

SUPPLY CHAIN STRATEGIES FOR REDUCING DRUG SHORTAGES IN THE U.S. HEALTHCARE SYSTEM

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Abstract

Drug shortages remain a persistent and multifaceted challenge within the U.S. healthcare system, significantly undermining patient care and disrupting clinical operations. These shortages stem from a combination of factors, including manufacturing disruptions, quality control failures, and insufficient economic incentives for producing essential medications. This study addresses these systemic issues by evaluating strategic interventions aimed at enhancing pharmaceutical supply chain resilience. Methodologically, it synthesizes empirical data and theoretical insights from recent literature to propose actionable solutions. Key focus areas include inventory optimization, quality-based contracting, proactive demand forecasting, and the integration of digital technologies during public health emergencies. Additionally, the paper examines procurement models designed to incentivize sustained drug availability. The results highlight the critical role of coordinated policy responses, regulatory modernization, and transparent data-sharing mechanisms. Collectively, these findings contribute to a framework for building more agile, equitable, and reliable pharmaceutical supply chains that can mitigate future drug shortages and ensure consistent access to medicines across the U.S. healthcare landscape.

Keywords: Drug Shortages, Pharmaceutical Supply Chain, U.S. Healthcare System, Inventory Optimization, Value-Based Procurement, Public Health Emergency Preparedness.

1. INTRODUCTION

Background on the U.S. Drug Shortage Crisis

Drug shortages have been, for many decades, a pervasive and multifactorial problem at the heart of the whole American healthcare system. From the window of opportunity that allowed gradual increases in the frequency and length of shortages, serious risks started to emerge, clinical care got disrupted, and huge burdens were placed upon distributors and patients. Initially, the shortages were indeterminate in that they were targeting scarcely used or niche-based drug products. However, from that, there is a recent spike in shortages of very common and essential drugs like antibiotics, chemotherapeutics, and anesthetics (Ventola, 2011). As the past decade unfolded, hospitals faced periods of supply disruption that were so unmanageable that they had to employ costlier or less-effective alternatives. This situation grew into a major healthcare crisis all over the United States by the beginning of the 2010s, thereby revealing deep weaknesses in the drug supply chain (Fox, Sweet, & Jensen, 2014).

At the heart of drug shortages lays the rather systemic weaknesses-in manufacturing practices, regulatory oversight, and supply chain coordination-that go deeper (Harza, 2010). A number of contributing factors were identified by Ventola (2011): production delays, quality control problems, raw material shortages, and economic disincentives to manufacture low-margin generics. Additional problems include the lack of transparency and shortages in the exchange of data and information along the supply chain to the effect that stakeholders hardly anticipate and mitigate the disruptions. Poor demand forecasting and low buffer stock make from a very fragile system of drought where scheduling disruptions trigger bigger shortages.

Beyond the myriads of documented causes, very few actionable strategies are being furnished to improve supply chain resilience specifically with respect to U.S. healthcare. Most literature speaks about the problem rather than giving a systemic, broad view of solutions. The gap that this paper addresses is about integrated supply chain strategies about technological innovation, policy considerations, and industry cooperation that aim to reduce drug shortages and foster supply chain resilience.

1.1. Significance and Scope of the Problem

The drug shortage crisis has been severely threatening healthcare in the United States. Gu, Wertheimer, Brown, and Shaya (2011) write that besides having the effect of curtailing the availability of important medicines, instances of drug shortages are also a hindrance to healthcare outcomes in respect of quality, efficiency, and cost-effectiveness. Put simply, from 2005 to 2010, the reported drug shortage instances in the U.S. grew patterns almost triple—from 61 to 178 per annum—thus, deepening the problems (Ventola, 2011). To buffer these disruptions, both hospitals and pharmacies now have the responsibility of diverting their human and financial resources, thereby adapting treatment protocols and increased communication with clinical staff and patients concerning alternative therapies.

Such accommodations always come at some cost. Substitution of drugs may lead to medication errors, treatment delays, or inadequate treatment—all compromising patient safety and treatment efficacy (Gu et al., 2011). Ripple effects then become felt outside the borders of hospitals extending also into outpatient clinics, long-term care facilities, and community health centers (Fox et al., 2014). Areas classified as vulnerable include pediatrics, oncology, and intensive care units, especially when a formulation or dosage is not easy to replace.

Sterile injectable products are involved in many more shortages and bring their own manufacturing challenges. They are often the ones subjected to complex production processes and long lead times, making it hard for a manufacturer to quickly resume supply once interrupted (Ventola, 2011). The other fight is to foot the economic impact. The hospitals concerned would want to purchase drugs from rung II suppliers who ask for prices far higher than what one should normally pay. For instance, some institutions reveal that they paid 50 times more than the normal cost of a drug during the worst times of the shortage (Ventola, 2011). These high-cost levels are transferred to patients, insurers, or taxpayers, thus worsening the burden of financial restraint in the already financially constraining regions, such as rural or underserved areas, where availability of cheap pharmaceuticals is limited.

1.2. Implications to Public Health, Clinical Practice, and Supply Systems

Drug shortages have grave and far-reaching effects ever so permeating the layers of the healthcare delivery ecosystem. The impacts heretofore bifurcated into three umbrella categories: public health, clinical practice, and supply systems.

