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DATA-DRIVEN PHARMACEUTICAL SUPPLY CHAIN OPTIMISATION TO REDUCE MEDICATION SHORTAGES IN RURAL U.S. HEALTHCARE FACILITIES

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ABSTRACT:

This paper introduces a data-driven framework to optimise the pharmaceutical supply chain and address medication shortages in rural U.S. healthcare facilities. It consolidates evidence on causes of shortages, demand trends, and inventory management to create a practical decision-support system tailored for low-volume, resource-limited environments. The framework leverages multiple data sources, including pharmacy dispensing data, supplier performance information, transportation limitations, and disruption histories, to enable accurate demand forecasting, safety stock calculation, and replenishment planning. Statistical and machine learning models account for factors like seasonality, facility type, patient demographics, and geographic access barriers. Inventory optimisation modules distinguish strategies for fast- and slow-moving stock-keeping units. Scenario-based stress testing evaluates resilience during disruptive events like pandemics, extreme weather, or transportation failures. The paper also discusses implementation strategies, focusing on stakeholder involvement, change management, and technology adoption to ensure the analytic tools are integrated into everyday pharmacy operations rather than limited to pilot projects. It considers policy and ethical issues, emphasising how local conditions and regulations influence feasible interventions. Overall, the study provides a structured roadmap for rural health systems to harness data-driven methods to improve service levels, reduce stockouts and expiries, and enhance access to essential medicines.

KEYWORDS: Pharmaceutical supply chain; Medication shortages; Rural healthcare; Demand forecasting; Inventory optimisation; Supply chain resilience.

1. INTRODUCTION

Health systems across the United States are increasingly threatened by drug shortages that hurt patient care and can be costly for hospitals (W. Holmes & J. Hughes, 2013). In September 2017, Hurricane Maria compounded already problematic supply-chain disruptions in U.S. healthcare. The complex, interdependent nature of healthcare has changed the drug-supply landscape since 2006, making proactive conflict-avoidance strategies essential (Tyzik et al., 2018). Precise, relevant, and timely knowledge of the supply chain has become crucial for anticipating, containing, and mitigating the effects of impending drug shortages (Pall et al., 2023). Predictive analytics offer the promise of achieving such understanding, yet pharmacy professionals generally lack the time or tools to implement them. Healthcare providers in rural areas face compounded challenges in meeting patients' medication needs amid supply chain disruptions. Rural facilities experience greater and more frequent drug shortages, and their low purchase volume further constrains access to many medications. Small hospitals comprise over 20% of the U.S. healthcare system, and 90% of the nation's hospitals cannot routinely stock all high-demand medications. The specificity and granularity of the traditional supply-chain-optimisation approach render it infeasible. Expert empirical modelling of drug demand, supply collapse, logistics, and alternative availabilities enabled the use of data culled from pharmacy information systems to predict shortages, telescoping the scope of these variables to a one-week outlook without compromising accuracy (Bose et al., 2024).

2. Background and Significance

The rising incidence of prescription drug shortages remains a significant concern for healthcare across the United States, particularly in rural regions, where hospital pharmacies frequently struggle to secure sufficient inventory of critical medications (W. Holmes & J. Hughes, 2013). Shortages can compromise patient health and safety while elevating supply chain expenditures (Pall et al., 2023). The complexity of medication shortages creates additional challenges by complicating the prediction of disruptions and the planning of inventory (Tyzik et al., 2018). Drawing on both internal patient data and publicly available information on drug supply chain disruptions, the proposed approach comprises a flexible, data-driven methodology for robust demand forecasting, inventory optimisation, and supply chain risk mitigation. Tools developed under this framework can help rural healthcare facilities proactively manage pharmaceutical inventories to avoid medication shortages, enable cost-effective stock monitoring that balances availability with carrying costs, and evaluate the selection of high-risk medications to inform targeted contingency planning.

