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Efficiency and Resilience of Healthcare Supply Chains in Emerging Economies: An Analysis of Cost Structures, Accessibility, and Service Delivery Outcomes

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Abstract

Healthcare systems in emerging economies often operate under persistent resource constraints, high demand variability, and infrastructure limitations that shape how medicines, diagnostics, vaccines, and consumables reach patients. Supply chains therefore act as a practical interface between financing, physical distribution, and clinical service delivery, with performance expressed not only in budget execution but also in stock availability, travel burden, and timeliness of care. This paper analyzes the efficiency and resilience of healthcare supply chains in emerging economies by integrating cost structures, accessibility, and service delivery outcomes within a unified analytical perspective. The discussion distinguishes procurement, transportation, inventory holding, cold-chain compliance, wastage, and administrative overhead, and it highlights how fragmented governance and heterogeneous provider mixes alter the marginal costs of reliability. Accessibility is examined through spatial and temporal dimensions, including facility catchments, last-mile constraints, and the interaction between stockouts and patient travel behavior. Resilience is treated as the ability to sustain essential product availability under disruptions such as supplier failures, port delays, currency shocks, and localized transport outages, with emphasis on trade-offs between redundancy and operating efficiency. A mathematical framework is presented to formalize multi-echelon flows, risk exposure, and service-level guarantees under uncertainty. The paper then links supply chain performance to service delivery outcomes by considering how availability, lead times, and product quality propagate into treatment initiation, continuity, and effective coverage. The analysis is intended to support structured reasoning about design and policy choices under realistic constraints rather than to promote a single optimal model.

1. Introduction

Supply chains in healthcare are frequently described as logistical backbones, yet in emerging economies they are also mechanisms that convert constrained public expenditure, donor financing, and household payments into tangible service capacity [23]. The relationship between supply chain design and health outcomes is not automatic, because medicines and supplies interact with clinical decision-making, human resources, diagnostic capability, and patient behavior. Even when clinical guidelines and treatment protocols exist, the operational reality of whether products are available in the right formulation, quantity, and condition at the point of care often determines whether care is delivered as intended. This operational dependence creates a dual requirement: supply chains must be efficient enough to stretch limited budgets, and they must be resilient enough to maintain continuity during routine volatility and episodic shocks.

Emerging economies exhibit a wide spectrum of institutional arrangements that complicate generalization. Some countries operate centralized procurement and distribution with national medical stores and regional depots, while others rely on mixed systems that include private wholesalers, faith-based networks, parallel donor pipelines, and informal retail markets. These arrangements coexist with infrastructure constraints such as limited cold storage, unreliable electricity, road quality variation, and port congestion, as well as with financial constraints including budget execution delays, foreign exchange exposure, and payment arrears. The resulting supply chain performance is therefore shaped by both engineering decisions, such as facility placement and routing, and governance decisions, such as contracting, payment terms, accountability structures, and information transparency.

A central tension is the trade-off between lean operation and protective capacity. Reducing inventory and consolidating facilities can lower working capital needs and operating costs, but can increase exposure to lead time uncertainty and disrupt the ability to buffer shocks. Conversely, holding higher safety stocks and maintaining redundant pathways can raise costs and induce wastage, particularly for temperature-sensitive or short shelf-life products. In emerging economies, this tension is intensified because demand uncertainty is often high, epidemiological patterns can shift quickly, and the costs of stockouts can include not only delayed care but also increased out-of-pocket spending and erosion of trust in public providers [24].

The analysis in this paper treats efficiency and resilience as related but distinct performance objectives. Efficiency is interpreted as the ability to deliver required service levels at minimal total system cost, where cost includes not only transport

and storage but also quality losses from spoilage, expiries, and substandard handling. Resilience is interpreted as the ability to sustain acceptable service levels under disruption scenarios, recognizing that disruptions can be structural, such as chronic underfunding and unreliable power, or acute, such as floods, conflict-related road closures, or supplier failures. Accessibility is treated as an intermediate outcome linking logistics to health system objectives: when products are geographically distant or administratively difficult to obtain, the effective availability faced by patients differs from the physical availability in warehouses [16].

The goal is to provide a structured, technically grounded discussion of how cost structures, accessibility constraints, and service delivery outcomes interact in the context of emerging economies. The approach is deliberately integrative. It combines operational cost accounting, spatial accessibility reasoning, and outcome mapping into a framework that can support decision-making and empirical analysis. Mathematical modeling is introduced as a formal language to represent multi-echelon distribution, uncertainties, and policy constraints, while recognizing that parameter estimation and institutional feasibility remain nontrivial in many settings.

The paper proceeds by establishing a measurement-oriented context for supply chains in emerging economies, describing data realities and the implications for inference. It then examines cost structures and their drivers, paying attention to currency risk, cold chain requirements, and the administrative costs of fragmentation. Accessibility is analyzed through network design and behavioral responses to supply availability. Resilience is developed through scenario-based and robust perspectives, focusing on where redundancy is most valuable and how disruptions propagate. Finally, supply chain performance is linked to service delivery outcomes, emphasizing that outcomes depend on joint availability of products, staff, and diagnostic capacity, and that improvements may be nonlinear and equity-sensitive. The concluding section synthesizes implications and identifies limitations inherent to the available data and institutional heterogeneity.

2. Context and Measurement in Emerging-Economy Healthcare Supply Chains

A practical analysis of healthcare supply chains in emerging economies must begin with measurement realities. Operational records often exist across multiple institutions, each with differing incentives and information systems. Public procurement agencies may record contract values and delivery schedules, central medical stores may record receipts and issues, district depots may record requisitions and dispatches, and facilities may record stock cards and dispensing logs. Parallel systems may operate for specific programs, and private sector flows may be partially observable through import records, wholesaler invoices, or retail audits. Data fragmentation implies that apparently simple quantities such as the stockout rate of an essential medicine can be defined in multiple ways, depending on whether measurement is done at the warehouse, facility, or dispensing point, and whether the definition considers complete stockout, partial stockout, or stockout of a specific formulation.

The context of emerging economies also complicates baseline assumptions about demand [10]. Demand in health supply chains is not purely exogenous. It depends on disease incidence and prevalence, but also on care-seeking behavior, affordability, trust, and perceived quality. If facilities frequently experience stockouts, patients may shift to private pharmacies, informal vendors, or self-treatment, which in turn can reduce facility consumption data and create an illusion of lower demand. Conversely, when supply reliability improves, latent demand may be revealed, causing apparent demand growth that can be misinterpreted as inefficiency. This feedback loop implies that demand estimation should account for substitution behavior, seasonality, and policy shifts such as insurance expansion or user-fee changes.

A related measurement challenge is the distinction between nominal availability and effective availability. Nominal availability might be defined as whether a facility has a product on the shelf at the time of inspection, while effective availability accounts for whether the product is usable, unexpired, appropriately stored, in the right dosage, and accessible to the patient given facility hours and administrative procedures. For vaccines and other cold-chain products, the difference between nominal and effective availability can be substantial, because temperature excursions may reduce potency without immediately removing vials from inventory. For diagnostics, consumables such as reagents and test cartridges may be present but unusable due to equipment downtime or power instability. These issues complicate the mapping from logistics performance to clinical outcomes.

