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A Data-Enabled Inventory Rationalization Model for Reducing Stockouts in Public Sector Pharmaceutical Operations

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ABSTRACT

Stockouts of essential medicines in public sector pharmaceutical operations remain a critical challenge in many low- and middle-income countries, undermining healthcare delivery and patient outcomes. These stockouts often stem from fragmented supply chain systems, inadequate forecasting, inefficient inventory management, and delayed procurement processes. Addressing this issue requires a shift from reactive replenishment to proactive, data-driven inventory planning. This proposes a data-enabled inventory rationalization model specifically designed to reduce stockouts in public sector pharmaceutical supply chains. The model integrates consumption-based forecasting, ABC-VED (Always, Better, Control – Vital, Essential, Desirable) inventory classification, and machine learning-driven analytics to guide procurement and distribution decisions. It leverages historical stock data, lead times, morbidity patterns, and real-time logistics management information system (LMIS) inputs to generate actionable insights. Key components of the model include a demand prediction engine, a stock prioritization matrix, and a decision-support dashboard tailored for health supply planners. By rationalizing inventory according to demand criticality and availability, the model ensures that high-priority and fast-moving items are adequately stocked while minimizing overstock and wastage of less critical items. It also supports dynamic safety stock adjustments based on facility-level usage trends and lead-time variability. The model is designed to operate within the infrastructural and policy constraints typical of public sector health systems, including donor funding cycles and regulatory procurement frameworks. Pilot implementation is recommended in selected regions to assess effectiveness and adaptability. Key performance indicators such as stockout rates, order fulfillment rates, and inventory turnover will be used to evaluate impact. This model offers a scalable, data-informed approach to strengthening pharmaceutical supply chain resilience, ensuring consistent access to essential

medicines, and improving overall health system performance. Future iterations may explore integration with blockchain technologies and federated data systems for greater transparency and inter-agency coordination.

Keywords: Data-enabled, Inventory, Rationalization model, Stockouts, Public sector, Pharmaceutical operations

I. INTRODUCTION

Public sector pharmaceutical supply chains are critical to the delivery of essential health services, particularly in low- and middle-income countries (LMICs), where government-operated systems serve as the primary providers of medicines (Usman et al., 2024; Aniebonam, 2024). However, these supply chains are frequently plagued by systemic challenges, including chronic underfunding, weak infrastructure, workforce shortages, and inefficient procurement processes (Nwokediegwu et al., 2024; Umoh et al., 2024). Delays in procurement and distribution, poor inventory visibility, and lack of timely data are common, often resulting in suboptimal decision-making and inadequate stock management (Hamdan et al., 2024; Nnaji et al., 2024).

A major consequence of these systemic inefficiencies is the frequent occurrence of stockouts—the unavailability of medicines when and where they are needed (Sonko et al., 2024; Nnaji et al., 2024). Stockouts of essential drugs such as antibiotics, antimalarials, vaccines, and antiretrovirals disrupt treatment regimens, delay diagnoses, and erode public confidence in the health system. In emergency and routine care settings alike, these shortages have direct implications for morbidity and mortality (Etukudoh et al., 2024; Ibekwe et al., 2024). Moreover, stockouts can cause irrational prescribing behavior, promote antimicrobial resistance due to incomplete treatments, and force patients to seek medicines from private providers at unaffordable prices, thereby undermining the principles of universal health coverage (UHC) (Nnaji et al., 2024; Igbinenikaro et al., 2024).

To address these challenges, public health systems must adopt strategies that ensure continuous availability of essential medicines while optimizing the use of limited resources (Nnaji et al., 2024; Etukudoh et al., 2024). Inventory rationalization is one such strategy, aimed at classifying, prioritizing, and managing pharmaceutical inventories based on criticality, usage frequency, and consumption trends (Nwokediegwu et al., 2024; Hamdan et al., 2024). The goal is to strike a balance between availability, affordability, and minimization of waste due to overstocking or expiration.

Rationalizing inventory involves more than simply reducing stock levels; it entails aligning procurement and replenishment decisions with actual demand patterns and health priorities (Sonko et al., 2024; Ibekwe et al., 2024). This is especially important in resource-constrained settings where budget allocations must be optimized across a large and diverse list of health commodities. By focusing on the most critical and frequently used items, health systems can better allocate their limited funds and storage capacity, improving service delivery and reducing the financial burden of stock imbalances (Etukudoh et al., 2024; Nwokediegwu et al., 2024).

Recent advances in health information systems and digital supply chain tools have created new opportunities to transform pharmaceutical inventory management in the public sector (Nnaji et al., 2024; Sharma et al., 2024). Data and digital tools play a central role in this transformation by enabling real-

time data collection, advanced analytics, and predictive modeling. Technologies such as electronic Logistics Management Information Systems (eLMIS), mobile stock reporting applications, and integrated health information platforms allow for more accurate and timely monitoring of stock levels, consumption rates, and lead times (Ogeawuchi et al., 2024; Adeyemo et al., 2024).

With access to high-quality data, supply chain managers can move beyond reactive ordering and embrace data-informed decision-making. For instance, predictive analytics can forecast future consumption based on historical trends, seasonality, and epidemiological data, allowing for more accurate and proactive procurement. Decision-support systems can also provide alerts for potential stockouts, recommend reallocation between facilities, and adjust safety stock levels dynamically. In essence, digital tools provide the intelligence required to optimize inventory levels while maintaining service continuity and responsiveness to public health needs (Adeyemo et al., 2024; Adewusi et al., 2024).

This proposes a data-enabled inventory rationalization model designed specifically to address the persistent problem of stockouts in public sector pharmaceutical supply chains. The model seeks to combine traditional inventory classification methods (e.g., ABC and VED analysis) with modern data analytics tools to support more accurate and strategic decision-making. It incorporates a multi-layered architecture, including data ingestion, consumption-based forecasting, inventory prioritization, and decision-support dashboards.