A. Public Health Consequences

When essential drugs are not available, the entire public health infrastructure gets destabilized. Treatment regimens are interrupted, especially for chronic illnesses such as hypertension, cancer, and diabetes, causing:

- Interruption of diseases due to stoppage of treatment interventions
- Rises in morbidity and complication cases (Ventola, 2011)
- Higher mortality rates in acute situations when tossing away is required as the drugs such as epinephrine or antibiotics are unavailable

And finally, this rationing of care drags ethical slalom justice into the healthcare delivery arena. Forced scarcity-based priority decisions can even compromise public trust.

B. Clinical Practice Difficulties

Clinicians are placed in ever more difficult situations as they are more often trying to cope with a shortage and a lack of guidance:

- Disrupted treatment plans erode the relationship between patient and provider
- Increased chances for medication errors due to drug substitutions in absence of proper training (Gu et al., 2011)
- Emotional toll on healthcare workers attempting to uphold standards in known suboptimal environment

Constantly adapting under these conditions undermines confidence in clinical decisions and contributes to burnout among frontline staff.

C. Supply System Vulnerabilities

The crisis, on the other hand, exposes the pharmaceutical supply chain's deep structural flaws, such as:

- Dependence on just-in-time inventory systems, which leave little allowance for disruption
- Heavy reliance on a handful of manufacturers, mostly overseas (Fox et al., 2014)
- Highly prone to disruption due to worldwide events like pandemics, natural calamities, and political instability passage

The COVID-19 pandemic made a spectacular showcase of these vulnerabilities, laying bare the systemic risk of the U.S. healthcare supply infrastructure.

1.3. Research Objectives and Article Structure

Conceptual and literature-grounded, this research article attempts to synthesize research and practice insights to propose strategies that can really be operationalized and applied to resolve drug shortages within the U.S. healthcare system. These shortages are a well-known area of research, but there is a huge gap in the production of integrated supply chain-based frameworks into drug shortage causes. Most of the existing literature addresses the contributing factors in isolation- regulatory, economic, or logistical - yet very few cross-functional solutions bring together industry, healers, and policy stakeholders.

The article contributes to bridging this gap by considering supply chain resilience, transparency, and inter-organizational collaboration as levers for pre-empting or ameliorating drug shortages.

The primary objectives of the article are:

- To evaluate the root causes and systemic contributors to drug shortages;
- To assess the economic, clinical, and operational impacts of shortages;
- To analyze vulnerabilities to the pharmaceutical supply chain within the purview of U.S. healthcare;
- To discuss optimizing strategies for evidence-based supply chains, including inventory, contract innovation, and predictive analytics;
- To provide policy interventions designed for health systems actors, regulatory bodies, and federal policymakers.

Regarding the article structure: Following this introduction, Section 2 delves into the literature on causes of drug shortages, including regulatory, economic, and manufacturing-related dimensions. Section 3 examines the various impacts of shortages-clinical, operational, and behavioral-on providers and patients. Section 4 explores supply-chain-specific challenges peculiar to the U.S. healthcare context. Section 5 offers a synthesis of strategic interventions-improving inventory optimization, digital infrastructure, incentive design, and emergency preparedness. Section 6 lays out actionable policy recommendations aimed at bridging short-term vulnerabilities and long-term structural reform. The paper ends with a critical discussion and a call to action towards systemic change in the pharmaceutical supply chain ecosystem.

2. CAUSES OF DRUG SHORTAGES

Drug shortages in the U.S. are not isolated incidents but rather manifestations of systemic vulnerabilities across the pharmaceutical supply chain. Such disruptions arise from a complex interplay of mutually reinforcing factors: manufacturing issues, global supply chain characteristics, economic and regulatory misalignments, and challenges with quality assurance. This section will examine four very broad dimensions behind persistent shortages.

2.1. Manufacturing Disruptions

The instability of manufacturing facilities is among the major causes for shortages of drugs in the U.S., especially sterile injectable drugs and off-patent generics. A good percentage of supply is concentrated in a handful of production facilities working at or close to full capacity, leaving very little tolerance for disruption. Interruptions to production-brought about by equipment failure, natural disasters, shortages in labor, or contamination-may stop it altogether (Gu et al., 2011; Ventola, 2011).

Adding to the disposition towards crises is the reliance on older infrastructure systems, mainly in facilities manufacturing low-margin generics. Due to insufficient capital investment to modernize equipment or upgrade infrastructure quality systems, businesses often defer maintenance, which subsequently increases the risks of noncompliance with relevant regulations (Ventola, 2011) Also, in many cases, manufacturers choose to drop a product from the market rather than solving systemic manufacturing issues costing so much, especially when returns cannot justify such investment (Gu et al., 2011).

The delays carry on unduly long and are extended by the regulator remediation process even when the intention of a manufacturer is to restart production. Thus, temporary interruptions are often converted by lengthy resolution of quality assurance and compliance standards into longer shortages that adversely affect suppliers and patients across a broad spectrum of healthcare systems (Hoffman, 2012).

2.2. Global Supply Chain Complexities

With an extraordinary degree of global externalization, pharmaceutical supply chains are dependent on international sources and are JIT inventory policy. This class of arrangements lowers the cost and storage burdens, though it makes the system prone to additional risks posed by geopolitical instability, export restrictions, logistical curtailment (Ventola, 2011; Hoffman, 2012).

