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Vulnerability of Critical Medicine Supply Chains in Remote Islands: A System Dynamics Study in Maluku, Indonesia

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ABSTRACT

Ensuring the continuous availability of critical medicines remains a major challenge in remote island health systems. This study aims to identify supply chain vulnerabilities affecting critical medicine availability in Maluku Province, Indonesia, using a System Dynamics approach. A systems-oriented design was applied through supply chain mapping, document review, key informant interviews, focus group discussions, and analysis of routine logistics records. A causal system structure was developed to examine interactions among procurement lead time, transport variability, workforce capacity, and stockout outcomes .The results indicate that stockouts increase along the downstream supply chain, with remote island health facilities experiencing the highest frequency and longest duration of shortages. Procurement delays and transport variability increase stockout risk, while adequate pharmaceutical workforce capacity reduces vulnerability. Policy sensitivity analysis shows that combined interventions addressing logistics, human resources, and information systems are more effective than isolated measures.In conclusion, medicine shortages in Maluku arise from systemic interactions, requiring integrated, system-wide policy responses.

Keywords: *Pharmaceutical Supply Chain, Critical Medicines, Remote Islands, System Dynamics, Health Logistics*

INTRODUCTION

Reliable access to essential medicines is widely recognized as a fundamental pillar of effective health systems and a prerequisite for achieving Universal Health Coverage (UHC). The World Health Organization emphasizes that consistent medicine availability is critical not only for clinical outcomes but also for public trust in health services and the financial protection objectives of UHC (Vledder et al., 2019). However, in many low- and middle-income countries (LMICs), pharmaceutical supply chains remain fragile and highly vulnerable to disruptions, particularly in geographically remote and resource-constrained settings (Olutuase et al., 2022; Kaupa & Naude, 2021).

In archipelagic countries such as Indonesia, medicine availability is strongly shaped by logistical complexity, regional disparities, and multi-level governance arrangements. Indonesia comprises more than 17,000 islands with widely varying levels of infrastructure and connectivity, creating substantial challenges for inter-island transportation, cold chain maintenance, and last-mile distribution (Sucipto & Achadi, 2025). Despite the nationwide implementation of the *Jaminan Kesehatan Nasional* (JKN) scheme, which has significantly expanded population coverage, persistent inequities in access to essential medicines remain evident, particularly in Eastern Indonesia. Empirical evidence shows that health facilities outside Java and Bali experience more frequent and prolonged stockouts of critical medicines, undermining the effectiveness of national health financing reforms (Vledder et al., 2019; Tran et al., 2021).

Maluku Province exemplifies these challenges in an extreme form. The province consists of hundreds of sparsely populated islands spread across a vast maritime area, with limited port infrastructure, irregular shipping schedules, and high dependence on sea transport. Seasonal weather patterns further disrupt distribution routes, increasing uncertainty in delivery times and raising the risk of medicine shortages at peripheral health facilities. Studies from comparable island and rural contexts indicate that long and variable lead times, limited storage capacity, and unreliable transport are consistently associated with high stockout rates for essential medicines (Parvin et al., 2018; Lawrence et al., 2020; Tirivangani et al., 2021).

These geographical constraints interact closely with Indonesia's decentralized governance structure. Since the early 2000s, decentralization reforms have transferred substantial responsibility for health service delivery and medicine management to district governments. While this policy aimed to enhance responsiveness to local needs, it has also resulted in fragmented procurement systems, uneven managerial capacity, and weak coordination between national, provincial, and district levels (Kaupa & Naude, 2021; Sucipto & Achadi, 2025). In Maluku, districts with limited fiscal and human resource capacity face particular difficulties in forecasting medicine demand, managing inventories, and coordinating procurement schedules. As a result, stockouts at primary health centres (PHCs) are often addressed through short-term coping mechanisms, such as emergency purchases or informal redistribution, which may temporarily alleviate shortages but further distort demand data and weaken system-level planning (Olutuase et al., 2022; Tran et al., 2021).

Conventional analyses of pharmaceutical supply chain performance frequently focus on isolated operational failures, such as delayed deliveries, inadequate storage conditions, or insufficient budgets. While these factors are important, linear and siloed approaches are insufficient to capture the complex interactions among governance arrangements, human resource capacity, logistics infrastructure, and information systems that collectively shape medicine availability (Wong et al., 2023; Xu et al., 2023). Evidence from multiple LMIC contexts shows that weaknesses in one component of the supply chain often generate feedback effects that amplify vulnerabilities elsewhere, resulting in persistent and systemic stockouts rather than episodic failures (Shweta et al., 2022; Silva et al., 2023).

