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Enhancing Hospital Supply Chains with 3PL Models Under Demand Uncertainty: A Case Study of a Tertiary Public Hospital in Thailand

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ABSTRACT

This study evaluates the integration of Third-Party Logistics (3PL) within hospital supply chain management under uncertain conditions, aiming to maintain service levels near 100% to prevent drug shortages and enhance patient care readiness. Employing a mixed-methods approach, it combines semi-structured interviews with logistics experts and simulations of four 3PL models for hospital Supply, Processing, and Distribution (SPD), including internal distribution (d), based on actual drug usage data. Results show that a hybrid model, which blends internal oversight with external logistics management, significantly enhances supply chain resilience and maintains optimal inventory levels. However, fully outsourcing logistics raises concerns about external control over internal drug distribution. The study concludes that integrating these 3PL/SPD models not only strengthens risk management but also adapts effectively to fluctuating demand. It offers a strategic framework for tertiary healthcare logistics, emphasizing the importance of aligning 3PL strategies with healthcare needs to optimize patient care outcomes and streamline logistics processes.

Keywords: *3PL, healthcare logistics, hospital supply chain, SPD, uncertainty*

1. INTRODUCTION

The healthcare system in faces significant challenges, including changing healthcare demands, an increasing elderly population, and rising drug resistance issues. The unpredictable nature of drug demand poses significant challenges to effective pharmaceutical management. Among the grave consequences of inadequate management are the potential for drug shortages or overstocks that endanger patient care and the efficiency of hospital operations (Kochakkashani *et al.*, 2023; Kamere *et al.*, 2023, Syahrir *et al.*, 2022). Frequent drug shortages, often exacerbated during pandemics or sudden surges in emergency care demands. These shortages highlight the need for precise planning and effective treatment protocols (Ageron *et al.*, 2018; Cappanera *et al.*, 2019; Phelan *et al.*, 2022). These factors have led to more severe and complex problems related to drug usage, necessitating exceptional care and attention from medical personnel. However, the public healthcare sector in Thailand is grappling with a shortage of medical personnel, not limited to physicians but also including nurses and pharmacists (Pongtriang and Matkaew, 2022). Despite ongoing efforts and policy implementations to address these shortages, the problem persists. According to the Ministry of Public Health of Thailand, the physician-to-population ratio in 2021 was one doctor per 1,680 people, and the pharmacist-to-population ratio was one pharmacist per 4,053 people. Similar to the U.S., where medical personnel shortages are compounded by labor cost increases and shifting consumer expectations (Landi, 2022, Werft, 2024), these shortages lead to operational inefficiencies and potential burnout due to excessive workloads (Shanafelt *et al.*, 2024).

The COVID-19 pandemic has further exacerbated the stress and impacted the quality of life of healthcare personnel worldwide (Miao *et al.*, 2022; Yi *et al*, 2022). Despite numerous studies on workforce planning in healthcare aimed at sustainable retention rates through compensation adjustments (Zakumumpa *et al.*, 2023), employee engagement (Bogaert *et al.*, 2,019; Pratap *et al.*, 2021) and motivation (Jia *et al.*, 2022), the complexity of the hospital supply chain (HSC) remains a concern. The hospital supply chain consists of distinct internal and external components, each employing different strategies for distribution, replenishment, and cost management. Advanced methods like RFID and simulation are increasingly used to optimize both chains and facilitate their integration (Orjuela *et al.*, 2023). The focus on risk management for patient safety often lacks coordinated logistics activities (Pamucar *et al.*, 2022; Skowron-Grabowska *et al.*, 2022). Implementing logistics strategies and collaborating with external organizations through third-party logistics (3PL) providers can effectively manage these complexities. Engaging with external partners fosters greater supply chain adaptability, enabling healthcare systems to respond more effectively to demand volatility and reduce disruptions (Sahab and Oulfarsi, 2024). This approach enables logistics experts to efficiently handle procurement, inventory management, and distribution (Meyer *et al.*, 2022; Moon *et al.*, 2019). During the COVID-19 pandemic, Spieske *et al*. (2022) specifically analyzed buffering and bridging strategies among 9 European medical supplies manufacturers and hospital groups. They found that strategies such as offering procurement support to suppliers or leveraging long-term buyer-supplier relationships are more effective for securing medical supplies than buffering measures.

The restructuring of both the internal and external supply chains in hospitals is crucial as it enables cost reduction in logistics and improves the efficiency and quality of services. For example, the University Hospital Tokyo implemented an external organization in 2002 to manage logistics operations, including activities related to materials management and the establishment of the Supply, Processing, and Distribution (SPD) department (Dembińska-Cyran, 2005). SPD models are gaining more attention from researchers in the field of HSCs. They have been used to solve management difficulties and complexities and to reduce the logistics costs of managing medicine with favorable results (Liu *et al.*, 2016). In Thailand, studies on the SPD model identified nine optimal models for a network of private hospitals using the AHP-fuzzy TOPSIS method. It was found that the SPD model with a 3PL-managed centralized warehouse, Group Purchasing Organization, and regional hubs was the most suitable (Senarak and Kritchanchai, 2020). More recently, the integration of SPD with VMI in continuous ambulatory peritoneal dialysis (CAPD) services has shown promising results (Lapmool and Kritchanchai, 2023), indicating potential for further development and growing interest in the SPD model in Thailand.

Controlling medication logistics is vital for ensuring the efficacy and safety of patient treatment. Rising healthcare costs in developed countries present significant challenges, emphasizing the need for effective inventory control strategies to ensure the availability of necessary items for patient care (Cappanera *et al.*, 2019; Deniz *et al.*, 2020). A commonly employed strategy at the point of use is the replenishment of medicines or medical supplies, guided by inventory policies such as the (s, S) policy. This approach dictates that when inventory levels reach the reorder point (s), replenishment is triggered up to the upper stock level (S), or decisions are made based on a specific time period (Deniz *et al.*, 2020; Moons *et al.*, 2019). In central inventory management within hospitals, a broader spectrum of inventory policies is applied compared to the point of use (PoU). These include the (s, S) policy, which provides directions for restocking items when inventory falls below a certain level (s), either refilling to level (S) or offering a set number (Q) of units (Attanayake *et al.*, 2014; Landry *et al.*, 2016; Priyan and Uthayakumar, 2014). Another variant, the (s, nQ, T) policy, involves periodic monitoring of inventory levels and initiating batch size-based replenishment or purchase orders when levels drop to (s) or lower (Yang *et al.*, 2019). These inventory policies and management strategies are essential for maintaining a balanced supply of medical supplies and drugs, ensuring healthcare providers can deliver timely and effective care to patients. Ultimately, the function of inventory control in the healthcare industry is multifaceted, encompassing not only the strategic management of supplies but also the integration of intricate rules and procedures to meet the changing demands of patient care.

Although the SPD model has shown positive outcomes, further analysis is necessary to optimize its integration with 3PL under uncertain drug demand conditions. Additionally, the integration of evidence-based strategies such as rational drug policy selection and strategic procurement significantly enhances drug supply management, helping to stabilize stock levels and accommodate fluctuations in supply and demand, ultimately improving patient care and public health outcomes (George and Elrashid, 2023; Ma *et al.*, 2023). This analysis will identify the most effective 3PL uses within the SPD framework to boost supply chain resilience and operational efficiency. It will assess the impact of various inventory policies through experimentation and refinement in diverse environments, enhancing the effectiveness and responsiveness of HSCs.