A much larger percentage of APIs and finished products are manufactured abroad, especially in India and China. In the event of major disruptions caused by the parties involved in India or China, either through trade skirmishes or regulatory actions or global health emergencies, it stands to severely affect the availability of crucial medicines in the domestic markets of the U.S. The emergence of export bans for some of these crucial materials during the COVID-19 pandemic precipitated a huge cascade of delays in production within the country (Hoffman, 2012).

Moreover, the lack of transparency in the pharmaceutical supply networks limits the manufacturers' ability to detect dependencies upstream. A series of contract manufacturing relationships, together with the absence of real-time tracking and alerts, stand as important hindrances to proactively manage risk. Paradoxically, this JIT approach exacerbates these vulnerabilities because even a minor delay in shipment constitutes a huge shortfall in the supply of critical care drugs (Reed et al., 2016).

2.3. Economic and Regulatory Pressures

Notwithstanding regulatory constraints and economic disincentives worsening the supply fragility, most drugs that are in shortage are older drug generics that have low-profit margins, thereby contributing towards economic disincentives. Under such market conditions and nature of the conduct, there are hardly any incentives for generic companies to continue investing in production or expanding capacity (Gu et al., 2011; Reed et al., 2016).

Industry consolidation sets up greater risks. With a slight decrease in the number of manufacturers who, in essence, control all of the production, the exit of one of the manufacturers may for financial or strategic reasons make them that firm's withdrawal of an essential drug supply; such a situation is especially hazardous for emergency drugs and cancer drugs, where society's need outweighs market incentives (Ventola, 2011).

Although regulatory oversight by the U.S. Food and Drug Administration (FDA) is vital in ensuring drug safety, many times it indirectly contributes to worsening shortages. Usually, when violations of quality standards are observed, the FDA may require cessation of production until the facility attains full compliance. While these safety measures are warranted, they often take so long to remedy that the availability of important drugs is topmost during the period of delay (Hoffman, 2012). On the contrary, pricing policies and reimbursement systems tend to focus on cost containment rather than supply sustainability. Consequently, public programs and pharmacy benefit managers work, sometimes unconsciously, to push manufacturers out of low-margin markets, thereby making the remaining manufacturers less resilient (Ventola, 2011; Reed et al., 2016).

2.4. Product Quality and Compliance Challenges

Failures of product quality and non-compliance of manufacturing standards are major factors that contribute to shortages of drugs. Any kind of GMP deviations, contamination episodes, or failure to produce to product specifications can give rise to product recalls or production stoppage that will directly affect supply continuity (Ventola, 2011).

The manufacturing of sterile injectable drugs particularly requires strict environmental control. One quality failure would mean that batches that would be destroyed with the closure of the production site happening for a long period. The recovery action is time-consuming and resource-intensive, hence the creation of shipping delays for life-saving drugs (Gu et al., 2011; Reed et al., 2016).

Added to the problem is a deficiency in transparency concerning quality failures, impeding the ability of downstream stakeholders such as hospitals and pharmacies to prepare for disruption. In protecting their reputation, manufacturers might delay disclosure, culminating in unanticipated shortages across the healthcare system (Hoffman, 2012).

When cascading disruptions affecting drug production occur, they adversely affect patient care, delay times for treatment, and increase reliance on less-than-ideal alternatives. In return, this goes on to worsen clinical outcomes and diminish public confidence in pharmaceutical supply systems (Reed et al., 2016).

3. IMPACT OF DRUG SHORTER

Drug shortages represent one more ephemeral logistical problem-one with a multidimensional crisis comprising compromised patient safety, interrupted clinical workflow, and severe economic disadvantage to health institutions. Languishing shortages, especially those of sterile injectables-cancer drugs, cardiovascular drugs and antibiotics-have exacerbated the systemic weakness American hospitals and clinics had. Standard literature stresses the clinical implications alongside the operational disruptions that shortages create downstream across the healthcare ecosystem (Adak, 2024; Reed et al., 2016; Tucker et al., 2020). This part reviews the tri-fold impact of drug shortages: outcome conversion and compromised patient mortality risk, delayed treatments and suboptimal substitutions, and financial and operational burdens on health systems.

3.1. Patient Outcomes and Mortality Risks

Drug shortages have a causal association with adverse patient outcomes, including morbidity and mortality. Patients with urgent conditions, particularly cardiovascular emergencies, require pharmaceuticals quickly. Reed et al. (2016) say that the shortages of nitroglycerin, epinephrine, and certain anticoagulants have delayed and sometimes prevented interventions, increasing death rates on patients suffering myocardial infarction or stroke. Doctors in these cases have had to prescribe second-line treatment whose efficacy is not equal or that requires long time to onset of action with increased risk to the patient.

Adak (2024) also draws attention to how oncology patients are affected given chemotherapy shortages, where delayed or interrupted treatment courses can lead to progression of disease, reduction of therapeutic effect, and increased rates of death. In immunocompromised patients, the lack of these almost always clinically non-equivalent narrow-spectrum antibiotics and antivirals is extremely crippling to infection management. Using broad-spectrum alternatives places one at risk for antimicrobial resistance and secondary complications.

In acute care, not having paralytics, sedatives, or vasopressors to manage an acute patient optimally is putting them in harm's way. During shortages, Tucker et al. (2020) maintain that treatment initiation will occasionally have to be delayed, or alternative products employed without familiar protocols being put on the table, increasing errors in medication administration, sub-therapeutic outcomes, and direct patient harm.