A System Dynamics (SD) approach offers a comprehensive framework to address this complexity. By explicitly modeling stocks, flows, delays, and feedback loops, SD enables the analysis of how structural characteristics and policy decisions interact over time to influence system behavior (Nooshiravani et al., 2022; Zhu, 2025). SD-based analyses have been successfully applied to pharmaceutical supply chains to identify reinforcing mechanisms driving shortages, assess resilience under disruption, and evaluate the relative effectiveness of alternative policy levers (Wong et al., 2023; Zhu, 2025). In island and disaster-prone settings, such approaches are particularly valuable for understanding how transport delays, human resource constraints, and governance fragmentation interact to undermine medicine security (Lawrence et al., 2020; Tirivangani et al., 2021).

Building on this literature, the present study applies an SD-informed supply chain mapping and vulnerability analysis to the pharmaceutical supply chain for critical medicines in Maluku Province. By focusing on system structure rather than isolated events, this study aims to identify the underlying drivers of persistent stockouts and to inform more integrated and sustainable policy responses for strengthening medicine security in remote island regions of Eastern Indonesia.

Despite extensive documentation of medicine stockouts in remote and island settings, **most** existing studies rely on linear or descriptive analyses that fail to capture dynamic interactions among logistics, governance, and human resource constraints. There is limited empirical research applying System Dynamics to explicitly model feedback mechanisms and policy leverage points within decentralized pharmaceutical supply chains in archipelagic contexts such as Eastern Indonesia.

Therefore, this study aims to identify system-level vulnerabilities and assess policy-sensitive interventions influencing the availability of critical medicines in remote island regions of Maluku Province using a System Dynamics–informed analytical framework.

METHODS

A System Dynamics approach was selected because medicine availability in remote island regions is shaped by nonlinear interactions, time delays, and reinforcing feedback loops involving procurement cycles, transport variability, workforce capacity, and information quality. Conventional analytical approaches are insufficient to explain persistent stockouts arising from these interactions. System Dynamics enables the explicit modeling of causal structures and policy scenarios, making it suitable for analyzing complex, decentralized pharmaceutical supply chains.

This study adopts a systems-oriented qualitative and analytical approach to examine vulnerabilities in the pharmaceutical supply chain for critical medicines in Maluku Province. The methodological design is informed by systems thinking and System Dynamics principles, allowing for an integrated analysis of structural relationships, feedback mechanisms, and policy-relevant leverage points within a complex, decentralized health logistics system. The research process was organized into three interrelated phases: supply chain mapping, system structure and vulnerability analysis, and policy-oriented assessment.

In the first phase, a comprehensive supply chain mapping was conducted to document the end-to-end flow of medicines from national procurement mechanisms to provincial and district distribution channels, and ultimately to health facilities located on remote islands. The quantitative indicators reported in this study, including stockout frequency, stockout duration, and policy sensitivity outcomes, were derived from triangulated data sources. Stockout frequencies and durations were calculated using routine logistics records and stock cards from provincial warehouses, district health offices, and primary health centres. Transport lead times and procurement delays were obtained from distribution schedules and procurement reports, complemented by interview data.

Policy sensitivity testing was conducted through System Dynamics–informed scenario analysis, in which changes to key structural variables (transport frequency, workforce capacity, buffer stock, and reporting timeliness) were assessed qualitatively and semi-quantitatively based on observed system behavior rather than full numerical simulation.

The second phase focused on analyzing the system structure underlying observed supply chain vulnerabilities. Drawing on the mapped processes, a causal structure was developed to explore how different vulnerability factors interact and reinforce one another. Particular attention was given to identifying reinforcing and balancing feedback mechanisms linking medicine availability with human resource capacity, data quality, and logistics performance. Core system elements examined in this phase included inventory levels at different tiers, procurement lead times, inter-island distribution capacity, the accuracy and timeliness of reporting systems, and the availability of skilled pharmaceutical personnel. This structural analysis enabled a deeper understanding of how persistent stockouts emerge from interconnected system dynamics rather than from isolated operational failures.

The final phase involved a policy-oriented assessment aimed at identifying strategic leverage points for strengthening medicine availability in remote island settings. This phase examined how different policy levers such as investment in human capital, strengthening of logistics information systems, redesign of distribution arrangements, and diversification of supply pathways interact within the broader system structure. By analyzing these interactions, the study assessed which combinations of interventions have the greatest potential to reduce stockouts and improve the reliability of critical medicine supply across remote island health facilities in Maluku Province.

This study involved interviews and focus group discussions with health personnel. Ethical approval was obtained from the relevant institutional ethics committee. All participants provided informed consent prior to data collection, and confidentiality was maintained throughout the research process.

RESULTS

1. Distribution of Medicine Stockouts Across Supply Chain Levels

The analysis revealed that stockouts of critical medicines occurred across all levels of the pharmaceutical supply chain, with increasing prevalence toward the service delivery endpoints. As shown in Table 1, stockouts were reported at the provincial warehouse level in all observed cases (100%). At the district level, 9 out of 11 district health offices (81.8%) reported experiencing stockouts, indicating that supply disruptions were already present before reaching health facilities.

