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Optimizing Pharmaceutical Supply Chain Configuration in Primary Healthcare: A Mathematical Modeling and Decision Support Approach

Manal AlZaidan[1,2], Majed Hadid[1], Regina Padmanabhan[1] and Laoucine Kerbache[1,*]

[1]Division of Engineering Management and Decision Sciences, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar.
[2]Primary Health Care Cooperation, Doha, Qatar.

[*]Corresponding author. Email address: lakerbache@hbku.edu.qa

Abstract

This research project aims to determine the optimal warehouse location allocation for medication distribution to ensure efficient and cost-effective pharmaceutical supply chain management. It also aims to make significant contributions to pharmaceutical inventory management and supply chain resilience while providing a tangible and practical solution for improving patient care in public health centers in Qatar. The paper presents a Mixed-Integer Linear Programming (MILP) model for strategically allocating warehouse locations in a pharmaceutical supply chain, designed to minimize the total operational costs while satisfying regional medication demands. Results demonstrated that a centralized warehouse in the West region, which has the highest number of health centers, offers the most cost-effective solution, indicating reduced transportation costs and improved distribution efficiency over decentralized alternatives. The optimal configuration results in significant cost savings and heightened operational efficiency, affirming the strategic advantage of aligning warehouse location with healthcare demand concentration. The expected impacts of the project extend to both practical and scientific realms. From a practical perspective, the project outcomes will enhance the quality of patient care by improving accessibility to medications, reducing the burden on pharmacies, and reducing cost and efficiency.

Keywords: Pharmaceutical Supply Chain, Warehouse Location, Mixed-Integer Linear Programming, Optimization, Medications.

1. Introduction, Background and Motivation

Ensuring access to medicine as a fundamental human right is a crucial goal within healthcare systems. The pharmaceutical supply chain should deliver medications in appropriate quantities, meet acceptable quality standards, reach the correct destinations and customers, adhere to timely schedules, and optimize costs. This alignment is essential to upholding the health system's objectives.

The pharmaceutical supply chain represents a substantial portion of healthcare expenditure globally (OECD, 2023). Logistics costs contribute significantly to the overall pharmaceutical supply chain costs (Landry & Philippe, 2004). In Qatar, healthcare spending is among the highest in the region despite the country's small population size (Abdel Rida et al., 2019). The healthcare market in Qatar was valued at QAR 22 billion (USD 6.04 billion) in 2020, accounting for 4.18% of GDP, with per capita healthcare spending ranking among the highest in the region at USD 1,781 (The World Bank, 2020). The government predominantly finances healthcare, covering 79.9% of healthcare expenditure (SEV, 2021).

Hamad Medical Corporation (HMC) and the PHCC are Qatar's leading pharmaceutical items providers (Qatar Development Bank, 2021). While HMC manages public coverage of pharmaceutical items, the PHCC procures all medications from HMC and relies on HMC's warehouse for storage and distribution to its health centers (HCs). Through collaborative discussions between academia and healthcare providers, it has become evident that the current pharmaceutical supply chain model presents challenges and impacts clinical care outcomes in the HCs. To address these issues, innovative solutions and research-based management practices are needed. The PHCC's 31 health centres (HCs) receive many pharmaceutical items each year, delivered directly from HMC. These items, valued at an estimated cost of 400 million QAR, consist of approximately 12 million items dispensed to patients per year, with more than 700 unique medication items listed under the medication formulary in PHCC.

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The HCs, located in the Central (C), Western (W), and Northern (N) regions, offer a wide range of healthcare services (PHCC, n.d.). Among the 31 health centers, three health center pharmacies obtained medications from Al-Wakra Hospital's main store, while four health center pharmacies received medications from Al-Khor Hospital. The remaining health center pharmacies acquired medications from the HMC main warehouse in the industrial area's free zone. HMC manages the distribution of medications via the Enterprise Resource Planning (ERP) system, while PHCC lacks an ERP system. PHCC pharmacies use the electronic medical records system Cerner® to request medications from HMC. Cerner® is an Electronic Medical Record system that lacks supply chain capabilities.

However, the current supply chain network configuration poses significant challenges that substantially impact clinical care outcomes. These challenges include, but are not limited to, stockouts, procurement of medications with short expiry dates (sometimes two weeks), and pharmaceutical items waste. The preliminary brainstorming and analysis concluded that the (ERP) and the Warehouse Management System (WMS) need to be revised to cut logistics costs, increase responsiveness and availability of pharmaceutical items, and implement innovative solutions.