Emerging economies often face a dual burden of chronic operational constraints and episodic disruptions. Chronic constraints include unreliable electricity, limited refrigerated transport, road quality deterioration during rainy seasons, and staffing shortages in logistics roles. Episodic disruptions include port strikes, sudden currency devaluations that disrupt import financing, floods that isolate districts, and political instability that interrupts procurement and transport. A measurement framework therefore benefits from distinguishing routine variability from disruption events, because the strategies that optimize routine performance may not be those that minimize disruption losses.

Cost accounting for healthcare supply chains similarly faces definitional issues [20]. Transport costs may be borne by central agencies, donors, third-party logistics providers, or facilities, depending on the distribution model. Staff costs may be embedded in facility budgets rather than supply chain budgets, even when staff time is a binding resource for inventory management. Wastage costs may be recorded as financial write-offs, physical disposal costs, or not recorded at all if expired products remain in storage. Currency and financing costs, such as the cost of delayed payments, import duties, and demurrage, may be external to health budgets but still economically relevant. To compare efficiency across systems, it is therefore necessary to specify the cost boundary and to interpret reported costs as partial views of total economic cost.

Accessibility measurement introduces additional complexity. Geographic access is often approximated by straight-line distance or road distance between populations and facilities, but actual access is mediated by transport availability, travel time variability, and safety constraints. Financial access interacts with logistics because stockouts in public facilities can shift patients to private markets where prices are higher, implying that the supply chain affects household financial risk. Ad-

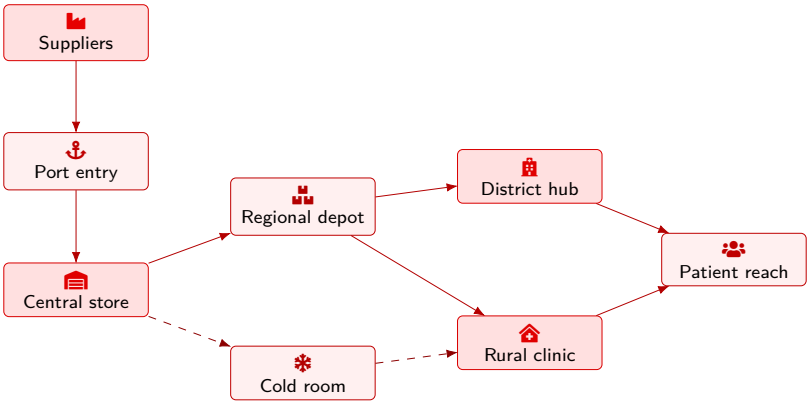


Figure 1. Multi-echelon healthcare supply architecture in emerging economies. The figure emphasizes how upstream import dependence, central storage, regional redistribution, and differentiated care points jointly determine whether products are physically positioned close enough to patients for timely dispensing.

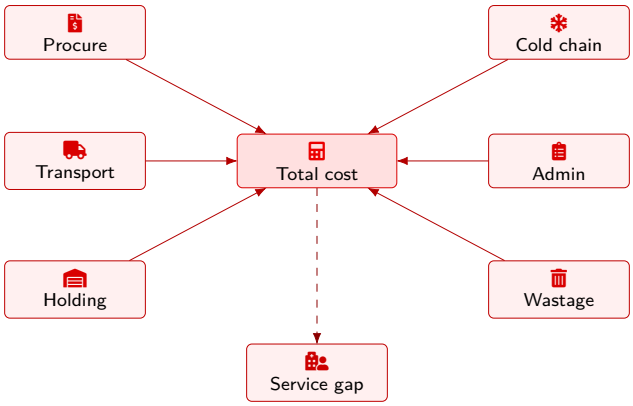


Figure 2. Supply-chain cost boundary with operational and quality-related components. Rather than reducing efficiency to purchase price alone, the diagram highlights how transport, inventory, refrigeration, administration, and wastage accumulate into economic cost and ultimately shape the probability of downstream service shortfalls.

ministrative access, including whether facilities require certain documentation or operate limited hours, also affects effective access. From a supply chain perspective, these access barriers can influence demand timing and distribution, which then affects replenishment patterns and inventory requirements.

Service delivery outcomes in emerging economies are frequently measured through facility service statistics, health surveys, or programmatic indicators such as immunization coverage. Each has limitations. Facility statistics can undercount populations that do not seek care, surveys can suffer recall bias and limited product specificity, and programmatic indicators may focus on priority diseases while overlooking routine essential medicines. Linking supply chain performance to outcomes therefore requires careful consideration of causal pathways and confounding factors. For example, a reduction in stockouts of an antibiotic might be expected to reduce untreated infections, but observed facility prescribing may also depend on diagnostic capacity and clinician behavior. Similarly, improved vaccine availability may not increase coverage if outreach services are constrained by staffing or fuel budgets [15].

Given these constraints, an analytical approach that combines operational modeling with empirically grounded parameters can still be valuable, provided it is interpreted as a structured representation rather than a complete depiction of reality. The modeling perspective helps clarify which variables must be measured or approximated, where uncertainty is concentrated, and how trade-offs emerge. In emerging economies, practical models often need to accommodate missing data, parameter uncertainty, and multiple stakeholders with distinct objectives. This motivates the inclusion of risk-aware objectives and constraints that can represent minimum service requirements and equity considerations alongside cost minimization.

3. Cost Structures and Financing Mechanisms: Drivers of Efficiency

The cost structure of healthcare supply chains in emerging economies reflects both physical logistics and institutional arrangements. Procurement costs are often the largest component for many commodities, but the procurement price alone rarely captures the economic cost of ensuring availability. Procurement costs are influenced by contract design, supplier competition, quality assurance, and the ability to forecast demand accurately. When demand forecasts are poor,

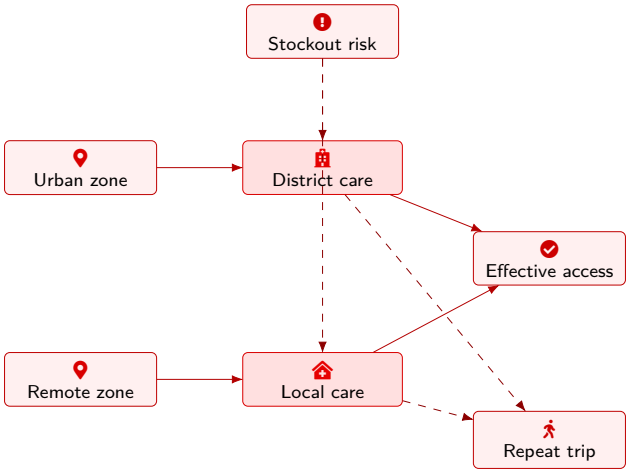


Figure 3. Accessibility as a joint function of geography and stock reliability. Even when facilities exist within plausible catchments, stockout risk can convert a single encounter into repeated travel, raising time and money burdens and reducing realized access relative to nominal service availability.

