers mitigates the danger of disruption when major sources are compromised, although balancing the risks and costs of redundancy is not straightforward. A deliberate investment in regional suppliers can further reduce risk by shortening supply lines and improving responsiveness, although broader strategic considerations will ultimately determine the most effective approach. Global Trading Company, Inc. (GTC) President and Chief Executive Officer Eric Boles advocates establishing manufacturing suppliers in a "near-shore" position to reduce the distance from major markets and makes the case for the creation of strong U.S. suppliers to strengthen U.S. preparedness, security, and supply chains.
Strategic stockpiling and additional inventory storage offer practical risk-mitigation measures. Countries have strategically stockpiled medicines, hospital supplies, and devices with recognized benefits to public health for decades. For example, the U.S. Strategic National Stockpile was created in response to the anthrax attacks, while the U.S. stockpile of vaccines and therapeutics for anthrax has been expanded. In 2020, the stockpiles of the Federal Emergency Management Agency (FEMA) and the Strategic National Stockpile provided masks and personal protective equipment after the initial waves of the COVID-19 pandemic, although constraints were quickly exposed. Federal purchasing agencies, including the Department of Veterans Affairs, the Defense Logistics Agency, and FEMA, recognized the need for supplemental storage to fulfill their missions.

6.2. Strategic Stockpiling and Warehousing

Mitigation Strategies and Best Practices: Strategic Stockpiling and Warehousing: Critical shortages of PPE and lifesaving medications have raised major concerns across health systems regarding the adequacy of regional and national

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inventories. In retrospect, leaders should consider stockpiling decisions guided by supply chain risk assessments that take into account the natural probability, severity, and duration of a broad range of globally disruptive events. Governments have defined some public health measures to focus on maintaining strategic stockpiles of specific commodities that are essential for pandemic response, but the authorities still do not comprehensively define the level of stockpiles or reservoirs of those items where the availability is extremely limited even for specific countries.
Mitigation Strategies and Best Practices: Supplies management means having the right product, in the right quantity, at the right time and place, and at the right cost. But it is also about using anticipated external shocks to Japan's supply chain caused by the Great East Japan Earthquake in March 2011, and the world's first, but not the last, growing political tension between the United States and China. The global supply chain is notoriously fragile and thin, one popular like "Just-in-Time". A false sense of security installed in the mind of management was burst by an unexpected natural disaster that severely affected the supply chain running around Japan. Following the closure of factories, with a dangerous risk of running out of stock, Japanese companies and authorities strongly appealed to their overseas suppliers to minimize their inventory, 대신IRECT, even if they incurred additional storage costs,üstung. At the same time, restoring sales affected by the production halt was the most important issue for these companies.

Equation 5: Multi-sourcing as mitigation → Probability of total supply failure
Let supplier i fail (be unavailable) with probability p_i.
Assume failures are independent (simplifying assumption).

$$P(\text{all fail}) = \prod_{i=1}^{n} p_i$$

Step-by-step

"All fail" means $F_1 \cap F_2 \cap \ldots \cap F_n$

If independent:

$$P(F_1 \cap \ldots \cap F_n) = \prod_{i=1}^{n} P\,(F_i) = \prod_{i=1}^{n} p_i$$

With a single supplier $n = 1$, $P(\text{all fail}) = p_1$

With 2 suppliers, p^2 (much smaller if $p < 1$)

6.3. Supply Chain Visibility and Digital Twins Implementing visibility solutions will enable a more effective focus on supply chain security and resiliency. Despite being an industry need for many years, there is still a lack of attention on visibility solutions in the healthcare space, limiting the ability to manage risks effectively. Lack of visibility leads to blind spots that do not allow stakeholders to monitor critical inventory levels at single-source suppliers or assess the risk of natural disasters at key transportation hubs, for example. Visibility usually enables intelligent decision-making centered on risk management. When visibility is improved at critical nodes, stakeholders can pro-actively course-correct and allocate scarce inventories to areas with higher demand, for example. In addition to supporting decision-making, visibility clearly exposes the state of supply networks to a broader group of stakeholders and increases accountability.
Digital twins can help address these issues. Virtual representations of a physical supply network enable stakeholders to continuously understand demand-supply balance without the friction involved when reaching out to several third parties to get snapshots of their status. Digital twins also allow organizations to experiment with different "what ifs," assessing what would happen if a specific supplier was hit by a hurricane or a specific transportation hub faced a slowdown. The demand-supply balance is assessed for various scenarios—all without affecting the real supply chain. With a digital twin in place, organizations can finally be better prepared to protect and manage their supply networks.

VII. CONCLUSION

Global health crises have consistently exposed vulnerabilities and weaknesses in healthcare supply chains. Reluctant to shoulder excess inventory carrying costs, many health systems have favored just-in-time inventory management strategies, leaving them exposed to stockouts during the events of the last decade. The fragmentation of global logistics and border disruptions have compounded the associated risk. Moving forward, the emergence of digital twins, combined with predictive capabilities and an increased focus on supply chain visibility, may provide an answer to age-old questions about when, where, and how much to stock. However, healthcare systems must also address previously identified supply chain fragilities.

Too often in the past, a lack of suitable supplier alternatives has resulted in otherwise avoidable stockouts. Segmented and nonuniform demand have compounded this fundamental issue. Yet, the COVID-19 pandemic has also highlighted

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the opportunities associated with closer-to-home sourcing and regionalized supply chains. Recent natural disasters involving critical healthcare infrastructure have driven similar conclusions—trade-offs between quality, cost, and lead time remain, but the balance evident in the behavior of many systems should be revisited. Political tensions and military actions have also resulted in unexpected changes in trade flows and supplier availability. Consequently, mitigating the risks associated with such supply chain dependencies has become essential. In short, recent developments demonstrate the need for a renewed focus on healthcare supply chain robustness and resilience against a wider range of potential future disruptions—separate from more conventional concerns surrounding agility.

7.1. Emerging Trends

Recent global health crises have revealed vulnerabilities in healthcare supply chains and highlighted the risks to patients. An increase in awareness has led some healthcare organizations to embrace technology to enhance the resilience of their supply chains. Digital twins, platforms that virtually replicate physical processes, are emerging as an important tool in this effort, providing insight into the past and present while anticipating change. Integrating advanced AI-based analytics and deterministic simulations, digital twins support new ways of understanding how supply chains evolve and what mitigation strategies will be most effective.

The COVID-19 pandemic has served as a wake-up call for health systems worldwide. Heavy reliance on a limited number of suppliers, just-in-time inventory strategies, and fragmented global logistics have all been revealed as weaknesses, exacerbated by natural disasters and geopolitical tensions. Healthcare has not been alone in facing such challenges; nearly every sector has recognized the need to integrate and strengthen supply chain management and resilience. The global COVID-19 pandemic and the continuing war in Ukraine have illustrated how new technologies can address the growing need for supply chain visibility. For the health sector, the vulnerability of supply chains to natural hazards has again become painfully evident, as examined in a recent analysis of the impact of natural disasters on health systems.

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