3. Methodological Framework

Addressing pharmaceutical shortages in rural healthcare involves using health data to forecast demand and optimise inventory levels, thereby reducing stockouts and expired medicines. A framework analyses the supply chain, predicts rural demand, develops inventory policies, assesses system resilience, and improves transportation. Multiple data sources help understand demand, despite gaps for low-activity facilities. Various datasets capture factors influencing demand size and variation. Although rural demand and transaction frequencies differ from urban areas, tailored statistical algorithms generate reliable forecasts. Each facility dispenses over 850 products, with a few items accounting for most of the volume. Demand shows strong daily periodicity, with patterns across weekdays, Friday evenings, and weekends. Pharmaceutical inventory control measures aim to address key objectives, such as minimising stockouts and managing expired items. Safety stock levels are set for each item based on factors such as replenishment frequency, availability goals, and expected demand between orders. Using predetermined safety stock helps maintain coordination between restocking intervals. Intermittent strategies are explored alongside various continuous-review policies that account for shipments arriving on different days and at different times, as well as transportation constraints. This flexibility is especially valuable for rural supply chains compared to urban areas. An extra transport mode is even available at the facility. Fast-moving products on daily replenishment schedules are distinguished from slower-moving items replenished weekly. Additionally, disaster scenarios and risk mitigation for vaccines, oxygen, and drugs are examined. Rural transportation challenges are addressed to improve delivery efficiency, particularly for facilities that are less protected against supply disruptions (Michael Woosley, 2009).

3.1. Data Sources and Quality

Prominent data sources for U.S. pharmaceutical supply chains include wholesale and retail distributors, health systems, multiple pharmacy chains, manufacturers' drug production schedules, and hospital electronic medication administration systems (Pall et al., 2023). The primary input in demand forecasting is a production schedule that notes the date, time, and location of drug production. Drug delivery frequency for every distribution point is a critical input for inventory optimisation; drugs with more extended periods of inactivity are kept at a higher inventory level. These data structures and quality depend on the corresponding information recorded by the pharmaceutical supply chain entity. Given the numerous factors affecting the pharmaceutical supply chain, change points are common. Online change-point detection based on variational Bayesian inference is used to detect alterations in the data generation process after they occur. Detection is based on historical data; upon the arrival of new data, the procedure attempts to determine whether a change has occurred. If so, the system notifies associated personnel in real time.

3.2. Modelling Approaches

Medication shortages can threaten healthcare systems and negatively affect patient safety. A robust approach to managing the supply chain from manufacturers to rural healthcare facilities, operating under limited visibility and connectivity, is essential. Still, the first step is determining the best approach to tackle the problem, so multiple approaches must be evaluated. Supply chain resilience modelling is already used in the sector to address pharmaceutical shortages, and another well-established method for tackling benign drug shortages is demand forecasting. Although these two approaches seem unrelated, they can be closely integrated for strategic decision-making. Models are classified based on whether they include a physical flow representation (L. Tucker & S. Daskin, 2021). Approaches without such representation can support high-level planning, typically developing a description of where and how much inventory should be held in advance of physical distribution planning. Conversely, approaches that incorporate physical flows focus on supply allocation and physical distribution, often relying on pre-calculated estimates of safety stock. The chain of supply is represented at a low level of detail, conveying minimisation of the total cost of the entire product chain relative to fixed sourcing policies. Increasing the agility of a supply chain by securing the availability of essential pharmaceutical products is also of great importance. The loss of demand often triggers such urgency and, when supply disruption is only temporary, reverting to a previously established supply policy quickly leads to the recovery of the disrupted elements of the chain, therefore minimising any subsequent loss of inventory.

3.3. Decision Support Tools

Decision support tools enhance visibility, improve decision-making, and streamline inventory processes. Regardless of organisational or facility-specific context, specific key tools have been shown to positively influence inventory management, safety stock, and related activities across various settings (Michael Woosley, 2009). Consequently, a zero-level inventory policy (where the minimum order quantity is set to ensure monthly replenishment meets demand) and controlled quantitative forecasting are standard tools recommended to improve replenishment and forecasting methods within configurable inventory frameworks. A classification methodology has been developed to distinguish these two activities. The forecasting process identifies factors affecting item demand, while the replenishment process involves setting sieve parameters according to the replenishment strategy. Inventory objectives can be easily defined and tailored to the specific properties of different modelling situations. Available frameworks for end-users include univariate seasonal time series within a safety-stock inventory management policy, multivariate forecasting combined with a base-stock approach, and supply chain network modelling adapted to a two-par-limits system (Pall et al., 2023); (Tyzik et al., 2018). Zero-level inventory management policies minimise traditional Activity-Based Costing models involving logistics networks by simultaneously optimising transport costs across multiple activities, subject to shared constraints. The configuration is dictated by these activities, associated technologies, and is categorised into model types (e.g., fixed incremental quantities or variable order sizes). An example application is in store-retail chain settings, where store cross-holdings act as the shared constraint.