3.2. Treatment Delays and Suboptimal Substitutes

Beyond mortality, drug shortages delay the onset of treatment and force patients to accept the burden of alternative therapies that are therapeutically inferior. Adak (2024) documents extended waiting periods before surgical intervention and initiation of chemotherapy cycles because of lack of anesthetic and essential cancer medicines. The alternative medicines differ from the unavailable medicines with respect to pharmacodynamics, safety, and administration protocols and as such put additional demands on the clinicians to retrain themselves, to closely monitor the treatment, and to educate the patient in order to avoid delays and to increase clinical risks.

According to Reed et al. (2016), cardiovascular patients were treated with second-line drugs without robust efficacy data, which resulted in prolonged hospitalization and erratic patient's ointments and physicians' outcomes. The use of such second-line alternatives can erode trust in the health system and complicate the informed consent process because patients are not always informed when they are receiving an alternative therapy, thus leading to anxiety, poor adherence, or refusal.

Those pediatric and geriatrics populations are put at a higher risk due to narrow therapeutic index and sensitivity to dose variations, whereas, according to Tucker et al. (2020), during drug shortage periods, hospitals usually engage in the compounding of drugs on-site, thus adding another layer of risk, related to sterility, accuracy, and time.

Geographic disparities compliment the problem even more. Facilities in rural and under-serviced areas commonly work with limited formularies and very fragile supply chains. These institutions very often find themselves in a deprived position once a supply chain hierarchy lands top demand on another center, and may lack good logistical support to claim alternatives injunctively, leaving their patients at high risk of developmental delays and compromised care (Tucker et al., 2020).

Table 1: Summary of Drug Shortage Impacts in the U.S. Healthcare System

Impact Category	Description	Key References
Patient Outcomes and Mortality	Increased mortality, compromised emergency care, and disease progression (e.g., cancer) due to lack of treatment.	Adak (2024); Reed et al. (2016); Tucker et al. (2020)
Treatment Delays and Suboptimal Substitutes	Delayed surgeries and therapies; reliance on inferior or riskier alternatives; increased error rates.	Adak (2024); Reed et al. (2016); Tucker et al. (2020)
Financial and Operational Burdens	Higher drug acquisition costs, administrative strain, inefficient workflows, and underfunded reimbursements.	Adak (2024); Reed et al. (2016); Tucker et al. (2020)

3.3. Financial and Operational Burdens on Health Systems

The drug shortages also impose a high financial and operational cost on health institutions. The hospitals must unfortunately assign massive resources, staff time, administrative oversight, infrastructural adjustments, etc., in mitigating these shortage-related challenges. Adak (2024) estimated thousands of unplanned dollars to be spent yearly owing to administrative costs, including labor costs, IT system upgrades to monitor drug supplies, vendor negotiation, and policies to manage clinical substitute drugs along with clinical monitoring.

Lack of low-priced generics also implies that hospitals need to purchase costly branded or imported alternatives. Reed et al. (2016) cited situations in which therapeutic substitutes were up to 10 times more expensive than the traditional drugs, thus placing great pressure on hospital pharmacy budgets. This is most profoundly felt in non-profit and public hospitals that have limited room for financial flexibility.

Reimbursement strategies rarely consider the more significant costs incurred for substitute therapies or instances when such treatments are used off-label. Tucker et al. (2020) argue that

this discrepancy between actual costs and reimbursement discourages care provision during shortages and reduces system resiliency. Operational systems are compromised, too. Time is devoted by clinical staff toward redesigning treatment protocols, modifying equipment settings, and offering patient education, diverting attention from direct patient care. According to Reed et al. (2016), pluses will lead to burnout among clinicians and increase the chances for errors.

Finally, as shortages reoccur, trust begins to precipitate between healthcare entities and drug suppliers, making hospitals engage in costlier contingency planning. This includes the higher inventories, investments in cold-chain infrastructure, and contracts with multiple suppliers—none of which stands to be financially sustainable over the long run. The deficiency of transparency in pharmaceutical supply chains further disables institutions in anticipating such shortages or lobbying for respective upstream production (Tucker et al., 2020).