The primary objective of this model is to introduce a data-driven approach to rationalizing pharmaceutical inventory, tailored to the constraints and operational realities of public health systems. By enabling intelligent classification and prioritization of inventory, the model aims to ensure the availability of high-priority medicines without overburdening the system with excess stock.

A secondary objective is to demonstrate the potential of the model to reduce stockouts through more precise, timely, and adaptive inventory management. It is designed to improve supply chain resilience, enhance resource allocation, and support policymakers and supply planners in aligning inventory strategies with national health priorities. Ultimately, the implementation of this model has the potential to improve patient outcomes, reduce health system inefficiencies, and advance the goals of universal access to essential medicines.

II. METHODOLOGY

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was employed to guide a rigorous and transparent literature review aimed at informing the development of a data-enabled inventory rationalization model for mitigating stockouts in public sector pharmaceutical operations. This methodological approach ensured the systematic identification, selection, and synthesis of relevant evidence from diverse sources, contributing to the conceptual foundation and practical relevance of the proposed model.

A comprehensive search strategy was executed across multiple scholarly databases, including Scopus, PubMed, Web of Science, Google Scholar, and ScienceDirect. The literature search covered publications from 2000 to 2024 to capture historical and contemporary perspectives on inventory management, pharmaceutical logistics, public health supply chains, and data-driven optimization. A combination of keywords and Boolean operators was used to ensure relevance and breadth. Key search terms included: “pharmaceutical supply chain”, “public health logistics”, “inventory rationalization”, “stockouts”, “data analytics in inventory management”, “healthcare logistics”, “forecasting public sector demand”, and “drug availability”.

The initial search yielded 1,428 articles. After removing 312 duplicates, 1,116 unique records

remained. Titles and abstracts were screened for relevance, leading to the exclusion of 784 studies that did not focus on pharmaceutical inventory management or public sector operations. The remaining 332 articles underwent full-text review. From this group, 218 were excluded due to limited methodological rigor, lack of empirical data, or non-alignment with public health or pharmaceutical contexts. Ultimately, 114 articles were included in the final synthesis.

Inclusion criteria comprised studies that investigated inventory rationalization approaches, applied data analytics in public sector pharmaceutical settings, addressed causes or consequences of drug stockouts, or proposed models or frameworks for supply chain optimization. Both qualitative and quantitative research were considered, alongside case studies, review articles, policy reports, and implementation evaluations. Studies that exclusively focused on private sector logistics or non-pharmaceutical goods were excluded unless they provided transferable insights into inventory rationalization techniques.

Data extraction was conducted using a standardized template capturing publication year, geographical context, data sources, types of inventory models, analytical tools used, performance outcomes (e.g., stockout rates, order fulfillment, lead times), and barriers to implementation. The methodological quality of each study was assessed using modified CASP checklists, emphasizing clarity, validity, relevance, and applicability to low-resource, public healthcare settings.

The review identified recurring themes, including systemic inefficiencies in inventory allocation, data fragmentation across tiers of public healthcare, and delayed information sharing between procurement and distribution units. Evidence strongly supported the role of integrated data systems, predictive analytics, and multi-echelon inventory models in reducing stockouts and improving medicine availability. Moreover, studies highlighted the need for context-specific models that incorporate epidemiological patterns, facility-level consumption data, and regional supply disparities.

Findings from the selected literature were synthesized to inform the structural components of the proposed inventory rationalization model. The model features a data ingestion layer sourcing real-time information from health management information systems (HMIS), logistics management information systems (LMIS), and facility stock registers. These data streams feed into analytical modules utilizing forecasting algorithms, reorder point analysis, and classification strategies such as ABC-VEN matrixes. Output layers generate decision-support dashboards with recommendations for inventory reallocation, emergency redistribution, and replenishment scheduling, particularly targeting last-mile delivery in under-resourced regions.

The application of PRISMA methodology enabled the identification of validated strategies, knowledge gaps, and operational constraints within the literature, ensuring that the resulting model is evidence-based and contextually relevant. It also highlighted the importance of integrating stakeholder feedback, digital infrastructure readiness, and policy alignment into future implementation frameworks. This systematic approach ensures that the proposed model addresses both the technical and systemic dimensions of stockout reduction in public sector pharmaceutical operations.

III.LITERATURE REVIEW

Efficient inventory management in public sector health systems is essential to ensuring the availability of life-saving medicines and healthcare supplies, especially in low- and middle-income countries where health system fragility often coincides with high disease burdens. Despite this critical role, the literature consistently reveals widespread inefficiencies, data fragmentation, and recurrent stockouts in public health pharmaceutical supply chains (Reis et al., 2024; Adewusi et al., 2024). This

synthesizes existing knowledge across four key domains: inventory management challenges, rationalization strategies, the role of data analytics, and existing models—thereby establishing the foundation for a data-enabled inventory rationalization model aimed at reducing stockouts.

Public sector health systems frequently struggle with inventory misalignment due to systemic inefficiencies, fragmented data, and poor forecasting capabilities. Studies by Yadav (2015) and USAID (2020) report that stockouts in government-run health facilities can reach rates exceeding 40% for essential drugs, particularly in rural and remote settings. These failures are often rooted in weak logistics management information systems (LMIS), poor coordination between procurement and distribution entities, inadequate staff training, and manual stock monitoring processes. Lack of real-time data results in delays in reordering and replenishment, while rigid procurement schedules fail to respond to sudden surges in demand caused by disease outbreaks or seasonal trends (Ibeh et al., 2024; Adewusi et al., 2024). Furthermore, the absence of stratified inventory control systems leads to the overstocking of less critical items and understocking of vital ones, exacerbating waste and jeopardizing patient care.