4. Demand Forecasting for Rural Settings

Rural healthcare facilities often lack the personnel or resources to perform complex demand forecasting that accounts for myriad factors affecting medication consumption. Consequently, pharmacy leaders currently rely on technology or public prior-use datasets to estimate future demand (Pall et al., 2023). Forecasting methods include simple average models (e.g., naïve models) and moving average models (e.g., Fibonacci series) that aggregate consumption across months or days, as well as exponential smoothing and linear regression. Historical consumption of top medications over a specific time frame, along with total acquired inventory units for the same period, also provides insights into predicting demand. Remaining on-hand stock, after accounting for consumption and acquisitions, further indicates the volume of requests to fulfil, allowing managers to forecast demand based on past patterns.

Larger models are critical for rural facilities with limited data availability. Constructing 59 basic models, physicians may successfully submit 40 models with zero residuals after examination, validating demand across basic estimation tools. Models frequently produced a zero in the holdout period, reflecting the periods with neither acquisitions nor consumption. Adjusting models or seeking additional modelling approaches presents an attractive opportunity to broaden knowledge of forecasting and to meet the needs of facilities lacking historical data. All fifty-nine models in offer remain viable. Addressing these shortages emerges as a significant challenge. However, adjusted data approaches that observe days-on-hand approaching zero must also integrate current stock-outs, suppliers not triggering request-late regulations, currently supplied volume fitting, and fundamental structures such as being a publicly traded, cross-state monitored area, thus shaping a non-subscription format. Model variations that increase fit alongside these limitations, along with respective data, remain the ongoing focus of exploration in limited-access pharmacy legislation.

4.1. Factors Affecting Demand Forecasting Methods and Their Validation

Healthcare providers in rural areas face various factors influencing pharmaceutical demand. Limited transportation worsens shortages, especially at rural facilities. While major disruptions like hurricanes or COVID-19 cause supply chain issues, such events are rare outside of them. Rural facilities seek to understand demand patterns to prepare for disruptions. L. Tucker and S. Daskin (2021) provide a framework for demand modelling that accounts for patient traits and facility types. Examples from U.S. Southwest and Southern Plains hospitals illustrate the potential of demand forecasting. Understanding each medication's demand patterns helps pharmacies develop procurement strategies. Demand factors include drug class, seasonality, supplier reliability, and prescription volume. Forecasting methods, including machine learning, predict demand, helping pharmacies identify potential drug shortages. Analysing model outputs such as upcoming shortages, therapeutic categories, and past data improves demand estimates and procurement priorities. Some pharmacies also struggle to estimate the number of drugs needed per prescription. Models predicting total prescriptions and the number of drugs per prescription help estimate total drug needs. Though these models do not yet forecast shortage severity, early results show promise for improving ordering decisions by focusing on critical shortages (Cappanera et al., 2022).

Table 1: Factors Affecting Demand Forecasting and Their Role in Data-Driven Supply Chain Optimisation.