Therefore, The PHCC is required to develop a supply chain strategy that is in line with the PHCC business strategy and to modify its supply chain design and configuration to include a dedicated network of single or multiple warehouses that will manage pharmaceutical services, including operations, inventory management, management of stores of HCs, and logistics services to standardize and adequately manage the pharmaceutical stock delivered from HMC's warehouse.

By taking a scientifically rigorous approach, our research aims to determine the optimal warehouse location allocation for medication distribution to ensure efficient and cost-effective pharmaceutical supply chain management. It also aims to make significant contributions to pharmaceutical inventory management and supply chain resilience while providing a tangible and practical solution for improving patient care in public health centers in Qatar.

2. Literature Review

Healthcare logistics and supply chain management have been extensively studied (Dixit et al., 2019). However, gaps still need to be in understanding pharmaceutical supply chain management, especially downstream activities such as storage and distribution (Ageron et al., 2018). The complex nature of the supply chain leads to inefficiencies, delays, and increased costs, negatively impacting clinical outcomes. Bridging these gaps and enhancing knowledge is crucial. This paper aims to investigate the "n-warehouses n-retailers" problem in the context of primary healthcare centers, addressing gaps highlighted by Peng et al. (2022). Compared to other contexts, there is limited research on this specific problem, with only 58 journal articles in Scopus. Fifty-eight articles were identified by search results of Warehousing of Pharmaceutical items: TITLE-ABS-KEY (*wareho* AND (*pharma* OR *drug* OR *medic*)) AND (LIMIT-TO (SUBJAREA , "DECI")) AND (LIMIT-TO (DOCTYPE , "ar")).

While 2,766 articles were identified by search results of Warehousing in other contexts TITLE-ABS-KEY (wareho ANDNOT (pharma OR drug OR medic)) AND (LIMIT-TO (SUBJAREA , "DECI")) AND (LIMIT-TO (DOCTYPE , "ar")). The 58 articles found by the search query were scanned, and only three relevant journal articles were found. The low number of articles highlights the research gap in considering the 'n-warehouses n-retailers' problem in the context of pharmaceutical items. Therefore, this paper makes a unique and significant contribution to new knowledge by studying the 'n-warehouses n-retailers' problem for pharmaceutical items and developing tailored models.

While some studies, such as those by Singh et al. (2018), Hasani et al. (2015), and Ahmadi et al. (2022), have included the perishability of products in their studies, their work was limited to a single decision, single-product, or different parts of the supply chain than the one addressed by this project. (El Mokrini et al., 2018) studied distribution network redesign but did not investigate warehouse capacity limitations. While the work of (Parvin et al., 2018) is relevant to this direction, their proposed model is limited to a single product for a seasonal disease. Moreover, more studies must be conducted on the resilience of the pharmaceutical items network.

A study by (Delfani et al., 2022) illustrated that incorporating logistics and multi-modal transportation options, and utilizing multiple echelons for medication transfer, processing, and distribution, holds significant potential for enhancing overall system value, moreover , they did not compare with other decision making methodologies. (Mabizela et al., 2023) (Mabizela et al., 2023) highlighted significant challenges in inventory management, particularly medication shortages, overstocking, and expiry-related wastage. This underscores the urgent need for more research in the area of inventory management systems.

A study by (Parvin et al., 2018) aimed to integrate strategic-level and tactical-level models to optimize medication distribution within a centralized health system. This would manage demand uncertainty and enhance medication accessibility, reducing medication shortages and transportation costs. The study emphasized that employing a two-stage stochastic programming model followed by a Markov decision process at a tactical level, informed by strategic-level solutions, can optimally manage pharmaceutical distribution.

In another study (Janatyan et al., 2018), they explored the design of the distribution network between a main distribution center and the local distribution centers, yet their model was tested for only one drug. On the other hand, Abbasi et al. (2021) studied a reliable four-level hub location network for a 3PL company for perishable products; however, they did not consider other variables, such as transportation and uncertain demand.

3. Materials and Methods

Data collection: The study utilized one-year estimated data for 22 health centers, distributed across three regions: Western, Central, and Northern. The breakdown of the health centers, the quantity of medications ordered, their associated costs, and the fixed costs for establishing warehouses are presented in Table 1.