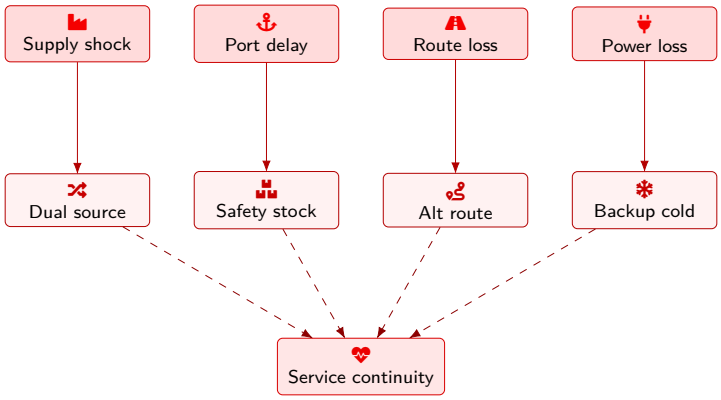


Figure 4. Resilience logic under correlated disruption. The diagram separates disruption sources from mitigation instruments and shows that continuity is not created by one universal buffer, but by a portfolio of sourcing, inventory, routing, and cold-chain safeguards targeted at different failure modes.

emergency orders can increase unit prices and shipping costs, while over-ordering can increase expiries. In systems with donor support, procurement may be done through pooled mechanisms or international agencies, sometimes achieving lower prices but potentially introducing longer lead times or reduced flexibility in adjusting volumes. In contrast, local procurement may be faster but may face higher prices, quality variability, and limited supplier capacity.

Transportation costs in emerging economies are shaped by road infrastructure, fuel price volatility, vehicle availability, and security constraints. Distribution models vary from push systems, where central agencies allocate stock, to pull systems, where facilities requisition based on consumption and stock status. Push systems can exploit economies of scale in routing but may allocate mismatched quantities, whereas pull systems can better reflect local needs but require reliable facility-level data and timely financing for orders. When last-mile distribution is underfunded, facilities may be expected to collect supplies from depots using their own resources, shifting transport costs and creating inequities because remote facilities face higher burdens.

Inventory holding costs include the cost of capital tied in stock, warehouse operation costs, and the risk of expiry and damage. In emerging economies, the cost of capital is not only a financial concept but also a representation of liquidity constraints [21]. Health agencies may face delayed budget disbursements and payment arrears, making it difficult to finance adequate safety stock even if it is cost-effective in expectation. Cold-chain commodities face additional holding costs due to refrigeration energy requirements, cold room maintenance, monitoring, and potential losses from temperature excursions. The interaction between cold-chain costs and transport constraints is central: maintaining temperature-controlled transport may reduce wastage but can increase per-unit transport costs and reduce routing flexibility.

Administrative and information costs are often underappreciated components of supply chain cost structures. Managing multiple funding streams, procurement channels, and reporting requirements increases staff time and introduces delays. Fragmentation can create duplicative warehousing and parallel distribution, which may be justified for program accountability but can reduce overall efficiency. Conversely, consol-

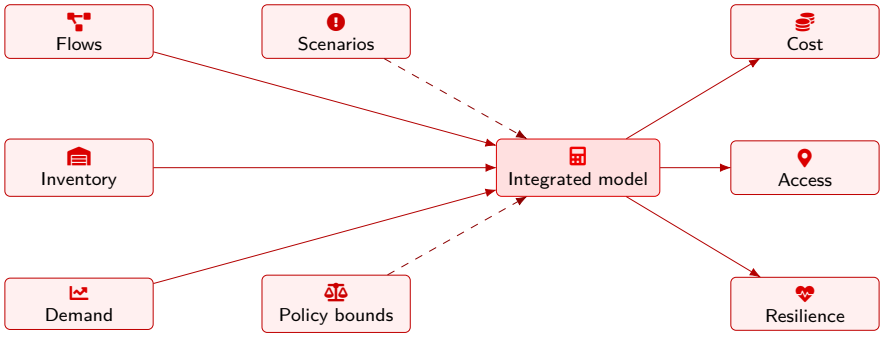


Figure 5. Integrated analytical structure for the paper' s mathematical perspective. State variables and demand conditions enter the model together with uncertainty and policy constraints, and the resulting solution space is interpreted through three linked performance dimensions: total cost, patient access, and disruption tolerance.

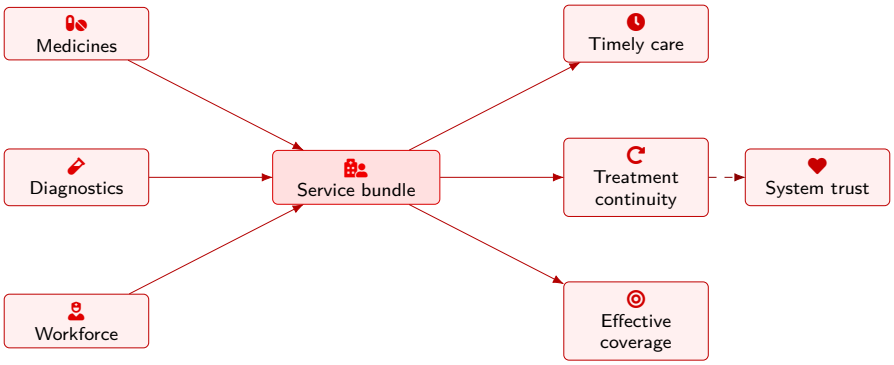


Figure 6. Service-delivery pathway linking logistics performance to health-system function. Commodity availability matters most when it combines with diagnostics and workforce to form an operational service bundle, which then influences timeliness, continuity, effective coverage, and eventually patient trust in the delivery system.

idation can reduce administrative overhead but may create single points of failure. The net effect depends on governance quality, the ability to enforce quality standards, and the reliability of information flows.

Currency and macroeconomic exposure is particularly important for imported commodities. Many essential medicines and vaccines are imported, with payment in foreign currency. Currency depreciation can increase local-currency procurement costs rapidly, while import financing constraints can delay shipments. These effects propagate into inventory decisions: agencies may attempt to front-load purchases to hedge against depreciation, increasing inventory and expiry risk, or may delay purchases due to budget uncertainty, increasing stockout risk. Import-related costs such as port handling fees, demurrage, and customs delays can be substantial and are sensitive to administrative efficiency and policy regimes.

Quality assurance costs are integral to efficiency when measured as cost per effective unit delivered. Substandard or falsified products, improper storage, and temperature excursions can produce nominal deliveries that do not translate into clinical benefit [22]. Investing in quality assurance, including supplier audits, sampling, and monitoring, increases operating costs but can reduce downstream waste and improve outcomes. In systems with constrained budgets, quality assurance may be underfunded, creating hidden inefficiency that appears as lower spending but results in lower effective supply [9].