Performance was evaluated using several key metrics. First, the fill rate measured the proportion of medication demand immediately satisfied from existing stock, crucial for uninterrupted healthcare services (Arikan *et al*., 2023; Dreyfuss and Giat, 2019). Complementing this, the order fulfillment percentage (also known as service level) assessed the supply chain's capability to meet expected delivery times and quantities, reflecting its reliability and responsiveness. This vital customer service metric (Raj *et al.*, 2024) is calculated by dividing the total number of entirely completed orders by the total orders received. It highlights the proportion of orders fulfilled without backorders, making it pivotal for ensuring uninterrupted patient care and maintaining operational efficiency through adequate medicine availability. Finally, the percentage of backorders (delayed orders) offered insights into supply chain resilience. These occur when insufficient stock prevents immediate fulfillment of patient prescriptions due to unpredictable demand, often necessitating return visits (Fox *et al.*, 2014). Collectively, these three metrics provided a comprehensive view of operational effectiveness.

The objective of this study is to assess the role of the SPD model in integrating 3PL within hospital supply chain management under conditions of demand uncertainty. Additionally, the study aims to evaluate the impact of various inventory policies on operational efficiency. The ultimate goal is to achieve service levels close to 100%, essential for preventing drug shortages and enhancing patient care readiness in the face of illness unpredictability (Ahmadi-Javid *et al.*, 2017; Imran *et al.*, 2018). Unpredicted drug demand significantly influences operational efficiency, contributes to the Bullwhip effect, and affects costs and operational stability within the supply chain (Oliveira *et al.*, 2016; Saha and Ray, 2019).

2. METHODOLOGY

This study adopts a mixed-methods research design, executed in three sequential phases to comprehensively address the research objectives. Phase1 involved a comprehensive literature review to establish a theoretical foundation and identify key variables. Phase2 consisted of a qualitative study, including semi-structured interviews with experts and a case study analysis of a tertiary public hospital in Thailand, to understand current practices, challenges, and validate the conceptual models. Phase3 employed discrete-event simulation (DES) to evaluate the performance of different 3PL/SPDd integrated models under various operational scenarios. Figure 1 illustrates the overall research flow and the connections between these phases.

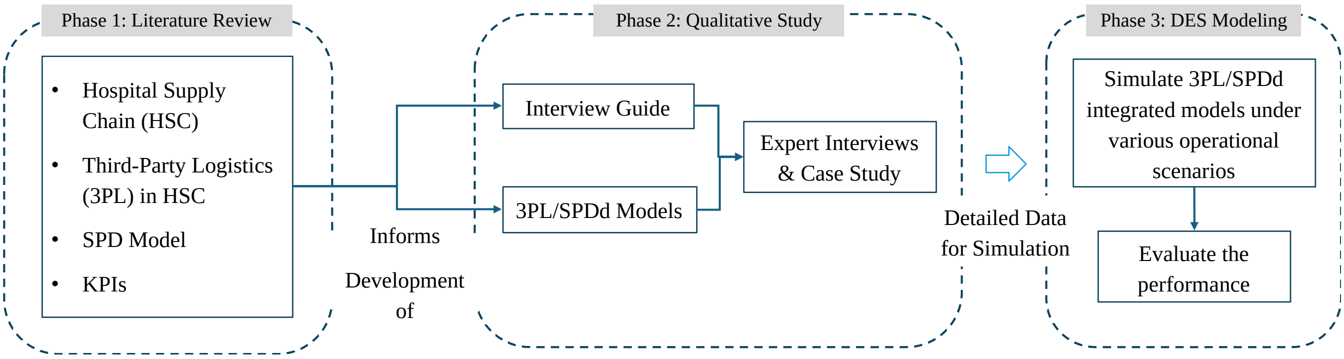

Figure 1 Research framework.

2.1 *Phase 1: Literature Review*

The initial phase of this study comprised an extensive literature review designed to achieve several key objectives. Primarily, the review aimed to establish a foundational understanding of HSC management, including common challenges such as demand uncertainty and drug shortages. It also sought to explore existing models related to 3PL integration in healthcare and to examine the applications of SPD or similar internal logistics systems in hospitals. A further crucial objective was to identify key performance indicators (KPIs) relevant to performance evaluation. Finally, these collective insights were synthesized to inform the development of the conceptual 3PL/SPDd models and the formulation of the interview guide for the subsequent qualitative phase. This review provided a coherent theoretical base and identified the research gaps this study aims to address.

2.2 *Phase 2: Qualitative Study*

This phase aimed to develop and validate the conceptual 3PL/SPDd models and to understand the specific context and challenges of a tertiary public hospital in Thailand. It involved two main components: (1) Development and expert validation of 3PL/SPDd modeling approaches, and (2) A detailed case study.

2.2.1 Development of 3PL/SPDd Modeling Approaches

The SPD concept, serving as the core of logistics operations, was deconstructed into four principal components for this research: Supply Management (S), Processing Management (P), External Distribution Management (D), and Internal Distribution Management (d). Supply Management (S) focuses on the procurement and inbound logistics processes that ensure timely and cost-effective acquisition of medical supplies and pharmaceuticals, while Processing Management (P) involves the handling, sorting, and preparation of medical supplies within the hospital settings. It ensures that materials are available and ready for use when needed, optimizing both space utilization and resource allocation. To provide a more nuanced analysis, distribution was subdivided into External Distribution (D), which manages the delivery from external sources to the hospital, and Internal Distribution (d), which deals with the circulation of supplies within the hospital premises, ensuring that various departments and service areas (Points of Use: PoUs) receive the right materials in a timely manner from the hospital's central warehouse (CW) or receiving points. This detailed breakdown facilitates a comprehensive exploration of how 3PL integration can enhance efficiency and resilience both inside and outside the HSC.

Based on these operational components and insights from the literature review, four distinct 3PL/SPDd integrated models were conceptualized, each characterized by varying degrees of 3PL involvement as shown in Figure 2. Model1-H(SPd)+3PL(D), adapted from the internal and external HSC research conducted by Volland *et al.* (2017), this model assigns 3PL the responsibility for managing all external delivery processes (D). The aim is to manage delivery times and minimize the impacts of late deliveries through various logistics activities (Batarlienė and Jarašūnienė, 2017). Hospitals retain responsibility for procurement, storage, and internal distribution operations. Model2-H(Pd)+3PL(SD), integrates 3PL into the procurement and external distribution phases, optimizing resource utilization and delivery processes as outlined in the study by (Duijzer *et al.*, 2018; Spieske *et al.*, 2022). The hospital continues to manage internal storage and distribution, ensuring that internal logistics operations align with the external enhancements provided by 3PL. In Model3-H(d)+3PL(SPD), a more comprehensive integration where 3PL is responsible for managing all aspects of supply, processing, and distribution, as suggested by (Moons *et al.*, 2019). This model is designed to maximize efficiency by fully leveraging 3PL capabilities to streamline every operational step from procurement to distribution, while hospitals focus solely on the internal distribution to various points of use within the premises. Finally, Model4-3PL(SPDd), extends 3PL roles to include internal distribution, thereby allowing hospital staff to focus solely on patient care. It shifts logistical responsibilities such as inventory and supply chain management entirely to 3PL providers. This approach not only streamlines operations but also enhances clinical efficiency by alleviating medical personnel from non-clinical tasks, thereby ensuring a more focused approach to patient care. These conceptual models formed the basis for discussions during the expert interviews and were subsequently operationalized and evaluated in the simulation phase.

2.2.2 Expert Interviews for Model Validation and Contextual Insights

Following the conceptualization of the 3PL/SPDd models from the literature review (Phase 1), this stage aimed to validate their practicability and gather rich contextual insights into current HSC challenges and practices within the Thai healthcare system. To achieve this, purposive sampling was employed to select seasoned experts. Participants included senior hospital pharmacy managers, procurement managers, and professionals managing drug inventories and logistics from 14 secondary and tertiary hospitals, with a key selection criterion being a minimum of five years of experience in HSC management to ensure in-depth knowledge and valuable insights.