Region	No. Health Centers	No. of ordered QTY of medications (12 months)	Price of medications ordered (12 months)- QR	Fixed cost for establishing a warehouse
Western	10	37086	503,784.09	195,000
Central	7	26136	327,677.39	220,000
Northern	5	26940	302,453.15	200,000
Total	22	90162	1,133,915	-

Table 1. Estimated data for medications' quantities and prices for 22 months.

The transportation data between the warehouses for the three regions is summarized in Table 2. The units represent the transportation costs between different regions.

Region	Western (Unit)	Central (Unit)	Northen (Unit)
Western	1.5	2	3
Central	3	1.25	2.5
Northen	4	2.5	1

Table 2. Estimated data for transportation between warehouses for 12 months.

Optimization Problem: Warehouse Location Allocation. The optimization problem focuses on determining the optimal warehouse locations to minimize total operational costs while meeting regional medication demands.

Input Parameters:

- CM: Average purchase value of each unit of medicine:11.2 QR
- D_j: Demand for medications in region j, where i can be {W, C, N}.
- F_i : Fixed cost of opening each warehouse i, where i can be {W, C, N}.
- H_i: Holding cost for each warehouse i, where i can be {W, C, N}.

Decision Variables:

Figure 1 illustrates the strategic allocation of warehouse locations and the distribution network for pharmaceutical supplies within primary healthcare centers across three regions: West, Central, and Northern. The design aims to optimize the supply chain by minimizing transportation costs and enhancing distribution efficiency.

- Q_{ij}: Quantity of medications to be shipped from Warehouse i to Region j, where i, j can be {W, C, N}.
- Y_i: Binary decision variable indicating whether Warehouse i is opened ($Y_i = 1$) or not ($Y_i = 0$).

Objective function: is to minimize the total cost

C total = $C1 + C2 + C3 + C4$

where,

$C1 = CM \cdot \sum_{i\in\{W,C,N\}}\sum_{j\in\{W,C,N\}} Q_{ij}$ (Medication cost)

$C2 = \sum_{i\in\{W,C,N\}} \sum_{j\in\{W,C,N\}} T_{ij} \cdot Q_{ij}$ (Transportation cost)

$C3 = H \cdot CM \cdot \sum_{i,j\in\{W,C,N\}} Q_{ij}$ (Inventory holding cost)
H = 0.3

$C4 = \sum_{i\in\{W,C,N\}} F_i \cdot Y_i$ (Fixed costs)

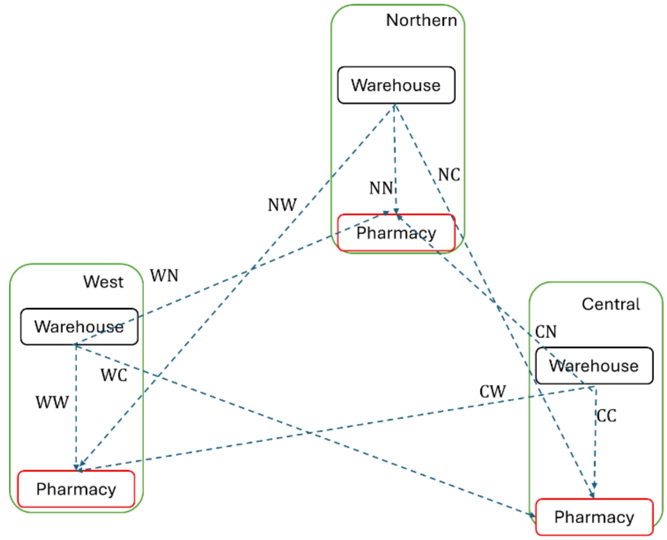

Figure 1. Decision variables.

Constraints:

1. Demand fulfilment constraint:

   $\sum_{i \in \{W,C,N\}} Q_{ji} Y_i = D_j$ for $j \in \{W,C,N\}$

2. Scenario 1: At least one warehouse selection constraint:

   $\sum_{i\in\{W,C,N\}} Y_i > 1$

3. Scenario 2: Each region has a warehouse constraint:

   $\sum_{i\in\{W,C,N\}} Y_i = 3$

4. Non- negativity constraints:

   $Q_{ji} \geq 0$ for all i,j

Model Formulation: This optimization problem was formulated within the framework of a Mixed-Integer Linear Programming (MILP) model, employing the Gurobi Optimizer interface in Python (gp).