To formalize these cost components, consider a multi-echelon supply chain with suppliers, central warehouses, regional depots, and facilities. Let products be indexed by k, nodes by i and j, and time by t. Let x_{ijkt} denote shipment quantity of product k from node i to node j in period t, and let I_{ikt} denote inventory at node i at the end of period t. Let D_{jkt} denote demand at facility node j for product k in period t, and let u_{jkt} denote unmet demand. A cost-based efficiency objective can be represented as a sum of procurement, transport, holding, wastage, and penalty costs, potentially augmented by risk and equity terms.

$$\begin{aligned}\min \sum_t \sum_k \sum_{i\in\mathcal{S}} c^{\text{proc}}_{ikt}\, x^{\text{in}}_{ikt} \;+\; \sum_t \sum_k \sum_{(i,j)\in\mathcal{A}} c^{\text{tr}}_{ijkt}\, x_{ijkt} \\ +\; \sum_t \sum_k \sum_{i\in\mathcal{N}} c^{\text{hold}}_{ikt}\, I_{ikt} \;+\; \sum_t \sum_k \sum_{i\in\mathcal{N}} c^{\text{waste}}_{ikt}\, w_{ikt} \\ +\; \sum_t \sum_k \sum_{j\in\mathcal{F}} c^{\text{unmet}}_{jkt}\, u_{jkt} \;+\; \lambda\, \Phi(\text{risk}, \text{equity})\end{aligned}$$

The term x^{in}_{ikt} can represent procurement inflow from external suppliers into the system at supplier-adjacent nodes $\mathcal{S}$. The arc set $\mathcal{A}$ represents feasible transport links, and $\mathcal{N}$ denotes all nodes. The wastage variable w_{ikt} can capture expiries, spoilage, and losses from temperature excursions, which can

be modeled explicitly through shelf-life dynamics or implicitly via expected wastage rates that depend on handling quality and storage conditions.

The financing mechanism affects these costs through constraints on cash flow and payment timing. In emerging economies, procurement may require prepayment or letters of credit, while government disbursement schedules can be irregular. If a budget constraint binds at period t, then feasible procurement and transport may be limited, creating intertemporal trade-offs where spending earlier can reduce future costs but may be infeasible. A stylized budget constraint can be represented by

$$\sum_{k}\sum_{i\in\mathcal{S}} p_{ikt}\, x^{\text{in}}_{ikt} \;+\; \sum_{k}\sum_{(i,j)\in\mathcal{A}} q_{ijkt}\, x_{ijkt} \;\le\; B_t \;+\; \omega_{t-1} \;-\; \omega_t \;+\; \eta_t$$

where B_t is the budget released in period t, ω_t is cash carried forward, and η_t represents emergency financing or arrears that can relax the constraint at the cost of future obligations. This representation is simplified, but it highlights that efficiency assessments should account for the cost of financial frictions. For example, a distribution model that appears cheaper in steady state may be infeasible under delayed disbursements, leading to costly emergency purchases and ad hoc transport.

Cost structure analysis should also account for economies of scale and scope. Centralized warehousing can reduce per-unit storage and handling costs if volumes are high and processes are standardized, but it can increase distribution distances and last-mile complexity. Decentralized storage can improve responsiveness and reduce last-mile distances, but it can increase fixed costs and variability in quality control. Scope economies arise when the same transport run can deliver multiple products, lowering marginal transport costs, but only if products share handling requirements. Cold-chain and ambient products often require different handling, reducing scope economies and encouraging either specialized distribution or hybrid solutions with differentiated lanes [7].

The private sector can provide logistics services that reduce certain costs through specialization, but contracting introduces transaction costs and requires capacity for performance monitoring. In emerging economies, third-party logistics can be effective when public fleets are unreliable, yet it may concentrate market power and expose the system to vendor risk. Additionally, private logistics may prioritize profitable routes, potentially increasing inequities unless contracts include service obligations and enforcement mechanisms.

In summary, supply chain efficiency in emerging economies depends on a nuanced cost boundary that includes procurement, transport, holding, wastage, administrative overhead, and financing frictions. Interpreting efficiency therefore requires distinguishing between observed expenditures and economic costs, and between nominal deliveries and effective units delivered. These distinctions motivate subsequent sections that integrate accessibility and resilience into the analysis rather than treating cost minimization as an isolated objective.

4. Accessibility and Network Design: From Physical Flows to Patient Reach

Accessibility in healthcare supply chains has both a logistical and a patient-facing meaning. Logistically, accessibility reflects the ease with which products reach facilities, determined by network topology, transport reliability, and lead times. Patient-facing accessibility reflects the ease with which patients reach products and services, determined by facility location, operating hours, fees, and the probability that a sought product is available at the time of visit. In emerging economies, these meanings interact strongly because travel burdens are often high, and repeated visits due to stockouts impose time and financial costs that can deter care-seeking and reduce adherence.

A common supply chain failure mode is the concentration of inventory in upstream nodes while downstream facilities experience stockouts. This can occur due to poor information, rigid allocation policies, or transport constraints that prevent timely redistribution. In such cases, aggregate stock levels may appear adequate, but effective access is low. Another failure mode is that products reach facilities but are not dispensed due to administrative restrictions, mismatches between delivered formulations and prescribing practices, or quality concerns. These failures highlight that accessibility analysis must consider both physical distribution and operational policies at facilities [14].

Spatial accessibility is often analyzed using catchment areas and travel time. In emerging economies, travel time is highly variable due to road conditions, seasonal disruptions, and transport availability. A facility may be within a nominal distance but effectively inaccessible during rainy seasons, which can coincide with seasonal disease peaks. Moreover, transport costs can be nonlinear with distance because of fuel availability, vehicle wear, and the need for multiple transport modes. For rural populations, the cost of travel may include lost labor time and childcare constraints, making repeated visits particularly costly.

Stockouts convert physical distance into an amplified accessibility barrier. If the probability of product availability at a facility is s_{jkt} for facility j and product k, then the expected number of visits required to obtain the product can be approximated by $1/s_{jkt}$ when each visit is independent and the patient attempts until success. While independence is a simplification, it conveys that a decline from 90% availability to 60% availability increases expected attempts from about 1.11 to 1.67, substantially raising travel burden. This is relevant in emerging economies where even a single visit can be costly, and where patients may abandon care after a failed attempt.

Network design decisions influence both facility-level service reliability and patient travel burdens. For example, centralizing depots can reduce upstream costs but may increase lead times to remote facilities, requiring higher safety stocks at facilities to maintain availability. If facility storage is limited or poorly managed, higher safety stocks may not be feasible, causing availability to fall. Conversely, adding intermediate depots can reduce lead times and improve responsiveness but can introduce additional handling and potential for mismanagement. The design problem therefore includes a multi-objective aspect: minimize total cost while ensuring geographic and temporal access.