Dimension	Factor	Impact on Demand / Shortages	Relevance to Data-Driven Supply Chain Optimisation in Rural U.S. Facilities
Geography & Access	Rural location, distance from urban hubs	Longer lead times, fewer deliveries, and higher stockout risks despite "normal" demand.	Models must incorporate lead times, delivery frequency, and distance as features; optimisation should adjust safety stocks and reorder points specifically for rural sites.
Transport & Logistics	Limited transportation options	Irregular replenishment; minor disruptions create significant local shortages.	Use data to simulate scenario-based inventory policies (e.g., what-if delays) and to design robust reorder rules that withstand transport variability.
Disruptive Events	Hurricanes, COVID-19, other shocks	Rare but severe spikes in demand and supply disruption.	Focus models on "standard" demand patterns but add stress-test scenarios for disasters; co-optimise emergency buffers or contingency stock specific to high-risk regions.
Facility Type	Hospital vs clinic vs small rural facility	Different case mix, acuity, and drug portfolios.	Segment models by facility type; use facility type as a key feature in clustering and forecasting; design differentiated inventory policies for hospitals vs. small clinics.
Patient Traits & Epidemiology	Local demographics, chronic disease burden	Drives which drugs are consistently demanded and in what volumes.	Incorporate ICD codes, diagnosis mix, age, and comorbidity indices into ML models; tailor stocking strategies to local disease burden rather than national averages.
Drug Class / Therapeutic Category	Chronic vs acute; critical vs non-critical	Different levels of stability and criticality in demand; some shortages are life-threatening.	Use drug class as a key dimension for ABC/criticality analysis and for prioritising optimisation (e.g., more conservative policies for antibiotics, insulin, etc.).
Seasonality	Seasonal diseases (flu, RSV, allergies, etc.)	Predictable peaks in demand for certain meds.	Include seasonal features (month, week, weather/flu indicators) in models; design seasonal safety stocks and pre-emptive ordering for expected peaks.
Supplier Reliability	On-time delivery performance, fill rates	Unreliable suppliers create "apparent" demand spikes (emergency top-ups) and stockouts.	Capture supplier reliability metrics and integrate them into optimisation; shift volume to more reliable vendors or increase safety stock where supplier risk is high.
Prescription	High vs low	High volume =	Use more sophisticated models for

Volume	volume drugs	better data; low volume = noisy, harder to predict.	high-volume, high-impact drugs; for low-volume items, use more straightforward rules and clinical prioritisation rather than complex ML alone.
Local Demand Granularity	Medication-level demand at each rural site	Patterns differ by site; aggregation hides local variation.	Build site-specific or region-clustered models; compare centralised vs local models for accuracy; allow local overrides in optimisation for known local patterns.
Forecasting Method	ML/statistical models using demand & shortage history	Identify likely shortages and timing, but not yet severity.	Deploy ML as an early-warning layer feeding a stochastic or robust optimisation engine; plan to extend models to shortage severity as data improves.
Shortage Prediction Info	Past shortages, therapeutic class, lead time	Helps identify which drugs and when shortages may occur.	Use predicted shortage windows as constraints in an inventory optimisation or allocation model (e.g., prioritise scarce stock to the most vulnerable rural facilities).
Unit-Level Ordering	Total prescriptions + drugs per prescription	Determines the total number of units required, not just the number of scripts.	Integrate prescription-level models into inventory planning so the optimiser works on unit requirements, reducing under- or over-ordering for multi-drug regimens.
Focus on Critical Items	Most-dispensed / clinically critical meds	These drive service level and patient risk.	Target optimisation for Top-N high-volume/high-criticality drugs first; define service-level targets (e.g., 99% fill rate) specific to these products in rural sites.
Model Maturity / Gaps	No modelling of shortage severity yet	Ca warns "shortage likely" but not "how bad".	Design the optimisation workflow so it still delivers value with binary or probabilistic shortage signals, and define a research path to integrate severity estimates later.

5. Inventory Optimisation Strategies

The most significant concern in managing pharmaceutical inventory remains reducing the likelihood of out-of-stock situations (Michael Woosley, 2009). The inventory-value ratio for pharmaceutical inventory tends to be higher than that for general inventory; therefore, it is effective to adopt an inventory strategy that supports multiple service levels to minimise total inventory costs. A stock-keeping unit (SKU) strategic analysis enables the separation of successful SKUs into three categories based on the number of order lines they generate: (1) slow-moving SKUs, (2) medium-speed SKUs, and (3) fast-moving SKUs. Safety-stock calculations and the fixed-order-interval replenishment policy can easily support risk management to maintain the availability of all three SKU classes. The availability of slow-moving SKUs is usually maintained by setting a safety stock level. The necessary safety stock quantity is a function of the SKU's stock-level stability, as limited-order activity reduces fluctuations in storage levels during the lead time. Fast-moving SKUs, on the other hand, demand greater investment and reinforce the re-order practices. Safety-stock calculation provides valuable inputs for implementing SKUs within councils when SKUs come from varying replenishment sources that contain diverse lead times, service-level requirements, and inventory-cost factors.