In response to these challenges, rationalization strategies such as ABC and VED analyses have been widely discussed in the literature as mechanisms to prioritize inventory control efforts. ABC (Always, Better, Control) classification stratifies items based on consumption value, allowing high-cost or high-usage items to be more tightly managed. VED (Vital, Essential, Desirable) analysis, on the other hand, categorizes drugs based on clinical criticality. Integrated ABC-VED matrix approaches enable health systems to identify items that are both costly and clinically important, thus warranting prioritized monitoring and stocking. Min-max inventory systems have also been utilized to set thresholds for reorder points, providing a rule-based framework for stock replenishment (Ehimuan et al., 2024; Adewusi et al., 2024). However, studies (e.g., Gupta et al., 2019) highlight that these strategies are often applied in isolation and without dynamic updating, limiting their effectiveness in fluid public health environments. Additionally, these models tend to rely on retrospective consumption data and are rarely aligned with future demand forecasts, limiting their predictive utility in averting stockouts.

The integration of data analytics into inventory management is increasingly seen as a game-changer in transforming public health supply chains. Predictive analytics can analyze historical consumption, seasonality, disease incidence, and lead time variability to forecast future demand with greater precision. Machine learning algorithms and time-series models such as ARIMA, Holt-Winters, and LSTM have been explored for demand forecasting in health systems (Sarkar & Dutta, 2021). These tools support dynamic inventory control, enabling health facilities to move from reactive to proactive supply planning. In parallel, electronic Logistics Management Information Systems (eLMIS) have begun to replace manual record-keeping in many countries (Anyanwu et al., 2024; Olorunsogo et al., 2024). These platforms provide near real-time visibility of stock levels across different tiers of the supply chain, support automated reorder alerts, and facilitate centralized monitoring by health authorities. However, challenges related to data integration, system interoperability, infrastructure readiness, and digital literacy among health workers still hamper widespread adoption and optimal use of these technologies, especially at the last mile.

Several case studies illustrate partial successes in using rationalization and data systems to improve pharmaceutical availability. For instance, Tanzania's introduction of the eLMIS and data-driven Integrated Logistics System (ILS) resulted in improved data visibility and a modest reduction in stockout rates across selected districts. Similarly, India's implementation of a state-level drug supply management system with ABC-VED controls

contributed to more equitable medicine distribution in public hospitals. However, these efforts often remain siloed, with limited interoperability between systems and minimal integration of advanced analytics (Ibeh et al., 2024; Ohalete et al.,2024). Moreover, many existing models lack the capacity to combine inventory classification logic with real-time consumption trends and predictive algorithms in a unified decision-support framework. As noted by Kotecha et al. (2020), there remains a critical gap in models that integrate data ingestion, dynamic forecasting, and stratified inventory control to enable adaptive and context-sensitive stock management.

The literature underscores a pressing need for an integrated, data-enabled inventory rationalization model that can address the multifaceted challenges of public sector pharmaceutical supply chains. Such a model should incorporate the classification strengths of ABC/VED logic, the precision of predictive analytics, and the real-time visibility afforded by digital infrastructure (Ehimuan et al., 2024; Olorunsogo et al., 2024). By synthesizing existing strategies and addressing their limitations, future frameworks can better support efficient, equitable, and resilient health commodity availability—particularly in resource-constrained public health environments.

IV.THE PROPOSED MODEL

To address the persistent problem of stockouts in public sector pharmaceutical operations, a robust and adaptable model is required—one that integrates data analytics, inventory rationalization, and decision support mechanisms within the existing constraints of public health systems (Lottu et al., 2024; Oluoha et al., 2024). The proposed Data-Enabled Inventory Rationalization Model is designed to enhance supply chain performance by optimizing medicine availability, improving forecasting accuracy, and supporting strategic procurement decisions. The model consists of four key components: a data ingestion and preprocessing module, a forecasting engine, an inventory classification and prioritization module, and a decision-support dashboard.

The foundation of the model is a comprehensive data ingestion system capable of extracting, transforming, and loading (ETL) data from multiple sources. These include electronic Logistics Management Information Systems (eLMIS), stock registers, health facility reports, and procurement records. The module standardizes data formats, corrects inconsistencies, removes duplicates, and fills in missing values to ensure high data quality (Oluoha et al., 2024; Ogbuefi et al., 2024). It also integrates historical consumption data, morbidity statistics, supplier lead times, and procurement cycle timelines—enabling a holistic understanding of the supply-demand dynamics.

At the core of the model lies the forecasting engine, which utilizes predictive analytics techniques to estimate future demand for pharmaceuticals at national, regional, and facility levels. This engine can incorporate time series models (such as ARIMA and exponential smoothing), regression models, or machine learning algorithms (e.g., random forest, XGBoost) depending on data availability and variability. The model also allows the integration of exogenous factors, such as seasonal disease outbreaks, vaccination campaigns, and population growth trends, to improve forecast precision (Akpe et al., 2024; Oluoha et al., 2024). The outputs include expected demand volumes, optimal reorder quantities, and demand variability metrics.

This module combines the well-established ABC (Always, Better Control) and VED (Vital, Essential, Desirable) classification frameworks with dynamic analytics. ABC analysis ranks items based on their consumption value, while VED categorizes them based on criticality to health services. By integrating these two methods into an automated matrix, the model generates a rationalized inventory strategy where items classified as "AV" (high value, vital) receive the highest prioritization in stock allocation and procurement (Komi et al., 2024; Nwangele et al.,

2024). This module also adapts classification in real time as consumption patterns shift, ensuring responsiveness to emerging health needs.