To represent accessibility within a logistics model, one can incorporate service-level constraints and travel-time bounds. Suppose τ_{ij} denotes expected transport time from node i to node j, and θ_j denotes a maximum acceptable replenishment time for facility j given its storage capacity and demand volatility. A simplified constraint can require that each facility is served from a depot within a time bound. If y_{ij} indicates assignment of facility j to depot i, then

$$\sum_{i \in \mathcal{D}} y_{ij} \;=\; 1 \qquad \forall j \in \mathcal{F}$$

$$\tau_{ij}\, y_{ij} \;\le\; \theta_j \qquad \forall i \in \mathcal{D},\ \forall j \in \mathcal{F}$$

where $\mathcal{D}$ denotes depots and $\mathcal{F}$ denotes facilities. In practice, transport time is uncertain, and τ_{ij} might represent a quantile rather than a mean. Moreover, assignment may be dynamic if routes change seasonally [11]. Nonetheless, the constraint expresses the principle that accessibility can be embedded as a design requirement.

Patient accessibility can be represented through a coverage function that depends on both travel time and availability. Let the population be partitioned into demand zones $z \in \mathcal{Z}$, with population-weighted demand for product k in period t represented by δ_{zkt}. Let T_{zj} denote travel time from zone z to facility j, and let a_{zj} represent the probability that patients from zone z choose facility j given travel time, perceived quality, and cost. A stylized effective access measure for product k can be

$$A_{zkt} \;=\; \sum_{j \in \mathcal{F}} a_{zj}\, g(T_{zj})\, s_{jkt}$$

$$\text{with} \quad 0 \le g(T) \le 1 \quad \text{and} \quad \sum_{j} a_{zj} = 1$$

where $g(T)$ is a decreasing function capturing travel friction. The term s_{jkt} links supply chain performance directly to patient access. When availability is low, A_{zkt} can fall sharply even if travel times are short. When travel times are long, improvements in availability may have limited effect if patients cannot feasibly reach the facility. This representation also highlights equity concerns: zones with long travel times and low facility density can have systematically lower effective access even if national averages appear adequate.

In emerging economies, accessibility is influenced by the coexistence of public and private channels. When public facilities are stocked out, private pharmacies may provide access, but at higher prices and with variable quality. The supply chain thus interacts with household financial risk. If the probability of stockout in the public channel is $1 - s_{jkt}$, and the private price is P^{priv}_{kt} compared with a subsidized public price P^{pub}_{kt}, then the expected household expenditure conditional on seeking the product can increase with stockouts, with implications for adherence and catastrophic spending. This is particularly relevant for chronic disease medicines, where continuity matters and repeated purchases can be financially burdensome.

Administrative accessibility can be modeled through delays and service times. Facilities may require specific clinic days for dispensing chronic medicines, or may impose rationing during shortages. These policies are often responses to supply uncertainty and aim to spread limited stock across patients, but they can increase patient waiting time and reduce adherence. In logistics terms, such rationing is an endogenous demand management response that can mask the severity of shortages when measured solely through stock card balances.

Thus, accessibility analysis suggests that efficiency cannot be evaluated solely by cost per unit moved. It must also consider where units are positioned in the network, how reliably they are available at dispensing points, and how patient travel and behavior respond [8]. Network design and inventory policy choices influence these outcomes, and the design problem becomes one of balancing cost, service reliability, and equity under uncertainty [12].

5. Resilience and Risk Propagation: Maintaining Service Under Disruptions

Resilience in healthcare supply chains can be understood as the capacity to sustain essential product availability when confronted with disruptions. In emerging economies, disruptions can be multifaceted and correlated. A currency shock can simultaneously reduce procurement capacity, delay supplier shipments, and increase fuel prices. Seasonal floods can impair road access, damage warehouses, and increase disease incidence, raising demand while reducing supply capability. Political instability can interrupt budget disbursement and increase security risks on transport routes. Resilience therefore involves both preparedness, such as having buffers and flexible contracts, and adaptive capacity, such as rerouting, substituting products, and reallocating stock.

A key concept is risk propagation across echelons. An upstream disruption, such as a supplier delay, can propagate downstream with amplification if inventories are low, information is delayed, and replenishment policies are rigid. Conversely, downstream disruptions, such as facility-level power failure for cold storage, can cause localized losses that waste upstream effort. This bidirectional propagation suggests that resilience strategies should be targeted to the most critical nodes and links, rather than applied uniformly.

Resilience can be quantified through service-level metrics under disruption scenarios. A common metric is the fill rate, the fraction of demand met without delay. Another is the stockout duration, the number of days a product is unavailable. In emerging economies, resilience may also be measured by continuity of treatment for chronic conditions, the ability to maintain vaccine potency, and the avoidance of forced substitution to less effective regimens [3]. These metrics are sensitive to both inventory buffers and response capability.

Scenario-based modeling provides a way to represent disruptions explicitly. Let $\omega \in \Omega$ index scenarios, each with probability π_ω. Scenarios can affect demand D^{ω}_{jkt}, transport capacity C^{ω}_{ijt}, lead times L^{ω}_{ijt}, and node availability indicators that represent facility or warehouse outages. A two-stage formulation can represent decisions made before disruptions, such as facility location and base-stock levels, and recourse decisions made after disruptions, such as emergency shipments and reallocations.

To incorporate resilience into an optimization framework, one can augment the cost objective with a risk measure that pe-

nalizes poor performance in adverse scenarios. Conditional value-at-risk (CVaR) is one such measure, capturing expected loss in the worst tail of scenarios. Let Z^{ω} represent total system loss in scenario ω, where loss includes unmet demand penalties and possibly additional emergency cost. A CVaR term at confidence level α can be represented by auxiliary variables, allowing linearization in many cases.

$$\begin{aligned} \min \quad & \sum_{\omega \in \Omega} \pi_{\omega} Z^{\omega} \; + \; \rho \left(\eta \; + \; \frac{1}{1-\alpha} \sum_{\omega \in \Omega} \pi_{\omega} \xi_{\omega} \right) \\ \text{s.t.} \quad & \xi_{\omega} \; \geq \; Z^{\omega} \; - \; \eta \qquad \forall \omega \in \Omega \\ \text{and} \quad & \xi_{\omega} \; \geq \; 0 \qquad \forall \omega \in \Omega \end{aligned}$$

Here η is a threshold variable approximating the value-at-risk, ξ_{ω} are slack variables capturing exceedances, and ρ controls the emphasis on tail risk relative to expected loss. In emerging-economy contexts, this approach can represent the preference to avoid severe stockout events even if average costs increase, reflecting the high social cost of disruptions and the political sensitivity of shortages.

Resilience also depends on redundancy and flexibility. Redundancy can be physical, such as multiple suppliers and alternative transport routes, or it can be functional, such as therapeutic substitution or multi-sourcing across quality-assured manufacturers. Flexibility includes the ability to reallocate budgets quickly, adjust order quantities, and deploy emergency distribution. These capabilities are influenced by governance, procurement regulations, and information systems.