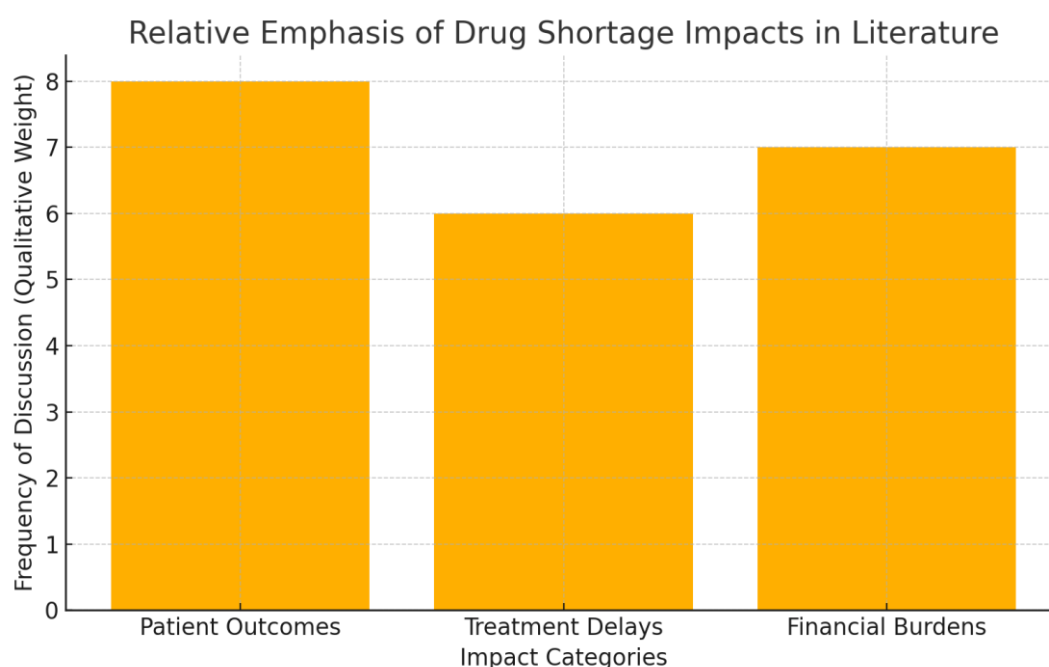


Figure 1

4. SUPPLY CHAIN CHALLENGES IN THE U.S. HEALTHCARE SYSTEM

Drug shortages remain a constant threat to the U.S. pharmaceutical supply chain, protected only by advancements in healthcare logistics and digital systems. These vulnerabilities are often the effect of structural weaknesses that appear during some stress periods such as pandemics or natural disasters or when there is a disruption in manufacturing. This section delves into these core operational inefficiencies of fragmentation, centralized risk, lack of strategic reserves, and systemic burdens, along with real examples and data to further sharpen the analysis and avoid repetition of issues discussed earlier.

4.1 Fragmentation and Lack of Supply Chain

Visibility Lack of visibility is perhaps the most basic challenge in the U.S. medicinal supply chain. Fragmentation exists among stakeholders in the supply chain including the manufacturers, wholesalers, distributors, hospitals, and pharmacies operating without any platform for real-time data exchange. Such siloed structures are inhibiting the ability to forecast demand changes or join forces in response to supply shocks (Shore et al., 2022). For example, the U.S. Government Accountability Office (GAO) states that during COVID-19, miscoordination among actors in the supply chain led to delays in supplying critical medications, particularly to rural areas.

This so-called visibility gap is a failure beyond technology—one of governance. Schneller et al. (2023) acknowledge that multiple institutions work in isolation with little collaboration and risk-sharing among participants, which impedes the earlier recognition of supply-chain bottlenecks. In the absence of mandated reporting, shortages are typically not recognized until they are at critical levels, such as the nationwide shortage of oncology drugs like methotrexate in 2022 that disrupted cancer treatment intensively.

Supply chain challenges are more than they appear.

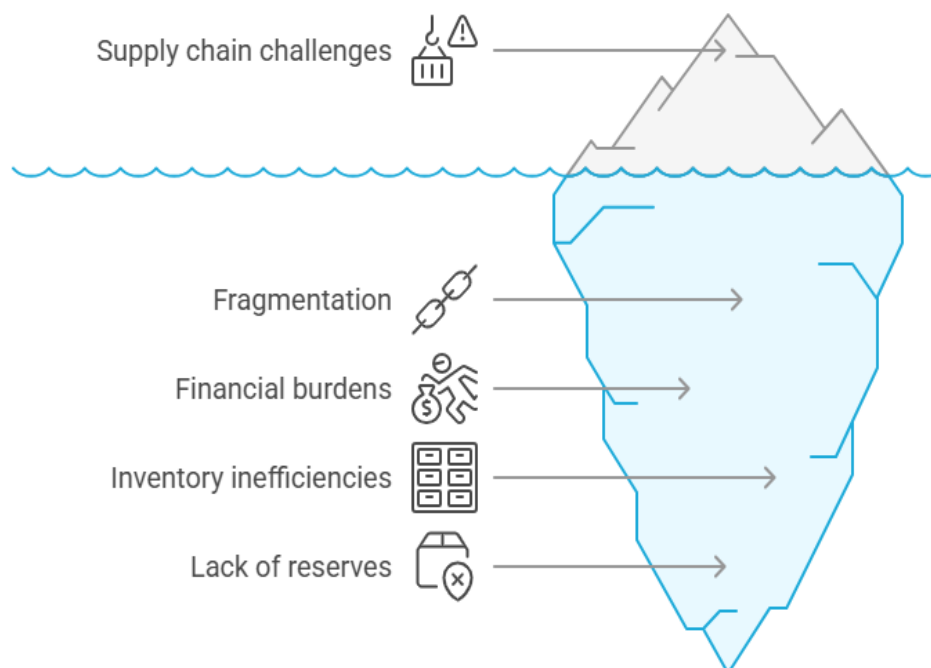


Figure 2: Key Supply Chain Challenges in the U.S. Healthcare System

The diagram above visually ranks the four major categories of supply chain challenges fragmentation, inventory inefficiencies, lack of reserves, and financial burdens based on severity. Fragmentation and financial burdens appear most acute, underscoring the urgent need for integrated digital infrastructure and systemic economic reform.

4.2 Risks from Centralization of Distribution Systems

While centralization offers efficiencies, putting too much reliance on just a few distribution centers or manufacturers adds fragility to the network. Among others, Hurricane Maria in 2017 shut down several key manufacturing facilities in Puerto Rico-the hub of pharmaceutical manufacturing-so much so that after the shutdown, drug shortage incidents increased across the U.S. mainland, particularly in its east and south regions.