An interview guide, developed based on the literature review and the proposed 3PL/SPDd models structures, was used to explore several key areas. The guide was designed to probe the current operational models for drug procurement, inventory management, and distribution; the specific techniques and strategies used for planning in each of these areas, including common inventory control policies at both CWs and PoUs; and the experts' recommendations for improving overall HSC efficiency and resilience. The insights gathered from these expert interviews were instrumental in validating the conceptual 3PL/SPDd models and refining input parameters for the subsequent simulation phase. These interviews also yielded several key findings regarding the current application and future feasibility of these models.

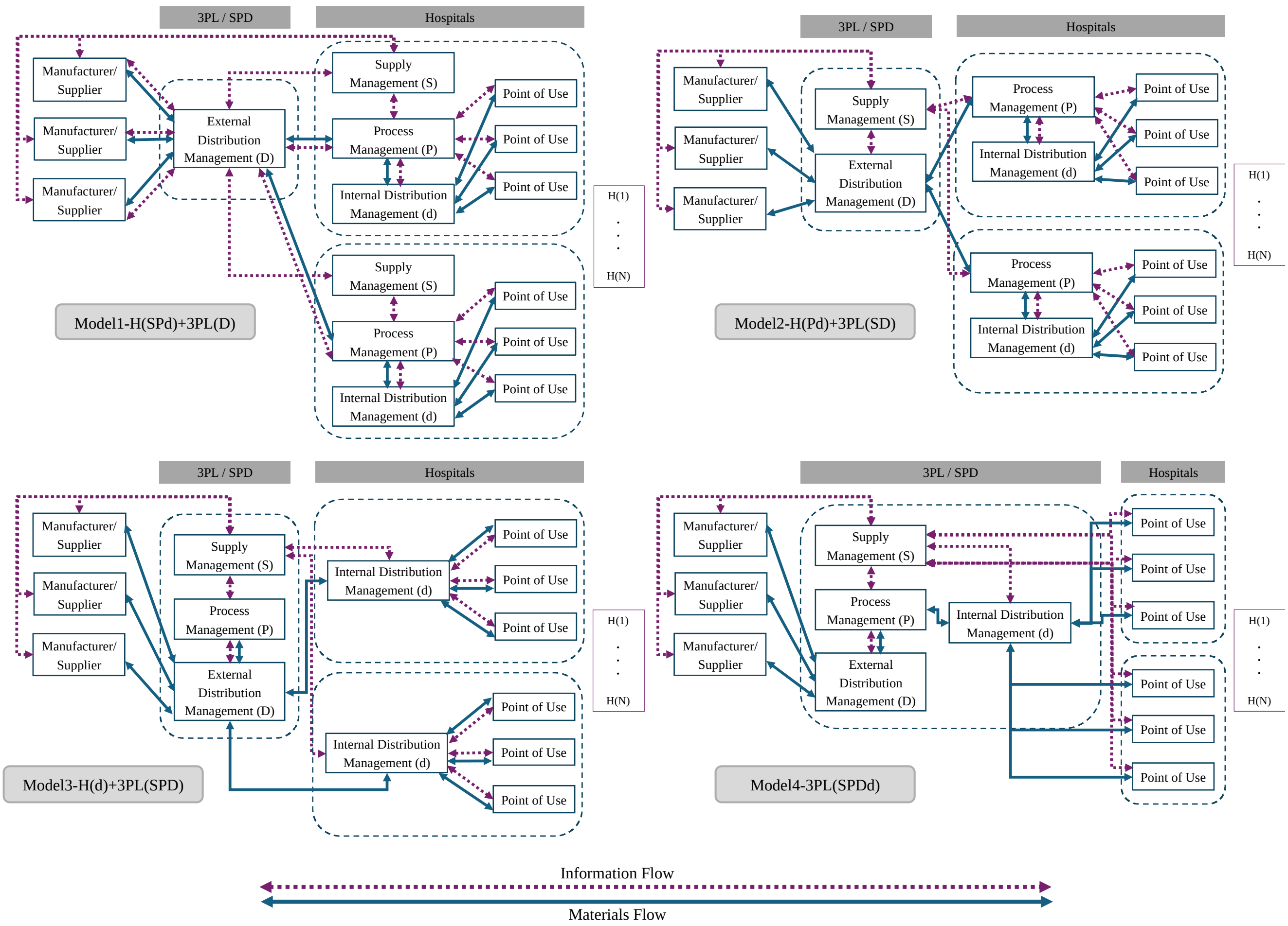

Figure 2 3PL/SPDd models.

Current Application of 3PL/SPDd Concepts (AS-IS): Model1-H(SPd)+3PL(D) and Model2-H(Pd)+3PL(SD) were confirmed as prevalent operational frameworks, widely adopted and familiar within the logistics operations of the participating Thai hospitals. These models, where hospitals retain significant control over most logistics activities while potentially outsourcing external distribution or procurement, were considered established practices. In contrast, Model3-H(d)+3PL(SPD) was reported as being piloted in some hospitals but was still in its early stages of implementation. The primary driver for exploring this model was to free up medical staff from logistics tasks, allowing them to focus more on patient care. Meanwhile, Model4-3PL(SPDd), representing full outsourcing including internal distribution, was not currently implemented in any of the surveyed Thai hospitals.

Future Directions and Feasibility (TO-BE): Experts suggested that Model 3 and Model 4 represent viable future directions for advancing hospital logistics, particularly for reducing the workload on medical personnel. The feasibility of adopting more comprehensive 3PL models (like Model 3 and 4) was often linked to hospital size and complexity, with larger tertiary and secondary level hospitals seen as more likely to benefit due to greater operational demands. This aligns with findings on resource optimization and the need for tailored strategies based on organizational context (Spaulding *et al.*, 2021).

Hospital Inventory Management System: Experts confirmed the common use of a two-tier inventory management system, with distinct practices at CWs and PoUs. At CWs, the (s, nQ, T) policy was commonly applied, aligning with batch-sized procurement from suppliers. At PoUs, a variety of policies were employed, including (s, S, T), (s, nQ, T), and (s, nQ), to manage minimum inventory levels based on pack quantities, facilitating batch-sized replenishment from the CW. The potential benefits of continuous review policies (like (s, nQ)) if managed by a 3PL were noted, particularly for reducing medical personnel workload, though this depends on the hospital's management structure and willingness to cede control.

These qualitative insights, particularly regarding existing operational models, inventory policies, and the perceived feasibility of future models, were directly used to define the AS-IS and TO-BE scenarios, select appropriate inventory control policies, and set realistic parameters for the simulation modeling in Phase 3.

2.2.3 Case Study

To provide an in-depth understanding of the operational context and to gather specific data for the simulation modeling, a case study was conducted at a tertiary-level regional hospital in Thailand, a pivotal institution for managing a healthcare network across nine provinces. The selection of this hospital for the case study is strategically relevant and enriches the research by providing a complex, dynamic setting ideal for analyzing operational and logistical strategies. As a central hub in the regional hospital network, it offers unique insights into efficient resource management across multiple facilities, making it an exemplary site for testing new logistical innovations and supply chain models. These models, once validated, could potentially be adapted to simpler settings within the network, broadening the applicability and impact of the research findings.