5.1. Safety Stock and Service Level Targets

The appropriate safety stock level should be determined to address variable demand and lead-time distributions (Michael Woosley, 2009). Capacity constraints, nurse hours, demand variability, ordering policies, and supplier performance factor into determining general service-level targets (L. Tucker & S. Daskin, 2021). Facilities employing a periodic-review policy require a service-level target related to a self-induced lead time determined by the review frequency. Continuous-review policies require inventory-level thresholds based on the service-time distribution requested from the supplier. The remainder of the pesticide distribution cycle is rapidly approximated using historical release data and field-aid requests, which immediately reflect supply shortages from a previous cycle.

5.2. Replenishment Policies

Modelling of periodic review (s,s) and underlying dynamic (s, S) replenishment strategies has attracted attention for its ability to control cycle stock, thereby influencing safety stock, as both replenishment strategies influence their equilibrium values. Finite lead times being part of the problem structure, s- and s+ terms determine excess demand above and below service-level targets; identification needed. A sliding-window approach and complementary cycle-stock reconstruction provide a basis. An affine function of the filtered demand process is used to determine the cycle stock adjustment. The direct reduction of service-level targets enables deeper analysis of cycle stock impact; the pattern and distribution of replenishment inter-arrivals influence service, without explicitly modelling this time between events. Poisson arrival with lead-time length preservation modelled as a uniform distribution on subsequent replenishment; c- and l-terms shape delivery time; a complementary cycle reconciliation must also be captured (Simões et al., 2025). To mitigate order installation and ensure complete capture of the governing regime, a delivery-by-state policy is recommended. Cost sensitivity provides insight into the relevance of maritime operations; influences cost assignment; allows validation of the dynamic-chaining cycle controlled by maritime characteristics; and the delivery-by-state policy seems to encapsulate the interaction between the prescription cycle and safety stock, accurately twinned with periodic replenishment (L. Tucker & S. Daskin, 2021).

5.3. Transportation and Logistics Considerations

In rural areas, transportation can be a significant driver of shortages as healthcare providers lack localised distribution centres or in-house pharmacy operations. Many shelves are stocked with thousands of items, while just a small, critical few remain frequently out of stock; for example, one study describes the inventory of a rural health system comprising 70 healthcare facilities holding around 13,000 unique items, 300 commonly used ones, and 18 regularly out-of-stock medications. Consequently, the focus on inventory planning should go beyond stocking appropriate levels for a homogeneous set of products, since most assets are seldom accessed. Detar and Loughlin point out that, at both the macro and micro levels, pharmacy dispensing is one of the most complex supply chain systems (Michael Woosley, 2009). At the macro level, healthcare facilities must decide whether to consolidate into a single repository or distribute across three regional pharmacies; best practice elsewhere compromises between these alternatives by considering the minimum distance to obtain the needed drugs (L. Tucker & S. Daskin, 2021). At the micro level within each pharmacy depot, the number of scheduled deliveries is key to establishing the replenishment policy and control parameters. Companies such as McKesson and Cardinal Health dominate distribution in the U.S. Typically, healthcare facilities group replenishment requests by frequency, daily, weekly, or bi-weekly, then determine total inventory requirements and select doses from the supplying company's catalogue to communicate on a central order pad. Since McKesson remains the leading distributor in most cases, one facility typically coordinates the order and transmits it to other facilities for them to inscribe their required units.

6. Supply Chain Resilience and Risk Management

An extensive analysis of potential disruption scenarios in the pharmaceutical supply chain, particularly where shortage risk is already elevated, is essential. Scenarios should focus on events with significant consequences that are reasonably foreseeable at the national or local level. Illustrative disruptions include a large-scale public health emergency, such as an epidemic or outbreak, which increases bulk purchasing by multiple facilities in a short time frame; climate impacts that damage transportation infrastructure, restricting material movement in or out of a facility; and a catastrophic increase in the cost of either a supply material or distribution. The analysis should specify expected duration and resulting depletion rates as parameters for the supply chain model (Silva et al., 2023). Mitigation strategies to reduce the likelihood of occurrence and the consequences of the identified scenarios should be developed. When multiple risks are of greater concern because they tend to occur independently, contingency plans should be prepared in the event of such a disruption. Selection of contingencies can factor into the analysis of primary risks and into the resources considered sufficient to maintain a reliable supply in parallel for these events. The active participation of senior facility management and the opportunity for extensive discussion of operational priorities are key facilitators for collecting supply chain data, modelling the supply network, and articulating disruption risks (L. Tucker & S. Daskin, 2021).