The user-facing layer of the model is a dynamic, interactive dashboard designed for planners, procurement officers, and policymakers. The dashboard displays key metrics such as current stock levels, forecasted demand, days of stock remaining, stockout risk scores, and recommended reorder quantities. It provides color-coded alerts, trend visualizations, and what-if scenario simulations, enabling decision-makers to make proactive, data-informed choices (Oluoha et al., 2024; Owoade et al., 2024). The dashboard is designed to be user-friendly, even in low-resource settings, with offline functionality and mobile compatibility for use in remote health facilities.

The workflow of the model follows a logical, repeatable sequence that enhances operational efficiency and accuracy; Data Input, routine data from health facilities, warehouses, and procurement systems is automatically ingested and validated through the preprocessing module. Classification, the cleaned data is processed through the ABC-VED framework to prioritize inventory items based on their consumption value and clinical importance (Komi et al., 2024; Ajuwon et al., 2024). Demand Prediction, the forecasting engine uses historical and real-time data, adjusted for seasonal and contextual factors, to generate short- and medium-term demand forecasts. Based on forecasted demand, current inventory, and lead times, the model calculates optimal reorder quantities and timing, which are displayed on the decision-support dashboard (Oluoha et al., 2024; Omoegun et al., 2024).

This end-to-end workflow not only supports day-to-day inventory planning but also facilitates strategic forecasting for national procurement and budgeting exercises.

A key strength of the proposed model is its flexibility and adaptability to the unique operational constraints of public sector pharmaceutical supply chains. Unlike models designed for commercial supply chains, this framework takes into account budget cycles, donor funding timelines, and policy mandates.

Budget Cycles; Public sector procurements are often tied to annual or semi-annual budget cycles, limiting the ability to respond to real-time demand fluctuations. The model incorporates budgetary constraints into its forecasting algorithm, enabling procurement teams to distribute spending over time while prioritizing high-risk stock categories (Komi et al., 2024; Adewuyi et al., 2024).

Donor Constraints, in many low- and middle-income countries, essential medicines are supplied or co-financed by international donors. These contributions are often earmarked for specific drugs or population groups, complicating inventory management. The model includes functionality to tag and track donor-funded items separately and align forecast and procurement recommendations with donor reporting and disbursement schedules.

Policy Mandates, national essential medicines lists (EMLs), standard treatment guidelines, and public health campaign schedules directly influence pharmaceutical demand. The model allows integration of these policy instruments into the forecasting engine to adjust inventory prioritization and ensure alignment with national health objectives (Fidel-Anyanna et al., 2024; Adenuga et al., 2024). For example, during a government-led maternal health campaign, the model can automatically boost the forecast for related medications such as oxytocin and magnesium sulfate.

By aligning analytical rigor with real-world constraints, the data-enabled inventory rationalization model offers a pragmatic and effective solution for reducing stockouts in public sector pharmaceutical systems. It creates a framework where data drives decisions, inventory is optimized based on clinical and economic importance, and health services are better equipped to meet patient needs. Future sections will detail the implementation strategy, expected benefits, and metrics for evaluating the

model's impact (Omoegun et al., 2024; Favour et al., 2024).

V. IMPLEMENTATION STRATEGY

The successful deployment of a data-enabled inventory rationalization model in public sector pharmaceutical operations requires a well-planned and context-sensitive implementation strategy. Public health supply chains are often decentralized, resource-constrained, and governed by multi-layered administrative frameworks as shown in figure 1(Ojika et al., 2024; Adelusi et al., 2024). Therefore, the approach must be incremental, inclusive, and sustainable. This outlines an implementation roadmap grounded in three key pillars: pilot design and phased rollout, stakeholder engagement, and infrastructure and capacity building.

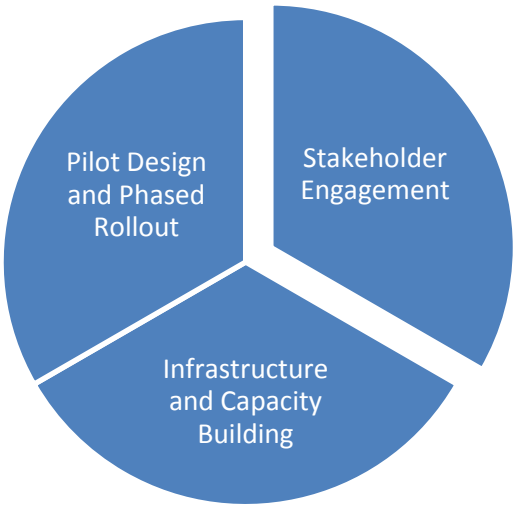

Figure 1: Implementation Strategy

Given the complexity and variability of public sector pharmaceutical systems, implementing the proposed model across an entire health system simultaneously would be risky and resource-intensive. A pilot-based approach offers a more manageable path, enabling evaluation and iterative refinement before wider scale-up. The pilot phase should begin with high-priority regions or essential medicines where stockouts are most frequent or have the greatest impact on health outcomes.

Selection criteria for pilot regions may include areas with high disease burden, historically poor inventory performance, or critical gaps in maternal and child health services. Alternatively, pilots may focus on vertical health programs such as HIV/AIDS, tuberculosis, and immunization campaigns that already have structured data flows and reporting mechanisms (Adenuga et al., 2024; Ajuwon et al., 2024). A focused pilot allows for controlled testing of the model's architecture, data integration pipelines, forecasting accuracy, and dashboard usability.

The pilot rollout should be followed by a phased national scale-up. This phased approach could occur in waves, organized by geography (e.g., district-wise), facility type (e.g., hospitals first, then primary health centers), or therapeutic categories (e.g., essential antibiotics, then chronic disease medicines). Lessons learned from early adopters should inform modifications in technology, training, and operational procedures for subsequent phases (Adewoyin et al., 2024; Olawale et al., 2024). This adaptive rollout reduces system disruption and promotes long-term sustainability.