Drug demand characteristics and usage data were collected over a one-year period (2022-2023) from the case study hospital, covering 14 medications across seven drug categories—Antibiotics, Anticoagulants, Hormone Neuromuscular Blocking agents, Insulin, Vitamins, Inhibitors, and Laxatives, covering 14 medications in total. The findings indicated distinct demand characteristics for each category: Antibiotics exhibited Beta, Normal, and Lognormal distributions; Anticoagulants, Hormone Neuromuscular Blocking agents, Insulin, and Vitamins mostly followed a Beta distribution; Inhibitors showed Lognormal and Exponential distributions; and Laxatives demonstrated an Exponential pattern. This variation in demand poses significant challenges in managing drug inventories crucial for effective treatment delivery.

Furthermore, despite observing consistent distribution patterns among different drugs, notable fluctuations in minimum and maximum demand values were evident across various periods, as shown in Figure 3. These fluctuations highlight the considerable variability and management challenges in drug supply. The study also uncovered supply chain uncertainties, particularly in drug delivery lead times. From the case study, it was found that a Beta distribution, deviating from the commonly assumed Normal distribution (Saha and Ray, 2019) in previous research. This discrepancy underscores the challenges hospitals face in ensuring timely drug delivery and calls for a reassessment of logistics strategies to better manage the unpredictable nature of drug demand and supply chain dynamics in healthcare.

This empirical data directly informed the input parameters for the simulation models.

Figure 3 Examples of drug groups exhibiting Beta distribution.

The case study revealed that the hospital operates a two-tier inventory system for medications. At PoUs: Medications are stored to meet demand for approximately 1 to 7 days, depending on the drug's criticality. Inventory levels are typically reviewed every 7 days, and replenishment requests are sent to the CW. The replenishment quantity is determined either by reaching a predefined maximum stock level or by ordering in specific batch sizes. Internal distribution from the CW to PoUs generally takes 1 to 3 days; however, urgent requests can be fulfilled more quickly if stock is available at the CW. Otherwise, backorders may occur. At the CW: Inventory is physically counted every 30 days, with a target stock level of approximately 1.5 to 2 months' supply. Reorder points trigger procurement from external suppliers, with order quantities often based on negotiated batch sizes. The procurement process itself, including documentation and executive approval, averages 14 days.

Key logistics activities such as stocktaking, drug dispensing, quality checks, and intra-hospital distribution are predominantly managed by medical personnel. This practice, particularly during periods of high patient volume when patient care takes precedence, can lead to delays in routine logistics tasks like stock verification. Such delays were observed to potentially disrupt the regular supply cycle, contributing to issues like delayed ordering, the 'bullwhip effect', and subsequent drug shortages.

This detailed understanding of the current operational workflows, prevalent inventory policies (such as (s, nQ, T) at the CW and variations like (s, S, T), (s, nQ, T), and (s, nQ) at PoUs, as confirmed by expert interviews and case study observations), identified lead times, and existing challenges formed the critical baseline for establishing the 'AS-IS' scenarios in the simulation phase. The specific parameters for these AS-IS scenarios, primarily reflecting configurations aligned with Model 1 and Model 2, are further detailed in the simulation experimental design. This approach ensured a realistic comparison against the proposed 'TO-BE' models.

2.3 Phase 3: Discrete-Event Simulation (DES) Modelling

The final phase of this research employed discrete-event simulation (DES), implemented in Arena software, to quantitatively evaluate and compare the performance of four conceptualised 3PL/SPDd models under demand uncertainty. A conceptual model for the DES was developed to represent the flow of 14 selected medications through the HSC. These medications, categorized by VEN analysis (5 Vital, 4 Essential, 5 Nonessential), initiated by daily stochastic demand at PoUs, with demand patterns derived from the case study data. Demand is fulfilled from on-hand stock; any shortfall results in a backorder. The inventory replenishment logic is two-echelon. At the PoUs, a 7-day periodic review triggers replenishment orders to the CW based on the (s, S, T), (s, nQ, T), or (s, nQ) policies. The CW, in turn, performs a 30-day periodic review, placing procurement orders with external suppliers using an (s, nQ, T) policy. The model incorporates uncertainty through stochastic lead times: a Uniform distribution from 0 to 3 days for internal distribution (CW to PoU) and a Beta distribution for external procurement (supplier to CW). Key assumptions include that all backorders are eventually filled (no lost sales), supplier capacity is unlimited, and drug expiration is not considered.

To clarify the logic of the inventory policies evaluated, they can be categorized into two primary review systems identified during the qualitative phase: periodic and continuous review. For policies involving an order quantity of nQ, this quantity is based on practical pack/batch units such as bottles, boxes, or blister packs. This procurement approach is carried out in standardized batches to facilitate easier distribution to the various Points of Use. Periodic Review Policies: In this system, inventory is checked at fixed time intervals (T). If the stock is at or below a certain threshold, an order is placed. The (s, S, T) Policy: Every review period (T), if inventory is at or below the reorder point (s), a variable-sized order is placed to bring the stock level up to the maximum level (S). The (s, nQ, T) Policy: Like the above, inventory is checked every period (T). If an order is triggered at level s, a pre-defined quantity nQ, based on the pack/batch units described above, is ordered. Continuous Review Policy: In this system, the inventory level is monitored constantly, and an order is placed at any time the reorder point is reached. The (s, nQ) Policy: This policy involves continuous review of inventory levels. An order for a fixed quantity nQ, determined by the pack/batch size, is placed immediately when the stock level drops to the reorder point (s). This framework connects the general formulas for inventory parameters to the specific operational logic of each control policy tested.

Quantitative data for the simulation, including demand patterns and lead times, came primarily from the in-depth case study and were validated by expert interviews. Reorder points (s), maximum stock levels (S), and safety stock (SS) were calculated for each relevant scenario using Equations (1)-(4), with a Z-value of 3.09 for a 99.9% service level target.

$$\text{Reorder points } (s) = (\mu_d * \mu_l) + SS \tag{1}$$

$$\text{Maximum stock } (S) = \mu_d * (\mu_l + t) + SS \tag{2}$$

$$\sigma_{dl} = \sqrt{\mu_l * \sigma_d{}^2 + (\mu_d)^2 \sigma_l{}^2} \tag{3}$$

$$SS = z * \sqrt{\mu_l * \sigma_d{}^2 + (\mu_d)^2 \sigma_l{}^2} \tag{4}$$

Where μ_d is average daily demand, μ_l is average lead time in days, t is review period (Ordering cycle time), SS is safety stock with uncertainty about lead time and demand (independent), σ_d is standard deviation for the demand per day, σ_l is standard deviation of lead time in days and σ_{dl} is standard deviation of demand during lead time. The model simulated a one-year period under the following parameters and assumptions:

- Supplier capacity was assumed to be sufficient to meet all orders.
- Backorders at PoU and CW were tracked and fulfilled upon stock arrival.
- PoU inventory was reviewed every 7 days; CW inventory was reviewed every 30 days (on the first day of the month).

A total of 168 distinct scenarios were simulated. These scenarios were combinations of: the 4 3PL/SPDd models, 3 PoU inventory policies ((s, S, T), (s, nQ, T), (s, nQ)) applied to CW replenishment strategies (where applicable per model), and the unique demand characteristics of the 14 medication types, each with its unique real demand distribution identified from the case study. Table 1 details.

Table 1 Summary of simulation scenario frameworks (as-is and to-be models).