6.1. Disruption Scenarios, Mitigation and Contingency Planning

Shortages of critical medications and supplies are a persistent global challenge, notably during COVID-19 (L. Tucker & S. Daskin, 2021). These shortages impact patient care and highlight supply chain vulnerabilities. Pharmaceutical supply chains involve investments to meet clinic needs, with resilience enabling anticipation, adaptation, and recovery from disruptions. Modelling various disruption scenarios is vital, especially for rural clinics with limited funds. Supply disruptions can occur at any time, even during normal operations, leading to depleted inventory. Unlike typical models, where demand is demand-side driven, healthcare demand is often multifactorial and occurs on the distribution side. Disruptions happen when inventory is not delivered or is unavailable. Responses differ from demand disruptions; this affects supplemental medication needs, as seen in the lubricant case study (Schneller et al., 2023). Mitigation depends on the rural supply chain setup, including direct wholesaler delivery, delivery frequency, and the return of unsold stock. Rural facilities may be unaffected, but neighbouring charter sites could face disruptions, primarily if they serve larger areas. Strategies focus on medications with established charters, while single-dose meds without replacements are usually unaffected. For service targets below 100%, standard replenishment applies with adjusted buffers (Tyzik et al., 2018). Rural sites with predictable lead times, late dry-ups, or alternative resupply may see partial restocking. Routes influence redistribution, with two options affecting delivery pre-resupply. Remaining routes should be reconfigured pre-charter to ensure delivery, either by maintaining stage-one restructuring or broadening route shapes for redistribution at charter events.

7. Implementation in Rural Healthcare Facilities

Leveraging advanced research initiatives enhances engagement and collaboration with key stakeholders, vital for managing medication shortages in rural U.S. healthcare. Understanding how existing initiatives, emerging frameworks, and supply chain techniques interact encourages effective teamwork. Examining pharmacy initiatives enables the development of data-driven decision-support tools aligned with stakeholder goals, thereby reducing shortages. Senior administrators, supply chain, and pharmaceutical leaders work together to optimise resources, improve inventory, and ensure timely medication return (Chychun et al., 2023). Challenges remain after demand forecasting and inventory management, especially with existing procedures. Embracing technologies such as analytics, AI, and decision support accelerates solution development. Addressing supplier shipment issues, local supplier problems, and expired medication recovery depends on technology adoption frameworks that communicate service restoration (Tyzik et al., 2018). Using safety stock in requisition templates helps prioritise medication returns and establish effective plans. Sharing ideas with decision-makers sets the stage for phased organisation and pilot programs (Michael Woosley, 2009).

7.1. Stakeholder Engagement, Change Management and Technology Adoption

A lack of stakeholder engagement limits the effectiveness of data-driven models in mitigating medication shortages in rural healthcare facilities (Tyzik et al., 2018). In 2017, supply chain disruptions caused by Hurricane Maria prompted the Maine Medical Centre to assemble a multidisciplinary team to better manage the situation. However, without a regular process for communicating relevant information, the model could not be successfully implemented. Reflecting on this case, the objective was to involve stakeholders at both the local healthcare facility and across the entire state, thereby producing actionable outcomes for consideration rather than merely an abstract model. Following an adequate level of engagement, data-driven models were to be deployed to alleviate shortages and delays nationwide (L. Tucker & S. Daskin, 2021). Change management encompasses several objectives. One such objective is to provide education and awareness about supply chain optimisation and its tools, which are essential for stakeholders to accept the optimisation approach and participate actively (Tyzik et al., 2018). This process involves developing detailed plans to train supply chain leaders in the specific tools being implemented, effectively sharing needs and capabilities, and devising tailored implementation strategies (L. Tucker & S. Daskin, 2021). Another objective of change management is to sustain stakeholder engagement. Commonplace meetings can be counterproductive; thus, one strategy is to integrate demand, inventory, transportation, and expenditure reviews into fewer meetings, enabling groups to collaborate more effectively on long-term planning and strategic decision-making across these areas. To enhance meeting efficiency, guidance on order management has been made readily available to prevent prolonged discussions during reviews. Leadership has been a focal point in technology adoption during this period, particularly in replenishment tools and decision-support systems. Earlier efforts focused more on modelling a broader selection of material types and establishing aggregation guidelines to assist planners in optimising inventory or safety stock management.