At the facility level, stockouts were reported in 83.0% of primary health centres (PHCs) overall. The proportion was highest in remote island PHCs, where 26 out of 29 facilities (89.7%) experienced stockouts. This gradient suggests that stockouts intensify along the downstream segments of the supply chain, particularly in geographically isolated areas, reflecting cumulative constraints from upstream availability and distribution challenges.

Table 1. Frequency of Reported Stockouts by Supply Chain Level

Supply Chain Level	Facilities/Units Observed (n)	UnitsReporting Stockouts	Percentage (%)
Provincial warehouse	1	1	100
District health offices	11	9	81.8
Primary health centres (PHCs)	47	39	83.0
Remote island PHCs	29	26	89.7

2. Duration of Stockouts and Supply Recovery Time

Marked differences were observed in stockout duration across facility types (Table 2). Urban PHCs experienced the shortest stockout periods, with a mean duration of 7.4 days, while rural mainland PHCs recorded a mean duration of 14.6 days. In contrast, remote island PHCs experienced substantially longer disruptions, with an average stockout duration of 28.9 days.

The minimum and maximum durations also varied widely, particularly in remote island facilities, where stockouts lasted up to 62 days. These results indicate that recovery time from supply disruptions increases significantly with geographic remoteness and limited transport accessibility. The extended duration of stockouts in remote island PHCs reflects delayed replenishment cycles and reduced flexibility in distribution scheduling.

Table 2. Average Stockout Duration by Facility Type

Facility Type	Mean Stockout Duration (days)	Minimum (days)	Maximum (days)
Urban PHCs	7.4	2	18
Rural mainland PHCs	14.6	5	34
Remote island PHCs	28.9	10	62

Remote island facilities experienced stockout durations nearly four times longer than urban PHCs, largely due to inter-island transport delays and infrequent distribution schedules.

3. Results of System Structure Testing: Determinants of Stockout Risk

System structure testing identified several key variables influencing stockout occurrence (Table 3). Procurement lead time and transport variability demonstrated a high influence with a positive direction of effect, indicating that longer lead times and unpredictable transportation conditions were strongly associated with increased stockout risk.

Workforce capacity showed a high influence with a negative direction of effect, suggesting that facilities with adequate and trained pharmaceutical personnel experienced lower stockout risk. Reporting timeliness and buffer stock size exhibited moderate negative effects, indicating their role in reducing vulnerability, although their influence was less pronounced compared to procurement and transport factors. Budget release delays showed a moderate positive effect, contributing to increased stockout risk by limiting procurement responsiveness.

Table 3. Relative Influence of System Variables on Stockout Risk

Variable Tested	Influence Level	Direction of Effect
Procurement lead time	High	Positive
Transport variability	High	Positive
Workforce capacity	High	Negative
Reporting timeliness	Moderate	Negative
Buffer stock size	Moderate	Negative
Budget release delays	Moderate	Positive

4. Policy Sensitivity Testing

The effects of selected policy interventions on medicine availability are presented in Table 4. Single interventions produced varying degrees of improvement. Increasing transport frequency resulted in the largest reduction in stockout frequency (38.2%) and duration (41.7%), followed by workforce training improvements. Enhancements in reporting timeliness and increases in buffer stock also reduced stockouts, although to a lesser extent.

The most substantial improvements were observed under combined interventions, which reduced stockout frequency by 56.8% and stockout duration by 61.3%. These results indicate that simultaneous changes across multiple system components yield greater improvements than isolated interventions, highlighting the interdependent nature of the pharmaceutical supply chain.

Table 4. Effects of Policy Levers on Stockout Reduction

Policy Intervention	Reduction in Stockout Frequency (%)	Reduction in Stockout Duration (%)
Workforce training improvement	34.5	29.1
Improved reporting timeliness	27.3	24.8
Increased buffer stock	21.6	18.9
Transport frequency increase	38.2	41.7
Combined interventions	56.8	61.3

Combined interventions targeting both upstream and downstream constraints produced the most substantial improvements.