Supplier diversification is a common resilience strategy, but its effectiveness depends on correlated risks. If multiple suppliers rely on the same upstream active ingredient source, diversification may not reduce risk. In emerging economies, procurement mechanisms may favor a single lowest-cost supplier to reduce unit price, potentially increasing vulnerability. A diversification constraint can require that no single supplier provides more than a share β of total procurement for a product, or that at least two suppliers are used. Such constraints increase administrative complexity and may raise unit prices, but can reduce disruption risk [18].

Transport resilience can be addressed through alternative routes and modes, but in emerging economies options may be limited by infrastructure. Nonetheless, some flexibility can be achieved through contracting with multiple transport providers, using a mix of public fleets and third-party logistics, and establishing transshipment points that allow rerouting around blocked roads. The effectiveness of these strategies depends on the speed of information and decision-making. If a disruption is not detected quickly due to poor tracking, rerouting is delayed and buffers are depleted.

Inventory buffers are central to resilience but must be balanced against expiry risk and storage constraints. For essential medicines with long shelf life, higher safety stock can be a relatively low-cost resilience strategy. For vaccines and short shelf-life diagnostics, buffers can induce wastage unless cold chain capacity is sufficient and stock rotation is managed. In emerging economies, buffer placement matters: upstream buffers at central warehouses protect against import delays but may not prevent facility-level stockouts if distribution is unreliable; downstream buffers at facilities protect patients but require storage and management capacity. An intermediate approach is to maintain buffers at regional depots with reliable transport to facilities, provided that last-mile routes can be executed under disruptions.

The interaction between resilience and accessibility is particularly relevant during disruptions. When a region becomes temporarily inaccessible due to flooding, facilities may be cut off. If the system has pre-positioned stocks in that region, patient access can be maintained. If not, patients may travel long distances to other regions, overloading facilities and increasing disease transmission risks in crowded settings. Resilience planning therefore has spatial equity implications: buffer placement decisions can advantage regions that are already easier to serve unless explicit equity constraints are included.

Information resilience is another dimension [1]. Systems that rely on periodic paper reports can have delays of weeks or months, leading to slow detection of stockouts and overstock. Digital logistics management information systems can improve visibility, but only if data quality is maintained, connectivity exists, and staff are trained and motivated. In emerging economies, partial digitalization can create uneven visibility, where some facilities are well monitored and others remain blind spots. Moreover, digital systems can introduce new vulnerabilities, such as dependence on servers and cybersecurity risks, although these may be secondary compared to physical disruptions in many contexts.

A useful way to conceptualize resilience is through the concept of performance degradation and recovery. After a disruption, service level may drop and then recover as emergency actions are taken. The area under the performance curve below an acceptable threshold can represent resilience loss. In operational terms, this loss depends on time-to-detect, time-to-decide, and time-to-deliver, each of which can be improved by better monitoring, decision authority, and pre-arranged logistics. In emerging economies, institutional delays can dominate physical delays, such as when procurement rules prevent rapid emergency purchasing or when funds cannot be reallocated quickly.

In sum, resilience in emerging-economy healthcare supply chains involves a combination of buffers, redundancy, and adaptive capability, constrained by budget, storage, and governance realities. Risk-aware modeling helps formalize trade-offs and can guide where resilience investments yield the largest marginal reduction in severe service failures.

6. Integrated Mathematical Framework: Multi-Echelon Flows, Uncertainty, and Policy Constraints

An integrated framework that connects cost efficiency, accessibility, and resilience requires representing the physical movement of commodities, the temporal evolution of inventory, and the uncertainty in demand and supply conditions. While the full complexity of real systems may be beyond tractable optimization in many cases, a structured model can still clarify trade-offs and guide empirical estimation.

Consider a discrete-time planning horizon $t = 1, \ldots, T$. Let $\mathcal{N}$ be the set of nodes, partitioned into suppliers $\mathcal{S}$, warehouses $\mathcal{W}$, depots $\mathcal{D}$, and facilities $\mathcal{F}$. Let $\mathcal{A}$ be the set of

feasible arcs between nodes, respecting the physical network and policy constraints. For each product $k \in \mathcal{K}$, define inventory dynamics at each node. Let r^{ω}_{ikt} denote receipts of product k at node i in period t under scenario ω, and let s^{ω}_{ikt} denote issues from node i in period t. Then

$$I^{\omega}_{ikt} \;=\; I^{\omega}_{ik,t-1} \;+\; r^{\omega}_{ikt} \;-\; s^{\omega}_{ikt} \;-\; w^{\omega}_{ikt}$$

$$\forall i \in \mathcal{N},\ \forall k \in \mathcal{K},\ \forall t,\ \forall \omega \in \Omega$$

Receipts are determined by inbound shipments that were dispatched earlier and arrive after lead times. If $x^{\omega}_{jik,t-L^{\omega}_{jit}}$ denotes shipments dispatched from j to i that arrive at t given lead time L^{ω}_{jit}, then

$$r^{\omega}_{ikt} \;=\; \sum_{(j,i)\in\mathcal{A}} x^{\omega}_{jik,\,t-L^{\omega}_{jit}} \qquad \forall i,k,t,\omega$$

This representation is compact but highlights that lead time uncertainty shifts receipts across time, increasing the need for safety stock [2]. In emerging economies, lead time can be affected by port delays, customs processes, and transport disruptions, making scenario-based lead times appropriate.

Issues from facilities are tied to demand fulfillment. Let f^{ω}_{jkt} denote fulfilled demand for facility j. Then

$$f^{\omega}_{jkt} \;+\; u^{\omega}_{jkt} \;=\; D^{\omega}_{jkt} \qquad \forall j \in \mathcal{F},\ \forall k,\ \forall t,\ \forall \omega$$

$$f^{\omega}_{jkt} \;\le\; I^{\omega}_{jk,t-1} \;+\; r^{\omega}_{jkt} \qquad \forall j,k,t,\omega$$

For upstream nodes, issues correspond to shipments dispatched. If s^{ω}_{ikt} is the total outbound quantity of product k from node i in period t,

$$s^{\omega}_{ikt} \;=\; \sum_{(i,j)\in\mathcal{A}} x^{\omega}_{ijkt} \qquad \forall i \in \mathcal{N}\setminus\mathcal{F},\ \forall k,\ \forall t,\ \forall \omega$$

Capacity constraints represent storage limits and transport constraints. Let $\overline{I}_{ik}$ denote storage capacity for product k at node i, and let $\overline{X}^{\omega}_{ijt}$ denote transport capacity on arc (i,j) in period t under scenario ω. Then

$$I^{\omega}_{ikt} \;\le\; \overline{I}_{ik} \qquad \forall i,k,t,\omega$$

$$\sum_{k\in\mathcal{K}} v_k x^{\omega}_{ijkt} \;\le\; \overline{X}^{\omega}_{ijt} \qquad \forall (i,j)\in\mathcal{A},\ \forall t,\ \forall \omega$$

where v_k converts units into volume or weight, relevant when transport capacity is constrained by vehicle size or cold-chain volume. For cold-chain commodities, transport capacity may be smaller and more uncertain.