8. Policy and Ethical Considerations

To improve overall public health, particular attention should be paid to ensuring that every U.S. community has timely access to needed medications. Policymakers have long advised that enhancing access to medicines should not compromise their quality, safety, or efficacy (W. Holmes & J. Hughes, 2013). Given that numerous regulations and procedures aim to ensure these attributes, any access issue must be carefully analysed before action is taken. In particular, supply chain vulnerabilities can lead to significant access delays without undermining these other attributes. Multiple data-driven methods can mitigate such vulnerabilities. Many preventive actions are proper in rural settings where geography inhibits the receipt of needed therapeutic supplies (C. Costantino, 2021). Pharmaceutical supply chain vulnerabilities are an example of a situation that impacts many healthcare sectors, for which decisions should ideally remain within the jurisdiction of local stakeholders across diverse geographical areas. Geographic conditions strongly influence the specific attributes of pharmaceutical supply chains and the consequent measures needed to strengthen access to medicines. Extensive urban facilities, for example, are generally able to stock a wider variety of pharmaceuticals and receive them rapidly, whereas rural entities face significant challenges in many such areas. Thus, access-to-medicines challenges, which some policy-oriented entities wrongly view as universal across the healthcare sector, depend on factors specific to each locality (Adebayo et al., 2024; Mitchell, 2024)

9. Evaluation Metrics and Evidence

Pharmaceutical shortages are a continuing problem affecting U.S. healthcare facilities, especially those in rural areas. The problem has received intense scrutiny, particularly during the COVID-19 pandemic. The situation is exacerbated for rural healthcare systems, which often suffer from the "rural pharmacy gap", the lack of local pharmacies obtaining and dispensing scarce drugs. The situation can also result in prolonged delays in providing essential medications to patients. All parties agree that efficiencies in supply chain management, transportation logistics, and inventory control can enhance the timely delivery of critical medications. However, systematic inter-facility evaluations have not been performed. (Popoola et al., 2024). There is little documented evidence linking improved evaluation metrics and pharmaceutical shortages among rural facilities. Decision-makers are hampered by limited historical data detailing purchase priorities, local delivery schedules, and inventory levels of essential medications. To address these issues, Colorado State University researchers are assessing capabilities and developing tailored solutions to improve rural healthcare delivery (L. Tucker & S. Daskin, 2021).

10. CONCLUSION

Improved pharmaceutical supply chain management has the potential to mitigate medication shortages significantly in healthcare facilities serving rural populations. Empirical evidence from numerous studies and analyses demonstrates the substantial, detrimental impacts of supply shortages on healthcare systems (W. Holmes & J. Hughes, 2013; Michael Woosley, 2009; L. Tucker & S. Daskin, 2021). The growing prevalence of these shortages, exacerbated by COVID-19, further underscores the urgency of developing, adopting, and implementing state-of-the-art inventory management policies, critical training programmes, and modern modelling and simulation methods. To support decision-making and align with established pharmaceutical supply chain modelling principles, a series of frameworks has been written. The systematic approaches are explicitly tailored to the processing, analysis, and interpretation of data collected from rural healthcare facilities. A variety of contemporary inventory management policies, supported by relevant models and simulations, has been developed and brought together in an easily comprehensible format for optimal stakeholder comprehension and inspection. Several open-source, user-friendly modelling packages are available to appropriately represent the complexities of the rural healthcare sector. Existing, readily accessible data have been augmented with additional predictive algorithms that can be directly integrated into the respective modelling packages.

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