4. Results and Discussion

Figure 2 represents the cost comparison of different warehouse configurations, which concluded that locating a centralized warehouse in the western region is the optimal solution with an optimal objective value of 1696479.7 (Figure 2). Figures 4 and 5 represent the other warehouse's cost in the northern and central regions with optimal objective values of 1753382.2

The scenario of the decentralized warehouses per the regions was more expensive, with an optimal objective value of 2042997.7. (Figure 6)

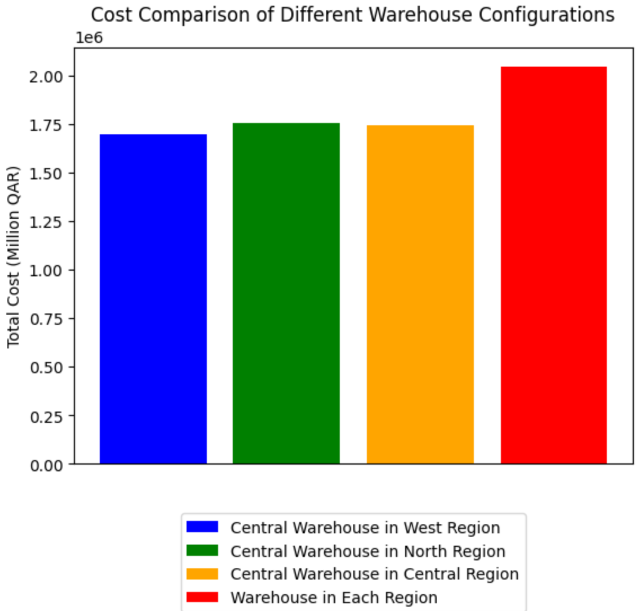

Figure 2. Cost comparison of different warehouse configuration.

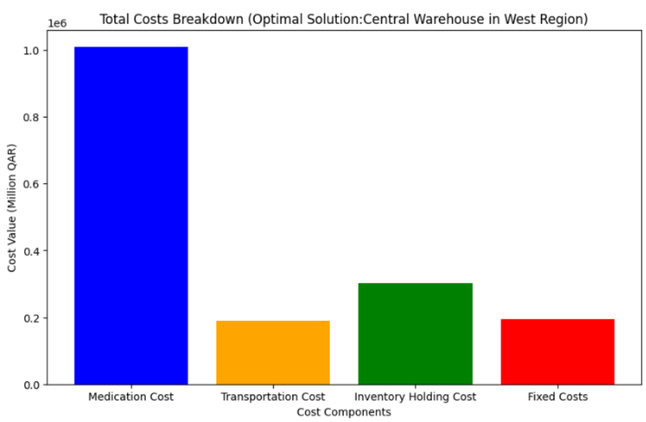

Figure 3. The optimal solution: Total costs breakdown of the central warehouse in western region.

Our solution for a central warehouse in the West region configuration is identified as the optimal solution, particularly due to the strategic placement relative to the region's high concentration of healthcare centers. With the West region housing the highest number of health centers at 10, compared to 7(central) and 5 (northern), the central warehouse positioning capitalizes on proximity to these centers, yielding reduced transportation costs and more efficient distribution networks.

The aggregation of medication, transportation, inventory holding, and fixed costs presents a favorable economic profile for this solution. The minimized transportation costs reflect the reduced distances and logistics complexities associated with servicing a greater number of healthcare centers within a shorter radius. This proximity allows for more responsive supply chain operations, aligning inventory holding costs with actual demand patterns and minimizing the risk of overstocking or stockouts.

Fixed costs, while non-negligible, are offset by the gains in operational efficiencies and the potential for bulk procurement and inventory economies. The overall cost structure suggests that the benefits of centralizing the warehouse in a region with the densest healthcare network significantly outweigh the associated expenditures, underpinning the rationale for this being the optimal supply chain configuration.

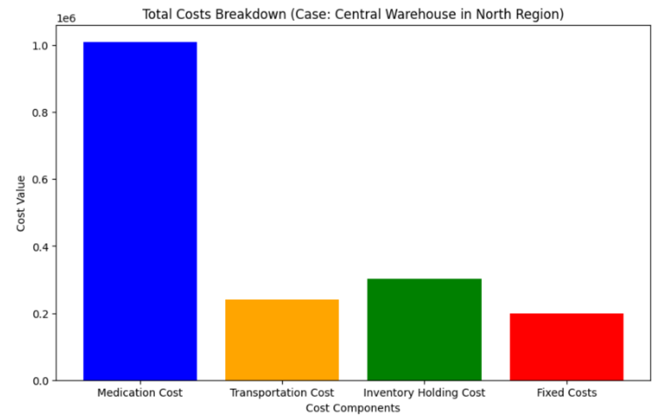

Figure 4. Total costs breakdown of the central warehouse in the northern region.