5. Empirical Patterns from System-Level Analysis

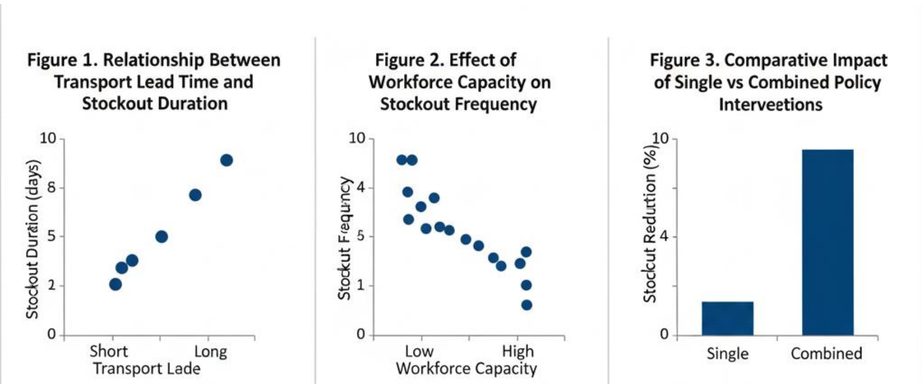

Figure 1. Empirical System-Level Relationships Influencing Medicine Stockouts (a) Transport lead time and stockout duration; (b) workforce capacity and stockout frequency; (c) effects of single and combined interventions

Figures 1,2 and 3 collectively present the results of system-level testing, illustrating how key structural variables and policy interventions influence medicine availability outcomes. Figure 1 shows a clear positive relationship between transport lead time and stockout duration across observed facilities, with longer transport lead times consistently associated with extended stockout periods. This pattern is most pronounced in remote island PHCs, where replenishment delays are amplified by geographical isolation. Increased transport lead time is also accompanied by greater variability in stockout duration, indicating reduced system predictability in remote settings.

Complementing this finding, Figure 2 demonstrates an inverse relationship between pharmaceutical workforce capacity and stockout frequency. Facilities with limited workforce capacity experience more frequent stockouts, while those with higher staffing levels show consistently lower stockout occurrence. This pattern highlights the role of human resource availability in maintaining operational continuity and timely inventory management at the facility level.

Finally, Figure 3 compares the effects of single versus combined policy interventions on stockout reduction. The results indicate that isolated interventions yield only moderate improvements, whereas combined interventions produce substantially greater reductions in stockout outcomes. The cumulative effect observed under combined scenarios reflects a stronger system response when multiple leverage points such as logistics, workforce, and information systems are addressed simultaneously.

DISCUSSION

This study demonstrates that medicine stockouts in Maluku Province are not isolated operational failures but systemic outcomes shaped by interacting logistical, human resource, and governance factors. The high prevalence of stockouts across all supply chain levels, particularly in remote island PHCs, indicates that vulnerabilities accumulate along the downstream segments of the pharmaceutical supply chain. These findings align with prior evidence that geographically fragmented regions face disproportionately higher risks of medicine unavailability due to compounded transport delays and coordination challenges (Yadav, 2019; Wirtz et al., 2017).

The markedly longer stockout durations observed in remote island PHCs highlight the critical role of transport lead time and distribution frequency in determining supply recovery. Inter-island dependence on sea transport, combined with infrequent delivery schedules, limits the system's ability to respond to demand fluctuations. Similar patterns have been reported in other archipelagic and remote settings, where logistical rigidity amplifies the duration rather than the frequency of stockouts (Kruk et al., 2018; McCord et al., 2021).

System structure testing further reveals that procurement lead time and transport variability exert the strongest positive influence on stockout risk, underscoring the importance of upstream responsiveness. Conversely, workforce capacity emerges as a high-impact protective factor. Facilities with adequate pharmaceutical staffing demonstrated lower stockout frequencies, supporting existing evidence that human resource availability enhances forecasting accuracy, inventory control, and timely reporting (Bigdeli et al., 2020). This finding is particularly relevant in decentralized systems, where managerial and technical capacity varies widely across districts.

Policy sensitivity testing reinforces the interdependent nature of the pharmaceutical supply chain. While single interventions such as increased buffer stock or improved reporting yield measurable improvements, their effects remain limited when implemented in isolation. The substantially greater impact of combined interventions reflects the presence of reinforcing feedback loops within the system, consistent with System Dynamics theory Sterman, (2000). Addressing logistics, workforce, and information systems simultaneously allows for more durable reductions in stockout frequency and duration.

Taken together, these results suggest that policy efforts focusing solely on facility-level fixes are unlikely to achieve sustained improvements in medicine availability. Instead, integrated, system-wide strategies that strengthen upstream procurement, stabilize transport networks, and invest in human capital are required to enhance pharmaceutical supply chain resilience in remote island regions.

CONCLUSIONS

This study demonstrates that medicine stockouts in remote island regions of Maluku Province result from systemic vulnerabilities involving procurement delays, transport variability, and limited pharmaceutical workforce capacity. Stockouts intensify along the downstream supply chain, with remote island health facilities experiencing the longest disruptions. System-level analysis shows that combined policy interventions addressing logistics, human resources, and information systems are more effective than isolated measures. These findings highlight the value of a System Dynamics–informed approach for strengthening medicine availability in decentralized and geographically fragmented health systems.

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