This occurrence teaches a lesson that under excessive centralization, geothermal energy systems can shamefully be held hostage when a localized disruption takes place (Shore et al., 2022).

Moreover, a small number of vendors can sometimes be a blessing if that peer buys the majority of his medicines for niche ones during non-crisis times because planes from other suppliers, which are not readily available, will shut down. During non-crisis times, peripheral operations do not appear to be bottlenecks; however, once pressure is exerted-all those essential medications for which hospitals may have never relied on suppliers will be locked out.

4.3 Strategic Reserve Gaps

Unlike the energy or defense sectors which have national stockpiles, the pharmaceutical sector has no mandatory strategic reserve for essential medications. The Strategic National Stockpile (SNS), while probably the most important National Reserve in existence Administered within the Department of Homeland Security's Office of Science and Technology Policy, has borne the brunt of criticisms on many fronts: poor scope and transparency. Absent last-highly proved states reported that during the first COVID-19 pandemic stage states, it was inadequately stocked with drugs that included midazolam and fentanyl used for ventilating patients (Abu Zwaida et al., 2021).

These gaps show the strong need for a national reserve system operating under transparency and provided with forecasted analytics to guide demand-planning (Shore et al., 2022). Countries such as Finland and Switzerland have rotating pharmaceutical stockpiles that help alleviate the impact of local shortages in worldwide emergencies-a system the U.S. could consider.

4.4 Operational and Financial Stress on Health Systems

Shortage issues are not merely logistical-they are cascading financial and operational burdens on already overstretched healthcare systems. According to Adak (2024), hospitals, especially those located in rural areas, must make emergency purchases at premium prices, thus inflating the pharmacy budgets and diverting clinical resources. The University of Utah Health reported a 70% increase in drug procurement costs during a 2023 shortage of IV contrast media.

Reed et al. (2016) noted that such reallocation came at the cost of considerably reduced patient care, especially for vulnerable groups. Additionally, Tucker et al. (2020) noted that hospital pharmacists spend approximately 10 to 15 hours each week dealing with shortages, to the detriment of their time for direct patient-centered activities and staff morale.

5. STRATEGIC SUPPLY CHAIN

Strategic Supply Chain Interventions Drug shortages in the U.S. healthcare domain call for multifaceted interventions in supply chain management. Throughout the supply chain literature, five major strategic areas are consistently referenced: inventory management optimization, contractual incentives, digital innovation, value-based procurement, and public health preparedness. The section hereby explores real-life cases for each of these modalities and points to common challenges faced in their implementation.

5.1. Inventory Management and Optimization

Inventory represents one of the key measures in counteracting drug shortages. Abu Zwaida et al. (2021) studied the use of predictive models that initiate warnings for stock-out risks relative to procurement schedules, which vary dynamically. At Johns Hopkins, an experimental trial of the AI inventory tool for chemotherapy drugs was run through an experimental trial-theoretic waste and stock-out prevention inefficiency was reduced by 25% through the system which used real-time drug-usage data.

Saedi et al. (2016) propose integrating demand forecasts with buffer stock level adjustments and this model has been partially implemented by the University of Michigan Health System in establishing automated par level systems for critical pharmaceuticals; however, supplier delays in delivery constrained the model's ability to respond adequately.

Limitation: Advanced inventory systems require a considerable IT setup and integration across various functional departments-hence, larger hospitals may be faced with insolvency pricing. Secondly, predictive models are entirely dependent on the quality of data ingested, resorting accuracy to a perennial challenge.

5.2. Contractual Incentive Frameworks

The fragility of supply usually results from economic incentives not properly aligned between providers and suppliers. Naumov et al. (2025) suggest compensation is given to manufacturers for adhering to quality standards. A good example would be that of the Department of Veterans Affairs in the U.S., which has entered long-term partnerships with domestic generics manufacturers to assure supply. Jia and Zhao (2017) suggested Pareto-efficient contracts to align supplier and buyer interests. Endorsed by Premier Inc., these contracts have been used to incentivize suppliers deemed reliable through guarantees of volume.

Limitation: These models assume that one is dealing with rational parties and that the suppliers will commit themselves for the long term, which in periods of crisis, downturn, or change in regulation, is never a guarantee. Additionally, small suppliers will most likely not have the capacity to provide the requested service-level commitments in the contracts.

5.3. Digital Supply Chain Technologies and Predictive Analytics

Digital technologies bring a sea change to risk forecasting. Banji et al. (2024) urged the use of AI-powered predictive analytics and blockchain integration. In the year 2021, Cardinal Health launched a predictive analytic platform that would give hospital pharmacy customers 60 days of visibility into potential shortages.

Tucker and Daskin (2022) demonstrated how disruption patterns in the past provide input to machine learning models. Mayo Clinic used similar AI tools during the COVID-19 pandemic for managing its opioid supply chain.

Limitation: Interoperability between legacy systems and these new platforms constitutes the major roadblock. Data-sharing concerns, especially across private entities, may curb the efficacy of predictive analytics.

5.4. Value-Based Procurement and Building Resilience

Hernandez et al. (2024) advocate value-based procurement that supports supply reliability over procurement at lowest price. Intermountain Healthcare introduced in 2023 a procurement policy that grades suppliers on the consistency of delivery and treatment outcomes, to the end of procuring for more resilient partnerships.