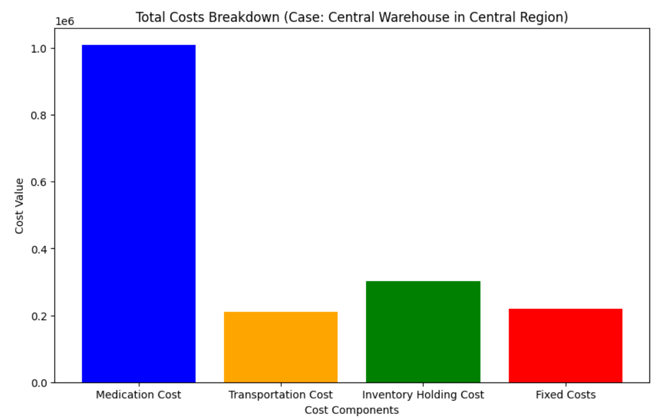

Figure 5. Total costs breakdown of the central warehouse in the Central region

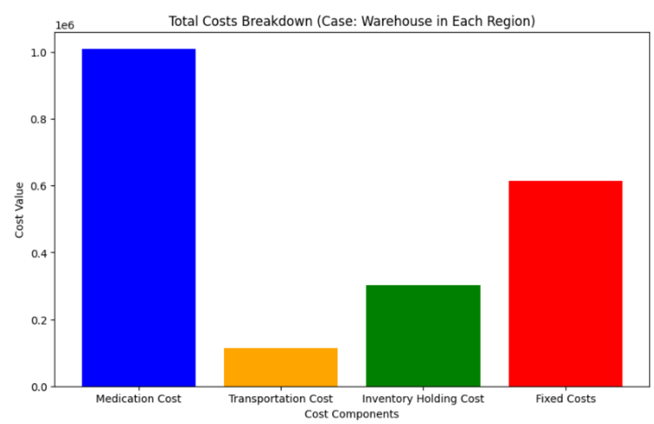

Figure 6. Total costs breakdown of warehouse in each region.

Efficient and reliable medication distribution is paramount to ensuring high-quality patient care. By optimizing the supply chain, pharmacies can maintain adequate stock levels, reducing patient waiting times and ensuring the timely availability of essential medications. This contributes to better health outcomes and increased patient satisfaction.

The optimization of the pharmaceutical supply chain configuration extends beyond mere cost analysis, necessitating a holistic

assessment that considers service quality, responsiveness to demand, and regional consumption patterns. Future research should integrate a multi-criteria decision-making framework that encapsulates quantitative cost factors and qualitative service-related parameters to determine the optimal supply chain configuration.
The limitation of this study is that the data was estimated to practice modeling and optimization to prepare for a broader study with real data. While the model provides a theoretically optimal solution, practical implementation may encounter challenges such as logistical constraints, regulatory requirements, and infrastructural limitations. Ensuring seamless integration of the optimized supply chain with existing systems requires careful planning and coordination. The successful implementation of the proposed model relies heavily on advanced technological solutions, such as electronic health records (EHR), ERP systems, and automated dispensing systems. Ensuring the interoperability and integration of these technologies across different regions and healthcare centers is crucial for achieving the desired efficiency gains.
For future research directions, While the MILP model provides a robust framework, exploring alternative optimization models and decision-support systems like simulation approaches could offer additional insights to enhance the resilience and efficiency of the supply chain.

5. Conclusions

The configuration of the pharmaceutical supply chain in a healthcare system is crucial to optimizing patient care and outcomes. This study provides valuable insights into optimizing the pharmaceutical supply chain in Qatar, demonstrating the potential for significant cost savings and improved healthcare delivery through strategic warehouse location-allocation. The findings contribute to the broader pharmaceutical inventory management and supply chain resilience field, offering practical solutions for improving patient care in public health centers. Our study will contribute to improving pharmaceutical supply chain systems and strategies by using a mathematical approach and decision science.

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