Scenario Category	3PL/SPDd Model Configuration (Roles)	Inventory Control Policy for CW	Lead time for hospitals' external distribution	Lead time for hospitals' internal distribution	Demand Data Source	PoU Inventory Control Policy Options
AS-IS	Model1-H(SPd)+3PL(D)	(s, nQ, T)	Beta	Uniform	Real	(s, S, T)
AS-IS	Model1-H(SPd)+3PL(D)	(s, nQ, T)	Beta	Uniform	Real	(s, nQ, T)
AS-IS	Model1-H(SPd)+3PL(D)	(s, nQ, T)	Beta	Uniform	Real	(s, nQ)
AS-IS	Model2-H(Pd)+3PL(SD)	(s, nQ, T)	Beta	Uniform	Real	(s, S, T)
AS-IS	Model2-H(Pd)+3PL(SD)	(s, nQ, T)	Beta	Uniform	Real	(s, nQ, T)
AS-IS	Model2-H(Pd)+3PL(SD)	(s, nQ, T)	Beta	Uniform	Real	(s, nQ)
***AS-IS**	Model3-H(d)+3PL(SPD)	Managed by 3PL	Beta	Uniform	Real	(s, S, T)
***AS-IS**	Model3-H(d)+3PL(SPD)	Managed by 3PL	Beta	Uniform	Real	(s, nQ, T)
***AS-IS**	Model3-H(d)+3PL(SPD)	Managed by 3PL	Beta	Uniform	Real	(s, nQ)
TO-BE	Model4-3PL(SPDd)	Managed by 3PL	Beta	Managed by 3PL	Real	(s, S, T)
TO-BE	Model4-3PL(SPDd)	Managed by 3PL	Beta	Managed by 3PL	Real	(s, nQ, T)
TO-BE	Model4-3PL(SPDd)	Managed by 3PL	Beta	Managed by 3PL	Real	(s, nQ)

**AS-IS means AS-IS means it is still in the early stages of testing.*

these operational frameworks and how they map to AS-IS and TO-BE situations

Each of the 168 scenarios was replicated 400 times to ensure statistically stable results, with each run simulating a one-year period. The performance of each scenario was evaluated using three key indicators: fill rate (%), order fulfilment (%), and number of backorders. Summary statistics were reported with 95 % confidence intervals to facilitate performance comparison across models. Furthermore, an analysis of variance (ANOVA) was conducted to test whether performance differences among the four 3PL/SPDd models and the associated inventory policies were statistically significant.

3. RESULTS

This study assessed the performance of four 3PL/SPD models to analyze the role of 3PL in conducting SPD activities, both internal and external to the HSC, under various fluctuating demand scenarios. Additionally, three point-of-use inventory policies—S1: (s, S, T), S2: (s, nQ, T), and S3: (s, nQ)—were examined to evaluate their effectiveness across different logistical setups. The results are described in three metrics: fill rates, order fulfillment, and backorder rates, which effectively reflect the workload involved in pharmaceutical inventory management and maintaining healthcare service levels.

Based on the evaluation of the three metrics - fill rate, percentage of orders fulfilled, and percentage of backorders, it has been determined that Model 3, managed by the logistics provider, which handles supply (S), process (P), and external distribution (D), delivers a more appropriate and superior service level compared to the other three models, shown as Table 2.

Considering the criteria of fill rate, order fulfilment, and backorders, Model3-H(d)+3PL(SPD) outperforms all others, achieving approximately 97% fill rate and 95% order fulfilment while keeping backorders below 3%. Model 4 (full 3PL, SPDd) ranks second overall, raising fill rate to ≈ 88 % but still trails Model 3, especially on order fulfilment. Models 1 and 2 (partial 3PL) deliver similar, lower service levels (fill rate ≈ 82–85 %, order fulfilment ≈ 76 %). Across all models, the continuous-review (s, nQ) policy yields the best results; notably, Model 3 with (s, nQ) attains the highest metrics (fill 98.68 %, orders 96.58 %, backorders 1.32 %).

An Analysis of Variance (ANOVA) was conducted to statistically evaluate the impact of the four 3PL/SPDd models and three inventory policies on key performance indicators: fill rate, order fulfilment, and backorders. The results provide strong evidence supporting the selection of an optimal logistics strategy, shown as Table 3.

The most significant finding is that the choice of 3PL/SPDd model has a highly significant effect on all three performance metrics ($p<0.001$ for all cases). The choice of inventory policy also had a statistically significant, albeit smaller, impact on fill rate and backorders ($p=0.045$), but showed no significant effect on order fulfilment ($p=0.606$). This suggests that while fine-tuning the point-of-use inventory policy can provide marginal benefits, its impact is secondary to the overall logistics model structure. Importantly, no significant interaction effect was found between the 3PL/SPDd models and the inventory policies ($p>0.8$ for all metrics). This finding is crucial as it implies that the superior performance of Model 3 is consistent and robust, regardless of which of the three inventory policies is employed at the point of use. In summary, the statistical analysis provides conclusive evidence that Model 3 represents the most effective operational framework among the scenarios tested, offering substantial improvements in service levels compared to other models of 3PL integration.

3.1 Model1-H(SPd)+3PL(D)

Figures 4-6 illustrate the effects of simulating Model1-H(SPd)+3PL(D), which employed inventory policies (s, S, T), (s, nQ, T), and (s, nQ) on medications D11 - D14, exhibiting demand patterns of beta and lognormal distributions. These models achieved service levels approaching 100% across three metrics: fill rate, orders fulfilled, and backorders.

Using the (s, S, T) policy, the vital medication group had an average fill rate of 77.10%, orders fulfilled at 66.01%, and backorders at 22.89%. essential medications showed a fill rate of 74.30%, orders fulfilled at 73.32%, and backorders at 25.70%, while nonessential drugs achieved a fill rate of 93.78%, orders fulfilled at 92.34%, and backorders at 6.22%. Under the (s, nQ, T) policy, vital drugs had a fill rate of 72.71%, orders fulfilled at 60.34%, and backorders at 27.29%. essential drugs showed a fill rate of 70.07%, orders fulfilled at 64.74%, and backorders at 29.93%, and nonessential drugs had a fill rate of 92.78%, orders fulfilled at 90.01%, and backorders at 7.22%. With the

Table 2 Overall performance comparison of four 3PL/SPDd models.

		Fill rate (%)	Order fulfilled (%)	Backorders (%)
Model 1	**Total average**	81.44	75.91	18.56
	(s, S, T)	82.26	**77.50**	17.74
	(s, nQ, T)	79.38	73.16	20.62
	(s, nQ)	**82.69**	77.08	**17.31**
Model 2	**Total average**	84.82	75.89	15.18
	(s, S, T)	85.50	75.02	14.50
	(s, nQ, T)	81.88	74.59	18.12
	(s, nQ)	**87.07**	**78.06**	**12.93**
Model 3	**Total average**	97.47	95.30	2.53
	(s, S, T)	97.46	95.67	2.54
	(s, nQ, T)	96.25	93.65	3.75
	(s, nQ)	**98.68 ***	**96.58 ***	**1.32 ***
Model 4	**Total average**	88.44	83.09	11.56
	(s, S, T)	86.54	**86.54**	13.46
	(s, nQ, T)	85.47	82.93	14.53
	(s, nQ)	**93.29**	79.51	**6.71**

Table 3 Summary of ANOVA results on the impact of 3PL/SPDd models and inventory policies.

Metric	Factor(s) Analyzed	*F*	*P-value*	Significant	Key Finding / Best Performer(s)
Fill Rate (%)	1. 3PL/SPDd Models	20.41	< 0.001	Yes	Model 3 is significantly superior (Avg. 97.5%)
	2. Inventory Policies	3.15	0.045	Yes	Policy choice has a significant, but smaller, impact.
	3. Interaction (Model × Policy)	0.37	0.897	No	The effect of the model is consistent across all policies.
Order Fulfillment (%)	1. 3PL/SPDd Models	17.62	< 0.001	Yes	Model 3 is significantly superior (Avg. 95.3%)
	2. Inventory Policies	0.5	0.606	No	Policy choice has no significant impact.
	3. Interaction (Model × Policy)	0.4	0.878	No	The effect of the model is consistent across all policies.
Backorders (%)	1. 3PL/SPDd Models	20.41	< 0.001	Yes	Model 3 is significantly superior (lowest avg. at 2.5%)
	2. Inventory Policies	3.15	0.045	Yes	Policy choice has a significant, but smaller, impact.
	3. Interaction (Model × Policy)	0.37	0.897	No	The effect of the model is consistent across all policies.