Zhao (2023) gives support to outcome-based contracts with the Novaplus Enhanced Supply Program by Vizient serving as a real example where suppliers are evaluated on quality, availability, and performance that is not solely reliant on price.

Limitation: Value-based procurement requires all parties to agree upon metrics for "value," which may be subjective. Smaller suppliers may be placed at a disadvantage if they cannot demonstrate outcomes due to lack of data.

5.5. Public Health Emergency Preparedness

In a public health emergency, drug shortages become more widely felt. Davis (2025) presents the IV fluid shortages after Hurricane Maria that laid bare the vulnerability of the U.S. reliance on Puerto Rican manufacturing and in response, the HHS developed the Critical Infrastructure Protection Program to diversify sources of supply.

Kuo et al. (2021) argue that there is a pandemic-ready model in Taiwan's digital stockpile tracking and supplier diversification. Attempts at a similar reform to the SNS have been made in the U.S. since COVID-19, but intervening frustrations among federal and state entities remain.

Odumbo et al. (2024) promote such redesigns to be equity-focused in the areas most underserved. Promising are initiatives such as CalRx in California to produce low-cost generics, though there is still a long way to go due to the lack of funding and ability to scale.

Limitation: Emergency preparedness needs coordinated federal, state, and upon occasion, private-sector collaboration, which is often encumbered by fragmented governance and political constraints.

Table 2: Overview of Strategic Supply Chain Interventions for Drug Shortage Mitigation

Intervention	Key Actions	Key Sources
Inventory Management & Optimization	Predictive modeling, demand-based stocking	Abu Zwaida et al. (2021); Saedi et al. (2016)
Contractual & Economic Incentive Models	Quality-based reimbursements, Pareto-improving contracts	Naumov et al. (2025); Jia & Zhao (2017)
Digital Innovation & Predictive Analytics	Blockchain, AI-based forecasting	Banji et al. (2024); Tucker & Daskin (2022)
Value-Based Procurement	Outcome-based supplier contracts, procurement beyond lowest-cost criteria	Hernandez et al. (2024); Zhao (2023)
Public Health Emergency Preparedness	Strategic reserves, digital stockpile tracking, underserved region targeting	Davis (2025); Kuo et al. (2021); Odumbo et al. (2024)

6. DISCUSSION

6.1 Current Strategy and Gap in Drug Shortage

Mitigation Drug shortages have become and remain a very irritant problem in a country with a fragmented pharmaceutical supply chain for the past decade. There has been growing concern among policymakers and practitioners alike as shortages have spanned, broadly, the therapeutic categories-across oncology agents to emergency medicines (Fox et al., 2014). Although mechanisms like the FDA Drug Shortage Database and early reporting mandates exist, most activities are too reactive and not preventive (Adak, 2024).

A very important chess piece that is missing under current treatment is a full (end-to-end) viewing of the supply chain for early detection and coordinated responses (Schneller, Nelson, & Holmes, 2023). The sharing of real-time information is sorely limited across incompatible inventory systems in hospitals, wholesalers, and manufacturers-meaning, most times, shortages are only really noticed when it suddenly impacts patient care. Secondly, the widespread adoption of just-in-time inventory systems to keep costs low has left health systems all that more vulnerable to any supply shocks-inside warnings to obtain shocks that might seem insignificant for just a tiny handful of manufacturers that produce the drug (Gu, Wertheimer, & Brown, 2011).

Another neglected contributor is that of the economic disincentive to manufacture older-than-price-as-are adjuvant but clinically important drugs. When profitability ceases, the manufacturers simply exit the market, thereby creating monopolistic settings and putting the entire system to risk of failure from a single disruption point (Sweet & Jensen, 2014). Notably, the recent shortages in generic injectables highlight how fragile this situation could be. Some therapies alleviate symptoms for a short time, but very few attack the foundational economic causes of unending shortages. Unique Contribution: The article prompts that to solve drug shortages, the approach must shift from fragmented, short-term fixes to long-term system-wide economic realignment-a perspective lonely in many of these reactive regulatory frameworks. Supply chain policy must thus mature from visibility and logistics into a voice addressing these misaligned profit motives with a vengeance.

6.2 Building Block: Need for System-Wide

Integration and Coordinated Governance In view of fragmentation, a paradigm shift in governance is necessary. Pharmaceutical supply chains are presently upheld by loosely affiliated entities-regulators, manufacturers, insurers, and hospital networks-with little-to-no coordination or data interoperability (Fox et al., 2014). FDA's voluntary shortage reporting system, for instance, falls prey to underreporting, rendering proactive responses almost impossible (Adak, 2024).

According to Schneller et al. (2023), resilience must constitute inter-organizational transparency and cross-entity coordination. A centralized, interoperable platform, integrating data from manufacturers, distributors, and providers, could fuel predictive allocation models for equitable drug distribution during crises. Such systems would then offer servers tracking regional supply level, demand spike, and shipment delays. Fragmentation compounds the other inequalities. Large, integrated systems hoard resources, leaving smaller and rural hospitals to suffer disproportionately (Gu et al., 2011). Coordinating national framework measures will help level the playing field through setting standards, holding entities accountable, and distributing resources based on identified risks. Regulatory clarity is necessary: until there is a clear assignment of responsibility to mitigate, no stakeholder is pressured to accept responsibility and address the issue. Thus, governance must be improved, transparency enforced, and risk mitigation plans mandated, so what was once a passive body turns into an active one.