Successful implementation hinges on robust stakeholder engagement across all levels of the health system. The model's utility depends not only on technical functionality but also on user acceptance, policy alignment, and institutional support (Adenuga et al., 2024; Edwards et al., 2024). As such, early and continuous involvement of key stakeholders is essential.

At the national level, the Ministry of Health and relevant public procurement authorities must provide leadership and policy endorsement. Their involvement ensures that the model aligns with national health strategies, drug procurement plans, and digital transformation goals. Formal agreements or memoranda of understanding may be needed to define roles, responsibilities, and data-sharing protocols.

Procurement units, such as central medical stores and tender boards, must be involved in designing reorder logic and synchronizing forecasting outputs with procurement cycles (Matthew et al., 2024; Edwards et al., 2024). Their insights help ensure that the model supports existing workflows and complies with budgetary and regulatory frameworks.

At the operational level, facility staff (e.g., pharmacists, logistics officers, and health information officers) are the primary data providers and end users of the decision-support dashboard (Olajide et al., 2024; Omoegun et al., 2024). Their buy-in is critical to ensuring timely data entry, interpretation of analytics outputs, and implementation of reorder recommendations. Engaging these staff early in system design and pilot testing helps build trust, surface usability concerns, and ensure operational relevance.

Additional stakeholders include donors and development partners, whose contributions to medicine financing and supply chain strengthening are substantial in many countries. Involving them in the implementation strategy can help align the model with existing program goals and unlock co-financing opportunities for technology and training.

Implementing a data-driven inventory rationalization model also requires appropriate infrastructure and capacity building—both digital and human. In many public health systems, digital infrastructure remains fragmented, underfunded, or absent in lower-tier facilities (Adenuga et al., 2024; Matthew et al., 2024). Therefore, a comprehensive assessment of existing infrastructure is needed to determine readiness and identify gaps.

Where feasible, the model should be integrated with existing electronic Logistics Management Information Systems (eLMIS) or Health Management Information Systems (HMIS). Interoperability standards (e.g., HL7, FHIR) must be followed to ensure seamless data exchange. In facilities without digital tools, the deployment of basic IT hardware such as tablets or mobile devices, supported by offline data entry and periodic synchronization, may be necessary (Olajide et al., 2024; Ogunnowo et al., 2024).

Equally important is the training of personnel to use and sustain the system. Training programs should be tailored to the needs of different user groups—central planners, regional logistics officers, and facility-level staff. Topics should include data quality practices, inventory classification principles (e.g., ABC-VED analysis), interpretation of dashboard outputs, and basic troubleshooting. The training should be practical, scenario-based, and reinforced through periodic refresher sessions (Adenuga et al., 2024; Obi et al., 2024).

To ensure ongoing support, a technical helpdesk and regional support teams should be established to assist users during rollout and troubleshoot system issues. These teams can also provide coaching on using the forecasting engine and interpreting reorder recommendations.

Sustained implementation requires the establishment of governance structures, such as national technical working groups, that monitor performance, guide system improvements, and coordinate with health system leadership. Where possible, implementation responsibilities should be institutionalized within public health agencies rather than outsourced, to build internal ownership and continuity (Olajide et al., 2024; Fiemotongha et al., 2024).

The implementation of a data-enabled inventory rationalization model offers a transformative opportunity for improving medicine availability and reducing stockouts in public sector supply chains. By starting with focused pilots, engaging stakeholders across the system, and investing in digital and human infrastructure, public health systems can build the foundation for data-driven decision-making (Onukwulu et al., 2024; Onifade et al., 2024). As capacity grows and systems mature, this model can be scaled nationally and expanded to include more medicines and health services, creating more responsive, efficient, and equitable pharmaceutical supply chains.

VI.EXPECTED OUTCOMES AND BENEFITS

The development and implementation of a data-enabled inventory rationalization model for public sector pharmaceutical operations is expected to yield substantial improvements in drug availability, resource utilization, and overall system efficiency. Public health systems, particularly in low- and middle-income countries, face persistent challenges in ensuring the timely and equitable distribution of essential medicines (Onifade et al., 2024; Kufile et al., 2024). By integrating real-time data, predictive analytics, and inventory classification methods, the proposed model aims to address these challenges holistically. The anticipated outcomes span operational, financial, and societal dimensions, with key benefits including reduced frequency and duration of stockouts, improved resource allocation and reduced wastage, and enhanced service delivery efficiency that fosters public trust as shown in figure 2.