Wastage can be modeled through shelf-life dynamics. Let a denote age in periods, and let I^{ω}_{ikta} denote inventory of age a. Shelf-life constraints can require that inventory older than a maximum age A_k expires. Managing age-structured inventory is data-intensive, but it captures a key inefficiency channel in emerging economies where first-expiry-first-out practices may be weak. In many applied contexts, wastage is approximated via rates that depend on node type and handling quality, which can still be linked to investments in cold-chain monitoring and training.

Policy constraints are often central in emerging-economy supply chains. For example, regulations may restrict which products can be stored at facilities, or may require that certain commodities flow through specific channels for accountability. Donor-funded commodities may have separate reporting and distribution requirements. These constraints can be represented by restricting arcs in $\mathcal{A}$ or by imposing flow balance rules that require separation of specific product categories. While such constraints may reduce efficiency in a purely cost-minimizing sense, they may be necessary for governance and quality assurance, and their inclusion allows an assessment of the cost of policy-induced fragmentation.

Equity constraints can also be represented explicitly. Suppose the planner wishes to ensure that service level for essential products in remote facilities does not fall below a threshold. Let $\mathsf{SL}^{\omega}_{jk}$ denote service level for facility j and product k over the horizon in scenario ω, defined as fulfilled demand divided by total demand. Then

$$\mathsf{SL}^{\omega}_{jk} \;=\; \frac{\sum_t f^{\omega}_{jkt}}{\sum_t D^{\omega}_{jkt}} \qquad \forall j,k,\omega$$

$$\mathsf{SL}^{\omega}_{jk} \;\ge\; \underline{s}_{jk} \qquad \forall j \in \mathcal{F}_{\text{priority}},\ \forall k \in \mathcal{K}_{\text{essential}},\ \forall \omega$$

where $\mathcal{F}_{\text{priority}}$ could represent remote or underserved facilities, and $\underline{s}_{jk}$ is a minimum service level requirement. In practice, requiring such constraints for all scenarios may be too strict, but it illustrates how equity goals can be integrated rather than treated as external considerations.

The integrated objective can combine expected cost with risk and accessibility penalties [4]. Accessibility can be represented indirectly through service level constraints and directly through penalties for delivering below a target in high-burden zones. Alternatively, accessibility can be captured by adding a term that penalizes unmet demand weighted by travel burden or vulnerability. If γ_j represents an accessibility weight for facility j, larger for remote areas, then

$$\min \sum_{\omega} \pi_{\omega} \left[\sum_{t,k,(i,j)} c^{\mathsf{tr}}_{ijkt} x^{\omega}_{ijkt} \;+\; \sum_{t,k,i} c^{\mathsf{hold}}_{ikt} I^{\omega}_{ikt} \right]$$

$$+ \sum_{\omega} \pi_{\omega} \left[\sum_{t,k,j} \gamma_j c^{\mathsf{unmet}}_{jkt} u^{\omega}_{jkt} \right] \;+\; \rho\, \mathsf{CVaR}_{\alpha}(Z)$$

This form emphasizes that unmet demand in remote facilities can be weighted more heavily, reflecting higher patient costs and fewer alternatives. Such weighting should be interpreted carefully, as it embodies a social preference function rather than a purely technical parameter.

The mathematical framework is not intended to suggest that emerging-economy supply chains can be optimized purely through computation. Rather, it offers a structured representation that can be calibrated with available data, used to test sensitivity to uncertainty, and employed to compare the implications of alternative policies such as centralization, diversification, and buffer placement. The next section uses this framework to connect supply chain performance to service delivery outcomes, recognizing that outcomes depend on additional system inputs beyond commodity availability.

7. Service Delivery Outcomes: Linking Logistics Performance to Health System Function

Service delivery outcomes in healthcare are shaped by the joint availability of commodities, workforce, diagnostic capability, and patient engagement. Supply chains contribute by ensuring that essential medicines, vaccines, diagnostics, and consumables are available when needed and are of adequate quality. The pathway from supply chain performance to outcomes can be conceptualized as a production process where inputs generate services, and services generate health improvements. In emerging economies, this pathway often contains bottlenecks and nonlinearities, making it necessary to interpret improvements in logistics performance in the context of the broader delivery system.

At the facility level, clinical service provision for many conditions requires a bundle of inputs. For example, effective management of diabetes requires availability of medicines, glucometers and test strips, trained staff, and follow-up mechanisms. If one input is missing, service quality can degrade. Similarly, maternal health services require not only oxytocin, magnesium sulfate, and antibiotics, but also equipment and skilled staff [5]. Vaccine delivery requires cold-chain integrity, syringes, safety boxes, and outreach capacity. Therefore, measuring the contribution of supply chain performance to service delivery should consider complementarity among inputs. When complementarity is strong, marginal improvements in commodity availability may have limited effect if workforce or equipment constraints bind, while improvements can have larger effects when multiple constraints are addressed jointly.

One way to represent this interaction is through a service capacity function. Let S_{jt} represent the quantity of a service delivered at facility j in period t, such as the number of treatments initiated or vaccinations administered. Let H_{jt} represent an index of human resource availability and capability, and let E_{jt} represent equipment functionality. Let Q_{jkt} represent the effective availability of commodity k at facility j, capturing not only inventory presence but also quality and usability. A stylized production relationship can be expressed as

$$S_{jt} \;=\; \varphi_j \, \Psi\Big(H_{jt}, E_{jt}, \{Q_{jkt}\}_{k \in \mathcal{K}_j}\Big)$$

where φ_j captures facility-specific factors and Ψ is an aggregator that can exhibit complementarity. In emerging economies, a Leontief-like bottleneck structure may be a reasonable approximation for certain services, where service volume is limited by the scarcest essential input. For instance, if a service requires one unit of each commodity in a set, then

$$S_{jt} \;\le\; \min_{k \in \mathcal{K}_j} \left(\frac{Q_{jkt}}{b_k} \right) \qquad \text{and} \qquad S_{jt} \;\le\; \kappa_j H_{jt}$$

$$\text{and} \quad S_{jt} \;\le\; \chi_j E_{jt}$$

where b_k is the commodity requirement per service unit, and κ_j and χ_j convert workforce and equipment indices into service capacity. This representation is simplified, but it captures the idea that improving Q_{jkt} for one commodity yields limited service gains if another essential commodity remains scarce.

The effective availability Q_{jkt} can be linked to supply chain variables. If I_{jkt} is inventory and π_{jkt} is the fraction of inventory that remains usable given expiry and cold-chain compliance, then

$$Q_{jkt} \;=\; \pi_{jkt} \, I_{jkt} \qquad 0 \le \pi_{jkt} \le 1$$

The parameter π_{jkt} can be influenced by cold-chain monitoring, storage conditions, and handling practices, which themselves are functions of infrastructure and training. In emerging economies, π_{jkt} may vary widely across facilities due to electricity reliability and equipment maintenance.