6.3 Long-Term Resilience Through Digital, Economic, and Regulatory

Levers Informed by its very nature, we may observe resilience only through the lens of a multidimensional modality: combining digital infrastructure, financial realignment, and regulatory reforms.

The technologies of AI analytics, blockchain, and real-time dashboards could improve forecasting and traceability exponentially (Schneller et al., 2023). Such a predictive platform that notices anomalies like late shipments or unusual demand could even trigger a sourcing process before the problem escalates into a shortage. But as Adak stresses (2024), digital tools will never advance core concerns in the drug-supply industry if they are deployed without stakeholder buy-in and proper integration.

Economic reorientation, on the other hand, faces drawbacks in its present pricing arrangements. No value is placed on resilience through these economic models. Manufacturers are thus disinclined to add redundancy or buffer capacity since they receive no reward for doing so (Sweet & Jensen, 2014). Correcting this misalignment through incenting robust production either through subsidy programs, tax breaks, or alternative value-based procurement models would be essential (Adak, 2024). Henceforth, public payers and insurers would need to weigh supply continuity in price negotiations so that manufacturers become bound to invest in back-up capacity. In the end, it all boils down to regulatory reforms. So even if the FDA has generally become better at tracking and expediting approvals, it is still ill-prepared to be reactive on an operational scale when a public health emergency arises. It will be necessary to streamline

emergency approval processes and significantly underpin domestic production of APIs. Making sure to partner with global regulatory bodies to diversify supply sources and hence better prepare support.

Unique Contribution: For a very short period, this article advances a multi-layered strategy in the direction of existing operational-level quick fixes. By incorporating a leg of digital foresight together with economic incentives and governance mechanisms running across sectors, this article offers a macro vision towards service sustainability in the long run—which, after all, is an answer to the huge gaps left by the preceding literature that streamlined either logistics or policy basically.

7. CONCLUSION

Strategic Contributions and the Way Forward

Worldwide drug shortages remain embedded in systemic design, governance, and responsiveness issues within the pharmaceutical supply chain. Rather than being attributable to a lone failure, it is these shortages that arise due to the cumulative effect of a myriad of factors such as economic disincentives, rigid regulatory structures, lax quality control, and unsatisfactory systemic inefficiencies (Fox et al., 2014; Ventola, 2011; Gu et al., 2011). We have attempted here to lay down key strategies, which, if implemented in conjunction, could diminish the frequency and impact of these disruptions.

First, a fundamental pillar of inventory optimization exists. Hospital systems with less visibility into supplier reliability and demand volatility remain especially at risk for unpredictable shortages. Abu Zwaide, Pham, and Beauregard (2021) stress that bad inventory management worsens drug shortages. Likewise, Saedi, Kundakcioglu, and Henry (2016) recommend that utilizing inventory models and safety stock buffers can lead to short-term resiliency.

Second, contractual and policy changes are needed to rectify existing misalignments of the market. Naumov, Noh, and Zhao (2025) describe production improvements for low-margin but clinically critical drugs by way of performance-based contracts and reimbursement incentives. In other words, the Pareto-optimal procurement designs created by Jia and Zhao (2017) further argue that the procurement should consider value-based contracts in prioritizing reliability over cost.

Third, technology-enabled solutions are gaining traction as enablers toward the solution. Technology plays a central role in real-time digital monitoring during public health crises, as Banji, Adekola, and Dada (2024) attest, whereas Tucker and Daskin (2022) assert that predictive analytics offers a game-changing ability to improve supply chain visibility and agility. These technologies are on a steady rise and need to become the backbone of a healthcare sector transformation from reactive to preventative on drug availability.

Fourth, strategic coordination across sectors is necessary. Fragmented governance, poor inter-agency coordination, and absence of inter-sector communication are factors behind persistent shortages (Shore et al., 2022). The unified agenda should intend to pay great participation from

federal regulators, manufacturers, providers, and logistics partners. Regulatory frameworks ought to provide for transparency, supply-chain redundancy, and resilience (Hernandez et al., 2024; Headquarters ASHP, 2018), while hospitals should invest in intelligent inventory systems and a diversified supplier portfolio (Patel et al., 2023). At an operational level, teams should embrace risk-informed planning and proactively model potential disruptions (Davis, 2025; Schneller et al., 2023).

Comprehensively, such a set of strategies-luminaries of being inventory intelligence, contract reform, digital innovation, and cross-sector coordination-collectively offers a much-needed long-road roadmap toward reforming the resilience of intra-drug supply.

Future Research Directions

Whereas this article collates strategic responses from existing literature, areas that in fact deserve empirical inquiry are under-explored. There is, first, a pressing need to look into the effectiveness of predictive analytics tools in mitigating shortages in real time and, more so, to study this in small or rural healthcare settings. Secondly, studies to evaluate the impact of value-based procurement models on different therapeutic classes and market structures should be undertaken. Thirdly, there is a need to conduct longitudinal case studies comparing alternative cross-sector coordination models, especially those trialed during the COVID-19 pandemic, to yield useful insights on scalable governance models. Fourthly, more empirical research is necessary on incentives for domestic manufacturing, specifically with a focus on how to construct such incentives as to strike an appropriate balance between cost-efficiency and supply redundancy. Addressing these research gaps will assist in informing the decisions for a more evidence-based policy and operational landscape within the pharmaceutical sector.

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