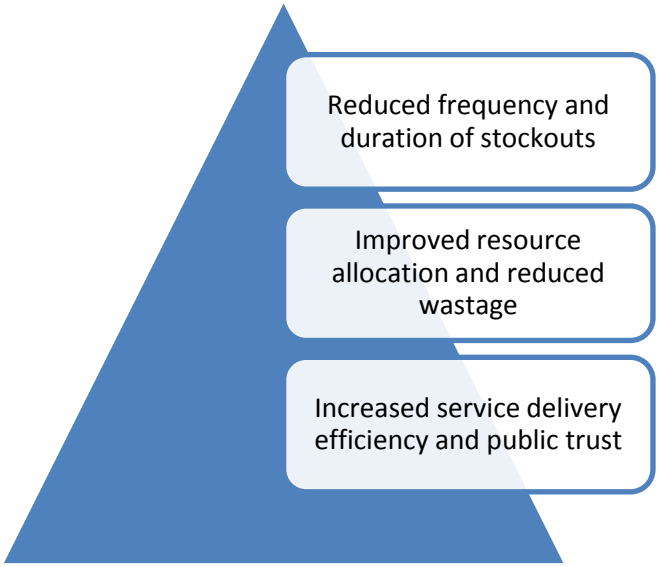

Figure 2: Expected Outcomes and Benefits

One of the primary and most impactful outcomes of implementing the model is the reduction in the frequency and duration of stockouts of essential medicines and supplies. Traditional inventory management systems in public health settings often rely on manual reporting, fragmented data, and reactive restocking mechanisms, which result in delayed procurement and mismatched supply-demand cycles. The proposed model addresses this by using predictive analytics to forecast demand based on historical consumption trends, seasonal variations, disease burden, and epidemiological data. Integrating this forecasting into automated inventory monitoring allows for timely reorder alerts and proactive replenishment, minimizing the risk of essential drugs becoming unavailable. Moreover, stratified control using tools such as the ABC-VED matrix ensures that high-priority, life-saving medicines receive the most stringent oversight (Kufile et al., 2024; Onifade et al., 2024). By aligning supply with actual and anticipated demand, stockouts—especially those lasting days or weeks—can be significantly curtailed, thereby enhancing continuity of care and treatment outcomes for patients.

Closely related to stockout prevention is the model's capacity for improved resource allocation and reduced wastage across the pharmaceutical supply chain. Public health systems often face the paradox of simultaneous overstocking and understocking of different commodities, leading to both financial losses and clinical risks. Overstocked items may expire unused, contributing to pharmaceutical waste, while understocked essential drugs result in missed treatments and disease progression. The data-enabled rationalization model mitigates this issue by balancing stock levels based on criticality, consumption rate, and shelf-life characteristics (Obianyo et al., 2024; Edwards et al., 2024). For example, fast-moving essential drugs with short shelf lives can be prioritized for frequent replenishment, while less critical or slow-moving items are stocked at optimized minimum levels. Predictive models can also factor in lead times and supply chain delays, enabling more precise planning and distribution. This targeted, data-informed approach prevents unnecessary purchases, reduces storage burden, and lowers the likelihood of drug expirations—thus improving overall cost-efficiency and sustainability in health commodity management.

Another significant benefit of the model is the increase in service delivery efficiency and the restoration or enhancement of public trust in the healthcare system. Availability of essential medicines at the point of care is a critical determinant of service quality and patient satisfaction. Recurrent stockouts not only hinder treatment but also erode confidence in public health facilities, driving patients toward private providers or traditional alternatives, which may be costlier or less effective. By ensuring more reliable access to medicines, the model helps public health facilities deliver consistent, timely, and effective care. This consistency is particularly crucial for programs managing chronic diseases such as HIV, tuberculosis, diabetes, and hypertension, where treatment adherence is directly linked to drug availability (Obianyo et al., 2024; Edwards et al., 2024). Additionally, improved logistics performance enables health workers to spend less time managing supply-related crises and more time delivering clinical services. Over time, as patients experience fewer disruptions and greater reliability, public trust in health institutions is likely to be strengthened. This can lead to increased health-seeking behavior, better health outcomes at the population level, and stronger community engagement with public health interventions.

Furthermore, the model promotes system-level transparency and accountability, as digital tracking and real-time dashboards allow for continuous performance monitoring. Key performance indicators such as stockout rates, order fulfillment times, and inventory turnover can be regularly assessed, enabling health administrators to identify bottlenecks and adjust strategies accordingly. This fosters a culture of data-driven decision-making and continuous improvement. Moreover, by providing actionable insights, the model empowers policymakers to allocate resources more strategically and respond to public health needs with agility and precision (Ogunnowo et al., 2024; Omisola et al., 2024).

The expected outcomes of the data-enabled inventory rationalization model in public sector pharmaceutical operations are multifaceted and far-reaching. By reducing stockouts, optimizing resource use, and enhancing service delivery efficiency, the model addresses critical weaknesses in current public health supply chains. These improvements not only contribute to better clinical outcomes but also restore public confidence in government-run healthcare services. In an era where healthcare systems face increasing demands and limited resources, such data-informed, proactive approaches offer a promising path toward more resilient, equitable, and effective pharmaceutical supply chains (Obianyo et al., 2024; Edwards et al., 2024).

VII. MONITORING AND EVALUATION

An effective Monitoring and Evaluation (M&E) framework is essential for assessing the impact, sustainability, and adaptability of the proposed data-enabled inventory rationalization model in public sector pharmaceutical operations. By systematically tracking performance and capturing real-time insights from users and data sources, the M&E process ensures that the model remains relevant, efficient, and responsive to dynamic health system needs (Kufile et al., 2024; Onifade et al., 2024). This outlines the two main components of the M&E approach: the use of Key Performance Indicators (KPIs) and a structured mechanism for continuous feedback and model updating.

To evaluate the performance of the inventory rationalization model, a set of measurable and actionable KPIs must be established. These indicators help quantify improvements in supply chain efficiency, medicine availability, and inventory management quality over time. The most relevant KPIs include the stockout rate, order fill rate, inventory turnover, and average days of stock.

The stockout rate is the percentage of time that an essential medicine is unavailable at a health facility

when needed. It is a direct indicator of service reliability and supply chain effectiveness. A reduction in stockout rates after implementation would signify improved forecast accuracy and inventory prioritization. This metric should be monitored for high-priority (e.g., vital and high-value) items across all tiers of the supply chain—national warehouses, regional depots, and frontline health facilities.

This indicator measures the percentage of ordered quantities that are successfully delivered in full and on time. It reflects the responsiveness of the procurement and distribution systems. Higher fill rates indicate better alignment between demand forecasts and procurement planning. The model is expected to enhance this metric by improving demand visibility and enabling more accurate, timely replenishment decisions.