Service delivery outcomes of interest can include timeliness, continuity, and quality. Timeliness is affected by whether products are available at the time of encounter and whether diagnostics can be performed promptly. Continuity is critical for chronic diseases and for multi-dose regimens, where interruptions can reduce effectiveness and contribute to complications. Quality is affected by product potency and adherence to protocol. Supply chain performance influences all three: stockouts delay initiation and interrupt continuity; long lead times increase the probability of stockouts; and poor storage reduces potency.

An important aspect in emerging economies is the role of rationing and informal coping strategies. When stocks are low, facilities may reduce dispensing quantities, requiring patients to return more frequently. This can maintain nominal coverage of more patients but reduces adherence and increases travel burden. Alternatively, clinicians may prescribe alternative medicines that are available but may be less effective or have different side effect profiles [19]. Such substitution can reduce immediate stockout consequences but can affect long-term outcomes and costs. From a supply chain perspective, substitution changes product mix demand and can create oscillations in ordering patterns if not anticipated.

The relationship between supply chain performance and outcomes is also mediated by patient behavior. When patients encounter stockouts, they may seek private alternatives, delay care, or abandon treatment. The probability of abandonment can increase with travel time and with previous failed attempts. In emerging economies where transport costs are high relative to income, the behavioral response can be substantial. This implies that service delivery outcomes may be more sensitive to reliability than to average availability. A

system that maintains 95% availability most of the time but experiences occasional long stockout episodes may produce worse adherence outcomes than a system with slightly lower average availability but fewer severe episodes, especially for chronic regimens.

Equity considerations are central. Improvements in national averages can mask persistent disparities between urban and rural areas, and between facilities with different management capacity. If supply chain reforms improve efficiency by consolidating distribution and reducing costs, but inadvertently increase lead times to remote areas, the resulting equity impact may be negative even if average availability improves. Conversely, targeted investments in last-mile distribution and buffer stock for remote facilities may increase costs but improve equity and reduce severe adverse events related to lack of access.

To connect the integrated logistics model to population-level outcomes, one can define effective coverage as the fraction of the target population that receives an effective intervention when needed. Let N_{zt} denote the population in zone z in period t requiring an intervention, and let S_{zt} denote the number who receive the intervention effectively. Then effective coverage is $C_{zt} = S_{zt}/N_{zt}$. If S_{zt} depends on effective access A_{zkt} for required commodities and on service capacity at chosen facilities, then logistics performance enters through A_{zkt} and through Q_{jkt}. This approach highlights that supply chain metrics such as fill rate and stockout duration can be mapped into coverage metrics, but only with assumptions about patient choice and service capacity.

A related outcome is the cost per effective service delivered, which combines supply chain costs with service delivery costs and adjusts for wastage and quality [13]. In emerging economies, focusing on cost per unit procured can be misleading if a substantial share is wasted or unusable. A more informative measure is cost per effective unit dispensed, and ultimately cost per successful treatment or prevented case. While measuring the latter requires clinical data, cost per effective unit dispensed can often be approximated by combining logistics costs with dispensing records and quality indicators. This measure can reveal that investments in cold-chain reliability and inventory management may reduce total cost per effective unit even if they increase operating costs, by reducing wastage and preventing emergency procurement.

The service delivery linkage also underscores that resilience investments can have outcome benefits disproportionate to their average cost. Preventing a severe stockout episode during an epidemic surge or during a seasonal malaria peak can avert a large number of adverse outcomes. Risk-aware models that penalize tail failures can therefore align with outcome objectives, particularly when health system credibility and patient trust are considered. In emerging economies, trust can influence care-seeking behavior broadly, meaning that repeated stockouts of essential products can reduce utilization of services even when other services are available.

Nonetheless, attributing outcome changes to supply chain reforms remains challenging due to confounding factors. Health workforce changes, policy reforms, and epidemiological shifts can coincide with supply chain changes. A careful analysis should therefore use designs that can isolate supply chain effects where possible, such as phased rollouts, difference-in-differences comparisons, or facility-level panel analysis with controls for staffing and demand proxies. When such designs are not feasible, model-based counterfactual analysis can still provide insight, but results should be interpreted cautiously as conditional on assumptions and parameter uncertainty.

Overall, linking supply chain performance to service delivery outcomes reinforces the need for integrated evaluation. Efficiency improvements that reduce costs but increase variability may not improve outcomes. Accessibility improvements that reduce travel time but do not address stock reliability may not increase effective coverage. Resilience improvements that reduce severe outages can improve continuity and trust, affecting utilization beyond the directly targeted commodities [6]. These interactions suggest that reforms in emerging economies should be assessed using a balanced set of metrics that capture cost, reliability, equity, and outcome relevance.

8. Conclusion

Healthcare supply chains in emerging economies operate at the intersection of constrained financing, infrastructure limitations, uncertain demand, and diverse governance arrangements. Efficiency and resilience are intertwined objectives but are not identical. Efficiency concerns the total economic resources required to deliver an acceptable level of service, while resilience concerns the ability to sustain service levels under uncertainty and disruption. Accessibility mediates how logistical performance translates into patient experience, shaping travel burden, continuity, and the practical ability to obtain treatment.

The analysis in this paper emphasized that cost structures extend beyond procurement prices to include transport, holding, cold-chain compliance, wastage, administrative overhead, and the economic effects of financing frictions. These costs are shaped by institutional fragmentation, macroeconomic exposure, and the degree to which quality assurance is implemented. Accessibility was treated as a combined function of network design, lead times, facility-level availability, and patient behavior, highlighting that nominal stock presence does not necessarily imply effective access. Resilience was developed as a risk-aware concept that accounts for correlated disruptions and for the propagation of failures across echelons, motivating the use of scenario-based reasoning and tail-risk measures in formal models.

A mathematical framework was presented to represent multi-echelon flows, inventory dynamics, capacity constraints, and policy requirements, while allowing for explicit uncertainty in demand, lead times, and transport capacity. The framework illustrated how equity goals and minimum service-level requirements can be represented alongside cost minimization, and how risk measures can penalize severe service failures that are particularly consequential in emerging-economy contexts. The linkage to service delivery outcomes underscored that commodities are complementary with workforce and equipment, and that improvements in supply reliability can influence timeliness, continuity, and trust, thereby affecting utilization and effective coverage.

The practical implication is that evaluation and design choices benefit from jointly considering cost, accessibility, and resilience rather than optimizing one dimension in isolation. However, implementing such integrated analysis is constrained by data fragmentation, measurement error, and institutional feasibility. Consequently, any applied use of

the framework requires careful specification of cost boundaries, explicit acknowledgment of uncertainty, and sensitivity analysis to key parameters such as lead time variability, wastage rates, and behavioral responses to stockouts. Within these limits, structured reasoning about trade-offs can support more transparent decision-making regarding buffer placement, diversification, contracting, and investments in information and cold-chain infrastructure, while keeping attention on service delivery outcomes and equity across populations [17].

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