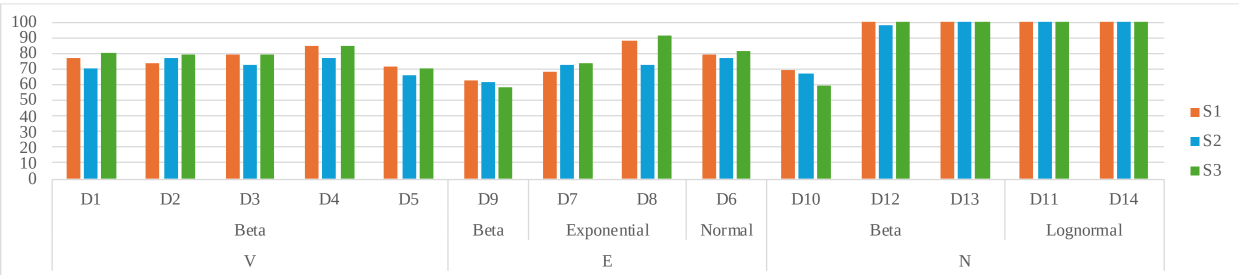

Figure 4 Percentage of fill rate of model 1.

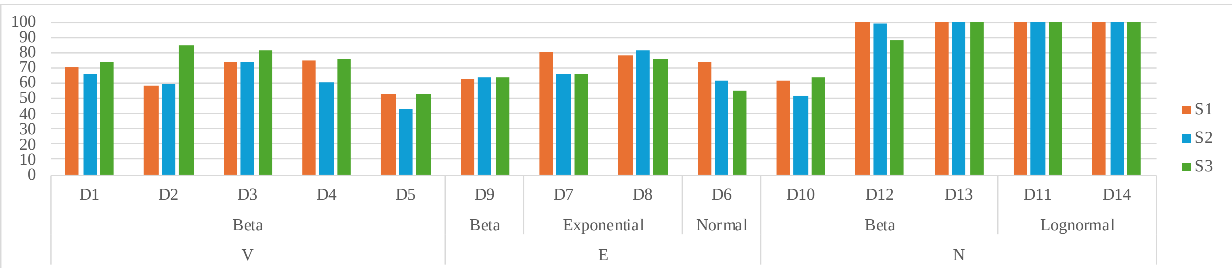

Figure 5 Percentage of order fulfilled of model 1.

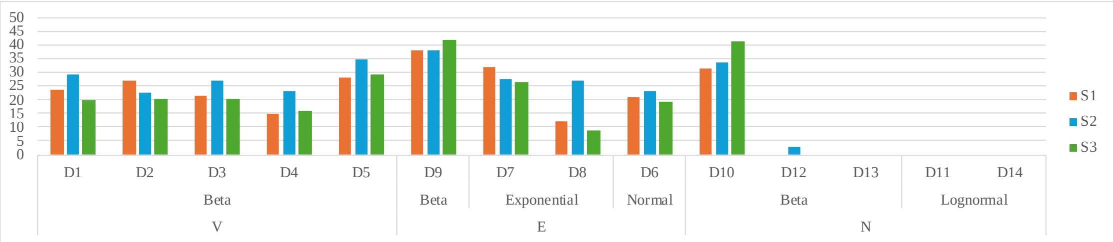

Figure 6 Percentage of backorders of model 1.

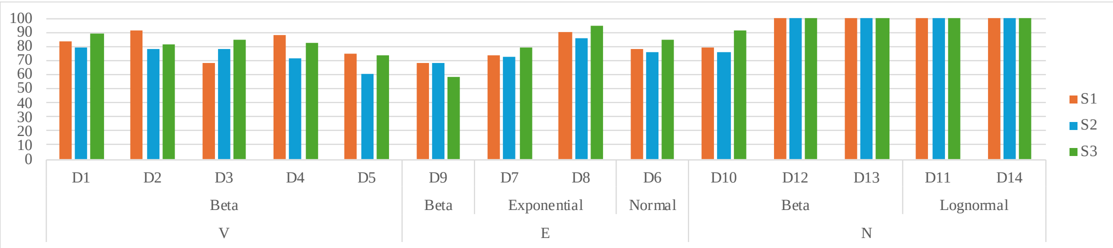

Figure 7 Percentage of fill rate of model 2.

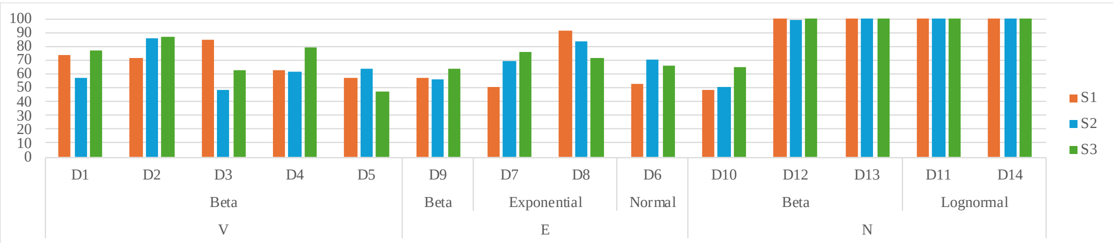

Figure 8 Percentage of order fulfilled of model 2.

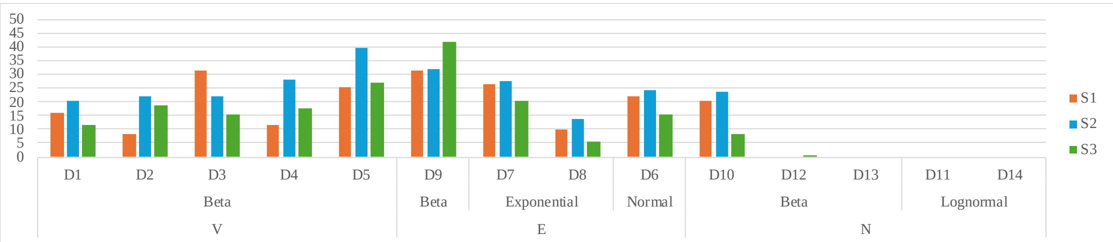

Figure 9 Percentage of backorders of model 2.

(s, nQ) policy, vital medications had a fill rate of 78.86%, orders fulfilled at 73.74%, and backorders at 21.14%. essential medications showed a fill rate of 76.09%, orders fulfilled at 64.84%, and backorders at 23.92%, while nonessential medications had a fill rate of 91.80%, orders fulfilled at 90.21%, and backorders at 8.20%.

3.2 *Model2-H(Pd)+3PL(SD)*

Figures 7-9 illustrate the effects of simulating Model2-H(Pd)+3PL(SD), which employed inventory policies (s, S, T), (s, nQ, T), and (s, nQ) on medications D11 - D14, exhibiting demand patterns of beta and lognormal distributions. These models achieved service levels of 100% across three metrics. Considering the (s, S, T) policy, the vital medication group had an average fill rate of 81.46%, orders fulfilled at 70.14%, and backorders at 18.54%. essential medications showed a fill rate of 77.57%, orders fulfilled at 62.87%, and backorders at 22.44%, while nonessential drugs achieved a fill rate of 95.89%, orders fulfilled at 89.63%, and backorders at 4.11%. The (s, nQ, T) policy, vital drugs had a fill rate of 73.59%, orders fulfilled at 63.34%, and backorders at 26.41%. essential drugs showed a fill rate of 75.67%, orders fulfilled at 65.76%, and backorders at 24.33%, and nonessential drugs had a fill rate of 95.24%, orders fulfilled at 89.81%, and backorders at 4.76%. With the (s, nQ) policy, vital medications had a fill rate of 82.06%, orders fulfilled at 70.16%, and backorders at 17.94%. essential medications showed a fill rate of 79.32%, orders fulfilled at 69.29%, and backorders at 20.69%, while nonessential medications had a fill rate of 98.29%, orders fulfilled at 92.99%, and backorders at 1.71%.