Inventory turnover is calculated as the ratio of medicines consumed over a period to the average inventory held during that period. A high turnover rate suggests efficient stock movement and minimal holding of excess inventory, whereas a low rate may indicate overstocking or slow-moving items. The model aims to optimize turnover by reducing excess and obsolete stock while maintaining service levels.

This KPI assesses how long current stock levels can sustain demand without resupply. It provides insight into supply chain resilience and buffer stock adequacy. Maintaining optimal DoS (neither too high nor too low) is critical to balancing availability and waste reduction (Ogunnowo et al., 2024; Omisola et al., 2024). The forecasting and classification features of the model are expected to enable more precise safety stock settings, leading to more stable DoS metrics.

These KPIs should be monitored regularly—monthly or quarterly depending on the health system's reporting cycle—and disaggregated by facility type, region, and product category. Dashboards that visualize these indicators in real time can support timely decision-making by planners and policymakers. While KPIs provide quantitative insights into performance, continuous feedback and iterative refinement are essential for ensuring the model's long-term effectiveness and adaptability. Given the dynamic nature of pharmaceutical demand and the evolving structure of public health systems, the model must incorporate mechanisms to learn from operational experiences and adjust accordingly (Omisola et al., 2024; Omoegun et al., 2024).

Feedback from end users—such as pharmacists, logistics officers, and central planners—is vital for identifying practical issues in the model's usability and relevance. Regular feedback can be collected through structured surveys, user forums, helpdesk logs, and supervisory visits. This qualitative information can uncover barriers to adoption (e.g., data entry challenges, unclear dashboard metrics, or resistance to automated reorder suggestions) and inform modifications to the user interface, training content, or communication protocols.

As new data become available, the forecasting engine and inventory classification modules must be recalibrated. For instance, shifts in disease burden, emergence of new treatment guidelines, changes in supply lead times, or seasonal trends can significantly affect demand forecasts. Automated model updating mechanisms—such as machine learning pipelines that retrain periodically using recent data—can be implemented to ensure forecasts remain accurate over time.

Safety stock thresholds, reorder points, and classification cutoffs (e.g., ABC/VED categorizations) should not be static. They must be updated based on changes in demand variability, lead times, and service level goals. Continuous monitoring of forecast error metrics (e.g., MAPE or RMSE) can guide adjustments in prediction models (Gbabo et al., 2024; Ezeilo et al., 2024). Likewise, simulations using historical data can be used to test different threshold settings and select those that minimize both stockouts and excess inventory.

An institutionalized governance mechanism, such as a national Supply Chain Analytics Steering Committee, should be established to oversee the M&E process.

This body would review KPI reports, validate feedback summaries, prioritize system changes, and coordinate with IT teams and supply chain managers to implement improvements. Embedding such oversight within existing Ministry of Health structures ensures long-term accountability and alignment with national health strategies.

Lastly, M&E results should be used not only for internal system refinement but also for broader learning. Sharing lessons from model implementation—through national review meetings, technical bulletins, or knowledge exchanges with peer countries—can accelerate improvements and support cross-institutional collaboration.

Monitoring and Evaluation is a core pillar of the proposed data-enabled inventory rationalization model. By using targeted KPIs such as stockout rates, fill rates, inventory turnover, and days of stock, the system provides quantifiable evidence of progress. Coupled with continuous feedback loops and data-driven updates, this approach ensures that the model remains agile, effective, and grounded in the realities of public sector pharmaceutical operations (Gbabo et al., 2024; Chima et al., 2024). Ultimately, robust M&E supports better governance, sustained impact, and continuous innovation in supply chain management.

VIII. CHALLENGES AND RISK MITIGATION

While the adoption of a data-enabled inventory rationalization model offers significant potential benefits for public sector pharmaceutical operations, its implementation is not without challenges. These challenges span technical, organizational, and policy dimensions, and if not adequately addressed, they could compromise the effectiveness and sustainability of the model as shown in figure 3. Key among these are issues related to data quality and availability, resistance to system changes among stakeholders, and the complexities of integrating new models with existing legacy systems and aligning them with current policies (Gbabo et al., 2024; Ochefu et al., 2024). Recognizing and addressing these challenges through appropriate risk mitigation strategies is essential to ensure successful deployment and long-term impact.

A major technical barrier to the successful implementation of any data-driven model is data quality and availability. In many public sector health systems, especially in low- and middle-income countries, data is often incomplete, inaccurate, inconsistent, or delayed. Manual entry errors, infrequent updates, lack of standardized data formats, and fragmented systems all contribute to poor data quality. Inaccurate consumption records or delayed stock reporting from healthcare facilities can severely compromise the performance of predictive analytics and forecasting algorithms. Furthermore, some facilities may not report data at all due to lack of infrastructure, internet connectivity, or trained personnel, creating significant blind spots in the inventory monitoring process.

Figure 3: Challenges and Risk Mitigation

To mitigate these risks, a phased data governance framework must be implemented. This includes establishing data standardization protocols, regular training of health facility staff on data entry and digital literacy, and deploying user-friendly digital platforms that minimize manual data handling. Automation of data capture through barcode scanning or mobile data collection tools can also improve

accuracy and timeliness (Gbabo et al., 2024; Komi et al., 2024). Additionally, setting up a central data validation and monitoring unit can help identify anomalies and rectify discrepancies in real time. Pilot testing in selected districts before full-scale rollout allows for early identification of data-related issues and iterative improvements to system design and protocols.

Another critical challenge is resistance to system changes among stakeholders. Health workers, supply chain managers, and administrative staff may be reluctant to adopt new inventory management processes due to perceived increases in workload, fear of technology, or attachment to familiar manual procedures. Institutional inertia, lack of incentives, and fear of accountability in more transparent systems can further impede adoption. Without stakeholder buy-in, even the most technically robust system may fail to be used effectively or consistently.

To overcome resistance, a comprehensive change management strategy is essential. This includes early engagement with stakeholders during the model's development and customization phases to ensure that the system addresses their needs and integrates into existing workflows. Providing clear communication about the benefits of the system—such as reduced workload in the long term, better patient outcomes, and enhanced facility performance—can help build acceptance. Additionally, targeted capacity-building programs, peer-led training, and user support helplines can improve confidence and ease the transition to new processes (Chianumba et al., 2024; Komi et al., 2024). Recognition and reward systems can further incentivize early adopters and exemplary users, fostering a culture of innovation and continuous improvement.

A third set of challenges arises from the need to integrate the new model with legacy systems and ensure policy alignment. Many public health supply chains operate on a patchwork of legacy platforms, often developed independently and lacking interoperability. These systems may have outdated architectures, limited data export capabilities, and rigid workflows that complicate integration with modern, analytics-driven platforms. Moreover, public health policies and procurement regulations are often not designed to accommodate dynamic inventory systems or real-time demand planning. Inflexible procurement schedules, bureaucratic delays, and centralization of decision-making can hinder the responsive actions that predictive models recommend.

Mitigating this risk requires a dual-pronged approach involving both technical and policy interventions. On the technical side, employing middleware or integration layers using open APIs can facilitate data exchange between new systems and legacy platforms without requiring complete system overhauls (Osamika et al., 2024; Komi et al., 2024). This interoperability ensures that data flows seamlessly and that new insights can be applied to existing operational structures. On the policy side, collaboration with government bodies, regulatory agencies, and procurement authorities is critical. The model must be designed in alignment with national health policies, essential medicines lists, and financial regulations. Engaging policymakers early in the process and presenting data-driven evidence of the model's impact can help secure necessary adjustments to procurement rules and support regulatory flexibility.

Furthermore, the success of such integration efforts can be reinforced by aligning the inventory rationalization model with national digital health strategies and donor-funded eHealth initiatives. Leveraging existing investments in digital infrastructure and ensuring compliance with health data governance standards also helps to streamline integration and institutionalization efforts.

While the implementation of a data-enabled inventory rationalization model in public sector pharmaceutical operations presents several challenges, these can be effectively managed through strategic risk mitigation measures. Addressing data quality through standardization and training, overcoming

resistance to change through stakeholder engagement and incentives, and ensuring technical and policy alignment through interoperability and regulatory collaboration are all critical to success (Komi et al., 2024; Oladuji et al., 2024). With proactive planning and adaptive strategies, these challenges can be transformed into opportunities for strengthening public health supply chains and advancing toward more responsive, efficient, and equitable healthcare delivery systems.

IX. CONCLUSION AND FUTURE DIRECTIONS

The proposed data-enabled inventory rationalization model presents a transformative approach to addressing stockouts in public sector pharmaceutical operations. By integrating advanced data analytics, real-time forecasting, and inventory classification frameworks such as ABC-VED, the model introduces a proactive, intelligent mechanism for pharmaceutical inventory management. Through the combination of predictive demand forecasting and prioritization based on criticality and value, the model enables more efficient use of limited resources while enhancing medicine availability, reducing waste, and ensuring timely replenishment of essential health commodities. The model's core components—data ingestion, forecasting engine, classification module, and decision-support dashboard—work in synergy to support health supply chain decision-makers at multiple levels. By leveraging historical and real-time data from electronic logistics systems, health management platforms, and facility-level reports, the model provides accurate reorder recommendations and risk-based inventory stratification. These functionalities are particularly beneficial in resource-constrained environments, where manual inventory practices and fragmented data often undermine procurement planning and service continuity.

However, the potential of the model can only be fully realized through a long-term scale-up strategy that addresses sustainability, system-wide integration, and institutional ownership. Pilot implementations and phased rollouts are essential first steps, but broader success will require strategic investment in digital infrastructure, data quality improvements, and capacity-building initiatives across health facilities and procurement units. National health authorities must embed the model within existing governance structures, ensure alignment with national health and digital strategies, and promote cross-functional collaboration to support model adoption and continuous improvement.

Furthermore, future research and development efforts should explore ways to enhance the model's functionality and scalability. One key area is the integration of health outcomes data into the inventory rationalization process. By linking pharmaceutical availability to treatment adherence, disease progression, and patient recovery rates, supply chain decisions can be better aligned with population health objectives. For example, prioritizing stock based on clinical outcomes can help optimize resource allocation in high-burden disease areas.

Additionally, the incorporation of blockchain technology offers opportunities to improve transparency, traceability, and trust in pharmaceutical supply chains. Blockchain could provide immutable records of procurement transactions, shipment histories, and batch-level tracking, thus enhancing data integrity and regulatory compliance. This is particularly relevant in environments with high risk of diversion, counterfeiting, or misreporting. Combining blockchain with predictive analytics could also support real-time alerts and automated validations at key supply chain nodes.

Finally, the model should be adapted and tested across multiple country contexts, especially in low- and middle-income settings where challenges in procurement efficiency, data visibility, and medicine accessibility are most acute. Comparative case studies can help identify context-specific barriers and enablers, providing insights for customizing the model to different regulatory environments,

infrastructure levels, and health system structures. A modular design approach, with configurable components and localized parameters, can support cross-country learning and facilitate regional implementation strategies under frameworks such as those supported by WHO, UNICEF, and Global Fund initiatives.

The data-enabled inventory rationalization model offers a scalable, evidence-based solution to a long-standing challenge in global health logistics. Its successful implementation, backed by rigorous evaluation, sustained investment, and ongoing innovation, holds significant promise for improving the reliability, efficiency, and equity of public sector pharmaceutical supply chains worldwide.

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