3.3 *Model3-H(d)+3PL(SPD)*

Figures 10-12 illustrate the effects of simulating Model3-H(d)+3PL(SPD), which employed inventory policies (s, S, T), (s, nQ, T), and (s, nQ) on medications D11 - D14, exhibiting demand patterns of beta and lognormal distributions. These models achieved service levels of 100% across three metrics.

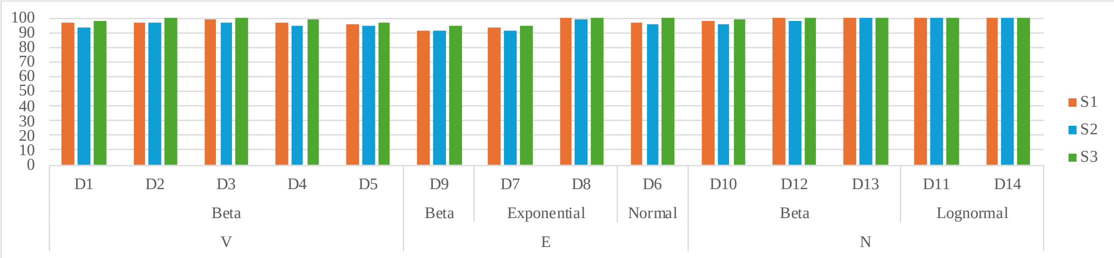

Figure 10 Percentage of fill rate of model 3.

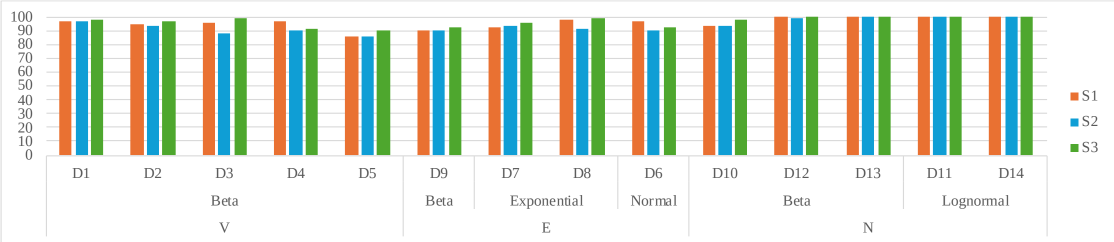

Figure 11 Percentage of order fulfilled of model 3.

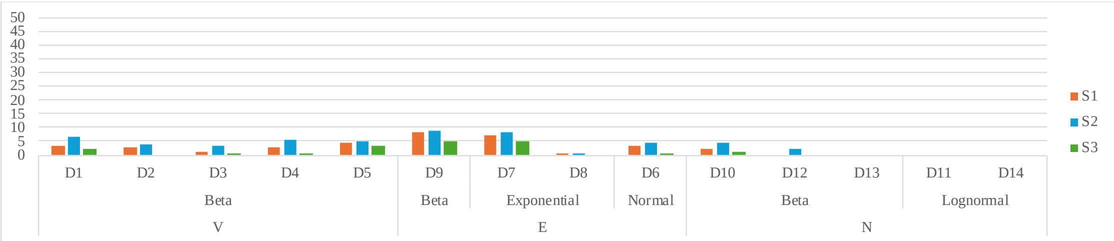

Figure 12 Percentage of backorders of model 3.

Considering the (s, S, T) policy, the vital medication group had an average fill rate of 97.08%, orders fulfilled at 93.82%, and backorders at 2.92%. essential medications showed a fill rate of 95.39%, orders fulfilled at 94.23%, and backorders at 4.61%, while nonessential drugs achieved a fill rate of 99.50%, orders fulfilled at 98.67%, and backorders at 0.50%. Under the (s, nQ, T) policy, vital drugs had a fill rate of 95.22%, orders fulfilled at 90.89%, and backorders at 4.78%. essential drugs showed a fill rate of 94.69%, orders fulfilled at 91.57%, and backorders at 5.31%, and nonessential drugs had a fill rate of 98.73%, orders fulfilled at 98.42%, and backorders at 1.27%. With the (s, nQ) policy, vital medications had a fill rate of 98.65%, orders fulfilled at 95.04%, and backorders at 1.35%. essential medications showed a fill rate of 97.41%, orders fulfilled at 94.75%, and backorders at 2.60%, while nonessential medications had a fill rate of 99.73%, orders fulfilled at 99.59%, and backorders at 0.27%.

3.4 Model4-3PL(SPDd)

Figures 13-15 illustrate the effects of simulating Model4-3PL(SPDd), which employed inventory policies (s, S, T), (s, nQ, T), and (s, nQ) on medications D11 and D13, categorized as nonessential and exhibiting beta and lognormal demand distributions. These models achieved service levels of 100% across three metrics.

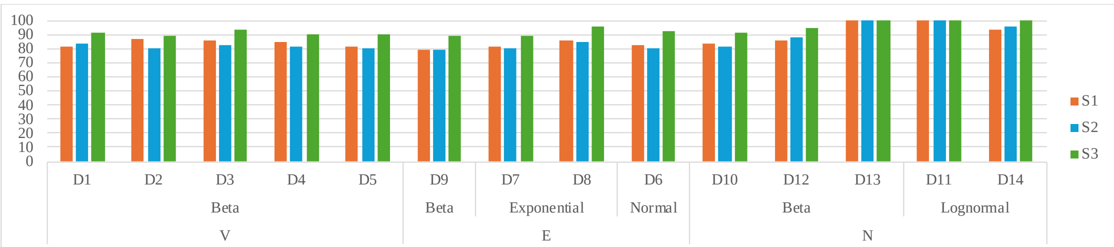

Figure 13 Percentage of fill rate of model 4.

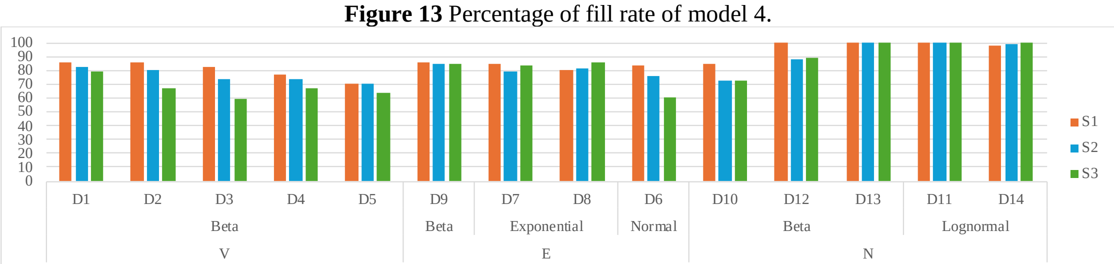

Figure 14 Percentage of order fulfilled of model 4.

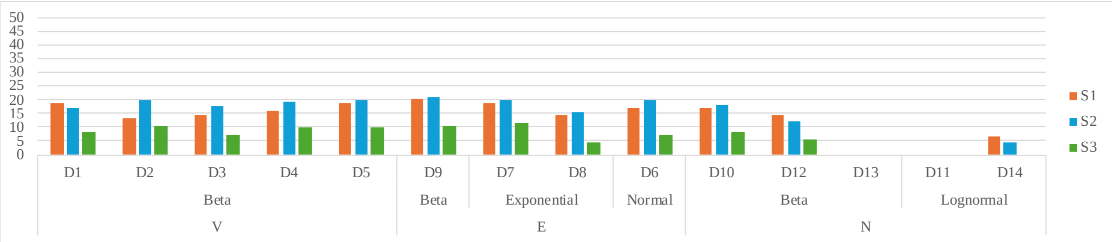

Figure 15 Percentage of backorders of model 4.

Considering the (s, S, T) policy, the vital medication group achieved an average fill rate of 83.92%, orders fulfilled at 80.27%, and backorders at 16.08%. Essential medications showed a fill rate of 82.43%, orders fulfilled at 83.57%, and backorders at 17.57%, while nonessential drugs reached a fill rate of 92.46%, orders fulfilled at 96.02%, and backorders at 7.54%. Under the (s, nQ, T) policy, vital drugs had a fill rate of 81.46%, orders fulfilled at 76.02%, and backorders at 18.54%. Essential drugs showed a fill rate of 81.10%, orders fulfilled at 78.80%, and backorders at 18.90%, and nonessential drugs had a fill rate of 93.09%, orders fulfilled at 91.92%, and backorders at 6.91%. With the (s, nQ) policy, vital medications had a fill rate of 90.79%, orders fulfilled at 67.34%, and backorders at 9.21%. Essential medications showed a fill rate of 91.55%, orders fulfilled at 78.63%, and backorders at 8.45%, while nonessential medications had a fill rate of 97.18%, orders fulfilled at 92.39%, and backorders at 2.82%.

In summary, the simulation results, validated by statistical analysis, consistently identify Model3-H(d)+3PL(SPD) as the most effective operational framework. This model, which outsources core logistics functions (Supply, Processing, external Distribution) while retaining hospital control over internal distribution, significantly outperforms all other configurations in raising service levels and minimizing stockouts. The analysis further reveals that the choice of the overarching logistics model is a more critical determinant of performance than the specific point of use inventory policy, providing a clear strategic direction for hospitals seeking to optimize their supply chain.

4. DISCUSSION

This study's findings provide significant insights into the optimization of hospital supply chains through 3PL/SPD integration, confirming some existing theories while also extending them into the specific context of Thailand's tertiary healthcare system. The statistical analysis conclusively demonstrated that the choice of the overarching logistics model is a more critical determinant of performance than the specific point-of-use inventory policy. Specifically, Model 3, a hybrid approach that outsources core SPD functions to a 3PL while the hospital retains control over internal distribution, emerged as the most effective framework for enhancing service levels under demand uncertainty.

These results both support and refine previous research on SPD systems. While early studies in Japan and Canada established the SPD model's effectiveness in cost reduction (Dembińska-Cyran, 2005), and subsequent work in China highlighted efficiency gains from integrating information systems (Liu *et al.*, 2016; Yang *et al.*, 2019), our study advances this understanding by demonstrating that a hybrid implementation (Model 3) is superior to both partial integration (Models 1 and 2) and full outsourcing (Model 4). This aligns with the principle of maintaining a balanced approach to 3PL integration, as advocated in the literature, which emphasizes the necessity of hospital oversight to ensure service quality and alignment with patient care priorities (Hossain *et al.*, 2023; Volland *et al.*, 2017). Our findings suggest that the "sweet spot" for 3PL integration lies in leveraging external expertise for complex, large-scale logistics while preserving internal control over the final, patient-facing "last mile" distribution within the hospital.

Furthermore, this research contributes to the literature by validating these models under more realistic demand conditions. Unlike previous studies that often assumed demand follows standard Normal or Poisson distributions (Saha and Ray, 2019; Vahdani *et al.*, 2023), our use of Beta, Lognormal, and Exponential distributions, fitted from real-world hospital data, provides a more robust test of the models' resilience to high variability. The consistent superiority of Model 3 across these diverse demand patterns underscores its robustness as a strategic choice for hospitals facing unpredictable environments, a common challenge in the Thai public healthcare system. This addresses a critical gap identified by Senarak and Kritchanchai (2020), who called for more analysis of SPD models within the specific context of Thailand's healthcare network. Conversely, the underperformance of the other models provides valuable insights into the pitfalls of both insufficient and excessive outsourcing. The moderate service levels of Models 1 and 2 suggest that partial 3PL integration, while beneficial, may still suffer from fragmented processes and communication gaps between the hospital's internal team and the external provider. On the other hand, the high variability and struggles of Model 4, particularly with vital medications, highlight the inherent risks of full outsourcing. This may be explained by the concept of information asymmetry, where a 3PL provider, despite its logistical expertise, may lack the nuanced, real-time clinical priority information that is critical within a hospital. This finding underscores the idea that for mission-critical supply chains, relinquishing complete control can introduce vulnerabilities that outweigh the benefits of operational efficiency (Ni, *et al.*, 2024; Wang *et al.*, 2025).

In essence, the findings strongly suggest that while 3PL involvement is beneficial, the degree of integration is paramount. The hybrid approach of Model 3 provides a promising and resilient framework by creating a synergistic partnership: the hospital dictates clinical needs and manages patient-facing activities, while the 3PL executes the complex, non-clinical logistics tasks. This model offers high service levels while mitigating the risks associated with both fragmented operations and a complete loss of internal control, serving as a benchmark for hospitals seeking to optimize their supply chain through 3PL partnerships.

5. CONCLUSION

This study addressed the critical challenge of managing hospital pharmaceutical supply chains under demand uncertainty by quantitatively evaluating four distinct 3PL/SPD integration models. The research provides conclusive evidence that a hybrid model, where core logistics functions are outsourced while the hospital retains control over final internal distribution (Model 3), represents the most effective framework for enhancing service levels. Crucially, the findings highlight that the strategic design of the overall logistics operating model is a more critical determinant of performance than the specific point-of-use inventory policy. This offers a clear, data-driven direction for hospital administrators: the optimal approach to improving supply chain resilience lies in creating a synergistic partnership with logistics experts, rather than pursuing partial or full outsourcing. Ultimately, this research underscores that aligning a well-designed logistics framework with core healthcare objectives is fundamental to mitigating supply chain risks and ensuring excellent patient care.

5.1 Practical and Policy Implications

The study's insights are instrumental for policymakers and healthcare administrators. The superior performance of Model 3 provides a clear, data-driven recommendation: fostering hybrid logistics models through strategic partnerships offers the most promising path to improving service levels and inventory management efficiency. Policies should encourage collaborations that allow hospitals to leverage 3PL expertise in procurement and large-scale distribution while empowering them to manage internal logistics that are closely tied to direct patient care. Additionally, the finding that inventory policies have a statistically significant, albeit secondary, impact suggests that hospitals should adopt flexible inventory management strategies tailored to medication type and demand patterns, rather than a one-size-fits-all approach.

5.2 Limitations and Future Research

The primary limitation of this study is its reliance on a simulated environment based on a single case study, which may not fully capture all the complexities of real-world hospital settings. Although multiple drug types and demand patterns were considered, the findings' generalizability could be enhanced by including more diverse hospital contexts. Therefore, future research should aim to validate these findings through implementation in multiple hospital settings. Comparative studies between simulated outcomes and actual performance post-implementation would be invaluable. Further research could also expand the scope to include additional performance metrics, such as cost-benefit analysis and the impact on medical staff workload, to provide a more holistic assessment of these 3PL/SPD models.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENTS

Data are available upon request from the corresponding author.

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