A tailored aggregation strategy for inventory pooling in healthcare: Evidence from an emerging market

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Abstract

Pharmaceutical consumption in hospitals and healthcare centers is characterized by demand uncertainty, particularly during unusual events, e.g., pandemics and other crises. Unlike other industries, healthcare management has been slow in implementing effective business logistics concepts, e.g., inventory pooling, i.e., aggregation, and extant literature on this topic is scant. Inspired by a public pharmaceutical supply chain, this study aims to investigate the feasibility and relevance of hospitals and other health care facilities collaborating through inventory pooling. While important savings could be achieved through aggregation, this strategy comes at a cost. In this study, we present a model that captures the costs of inventory pooling in an emerging market setting to find the optimal tailored aggregation, set of demand points, and products to aggregate so that inventory pooling costs and savings are balanced. The problem has been formulated as a mixed-integer conic quadratic program to minimize the total cost of pooling and hold safety stocks in the supply network, subject to budget constraints. We applied the proposed model to a real case study of pharmaceutical distribution in Morocco and analyzed inventory pooling schemes under different budget allocations to investigate how regional and product disparities affect costs and inventory pooling decisions. The findings reveal that when changing the pooling budget, the best customized aggregation varies substantially and is influenced by product type, regional population density, income per capita, and urbanization rate.

Keywords— inventory pooling, healthcare supply chain, safety stocks, pharmaceuticals, emerging market

1 Introduction

In supply chain management, inventory pooling refers to individual demand and/or lead time variabilities being consolidated through aggregation to lower total variability produced and, thus, uncertainty

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and risk (Oeser, 2015). It is a substantial approach to control inventory under uncertainties because it allows organizations to achieve economies of scale by centralizing goods at a single location, contributing to improved productivity (Chopra and Meindl, 2016). The efficient setting of safety stocks and inventory pooling also has been demonstrated to yield significant savings in general supply chains (Ghadimi and Aouam, 2021; Aouam et al., 2021). Inventory pooling can be performed physically, through actual consolidation of goods, or virtually. The latter option has received significant attention in recent years with the advancement of information and communication technologies because it enables a location within an organization to monitor and use other sites' inventory within the organization if a stockout occurs through transshipments. Despite its proven success and efficacy in different sectors and industries (Berman et al., 2011; Schmitt et al., 2015; Yang et al., 2021), inventory pooling rarely has been investigated and applied to the healthcare sector (Wu et al., 2015; Strozzi et al., 2019). Healthcare decision-makers usually have experience in medicine, politics, or human resource management while lacking expertise in supply chain management practices (Kelle et al., 2012; Beaulieu and Bentahar, 2021). However, now more than ever, they need to increase performance and build mechanisms that support effective operations while also rationally utilizing limited resources (Queiroz et al., 2020). Therefore, some studies in the literature have developed decision-support tools to optimize distribution networks and logistics functions in healthcare settings (El Mokrini and Aouam, 2022). Sharing inventory in healthcare potentially can allow decision-makers to amass significant savings that can be allocated toward significant health challenges and needs (Ramanathan, 2014; Rojas et al., 2021). Aside from savings, inventory pooling also can hedge the high rate of expired products that are not consumed and consequently discarded (Saedi et al., 2016). However, pooling comes at a cost, which needs to be quantified to assess actual savings. Pooling costs include setting up and operating an information system, inventory, and transportation management. Quantifying these costs also is important because public organizations, particularly in emerging or developing economies, are reluctant to allocate funds for such expenses despite the savings they can provide.

Based on the literature, several studies have presented models that demonstrate the benefits of inventory pooling in healthcare or other sectors (Oeser and Romano, 2021). However, very few studies have discussed the trade-off between inventory cost reductions and additional logistics costs. The literature reveals that most studies have not considered the costs of inventory pooling implementation, failing to quantify and factor them into their models. To the best of our knowledge, no extant studies have provided an approach that quantifies pooling costs and elaborates on a tailored aggregation model to achieve an optimal, cost-efficient scheme. The present study is the first effort to examine pooling costs in an integrated model within a healthcare supply chain. We aimed to answer the following questions: 1) How can we estimate the cost of pooling? 2) To achieve a good balance between savings and pooling costs, how should decision-makers create healthcare pooling schemes and decide which products to select and regions to include? 3) How do pooling budgets, product types, and regional characteristics affect healthcare pooling schemes? To address these questions, this study proposes a tailored aggregation framework in which decision-makers can design a supply chain inventory pooling

scheme that balances inventory pooling costs and savings. This study makes the following contributions to the literature on healthcare inventory pooling. First, we developed an approach for quantifying pooling costs. Second, we developed a tailored aggregation model to achieve an optimal, cost-efficient scheme by integrating pooling costs. Third, the proposed framework was applied to the Moroccan pharmaceutical supply chain as a case study to analyze results and derive managerial insights. The analysis of results obtained from the application of the approach aimed to investigate how regional and product disparities in an emerging market setting affect inventory pooling decisions. Three criteria were considered and included the population's geographical distribution, urban networks' density, and the differential in economic dynamism between regions. When pooling budgets are varied, the results demonstrate that pooling schemes vary widely, influenced by product type and regional characteristics.
The rest of the paper is organized as follows. We first provide a brief review of relevant literature in Section 2 and present our approach in Section 3. The approach's application to the Moroccan pharmaceutical supply chain is examined in Section 4. We discuss the results and implications in Section 5. Finally, we conclude the paper in Section 6, as well as provide recommendations for future research.

2 Literature review

Our research is similar to other studies that have investigated healthcare inventory pooling. In this section, we examine the relevant literature stream and highlight our contribution. The literature reveals that several studies have investigated inventory models with pooling. Schwarz (1989)'s study was one of the first to construct a multi-location inventory model to examine the value of using a warehouse to pool supplier lead time in a high-service-level system. The study concluded that the value of risk pooling depends critically on inventory-holding costs, highlighting the importance of considering the risk-pooling expenses incurred. Bendoly (2004) also highlighted the importance of the trade-offs between inventory holding costs and alternative transportation costs, developing a stochastic inventory pooling model to aggregate inventory and concluding that aggregating online and brick-and-mortar inventory reduces costs. However, these reductions are occurring simultaneously with rising in-store fulfillment unavailability rates and additional coordination and added transportation expenses. Paterson et al. (2011) presented an in-depth survey of inventory pooling papers on lateral transshipments and confirmed that inventory pooling can be practical for decision-makers as a way of improving the system's service level while significantly reducing costs. The authors also concluded that very few papers that have tackled inventory pooling in the literature have considered multiple products, a condition that characterizes real-world cases (Paterson et al., 2011; Oeser and Romano, 2021). Thus, the literature reveals that inventory pooling has been investigated widely by manufacturing and commerce companies as a way to improve inventory policies, reduce holding costs, and create better customer service (Paterson et al., 2011; Farasyn et al., 2011; Villa and Castañeda, 2018).
In healthcare, few studies have investigated inventory pooling for managing pharmaceutical inventory (Jin and Agirbas, 2013; Ahmadi et al., 2019; Oeser and Romano, 2021). Healthcare is viewed as operationally different from other industries because of the nature and characteristics of the products

handled, i.e., managing inventory for pharmaceutical products is particularly critical because medicine shortages contribute to loss of capital and can endanger patients. Nicholson et al. (2004) compared inventory costs and service levels in a healthcare setting comprising an in-house, three-echelon distribution network and an outsourced two-echelon distribution network using simulation modeling. They found that outsourcing with inventory pooling reduces inventory costs while preserving service quality. Bhakoo et al. (2012) investigated how partners in Australian hospital supply chains manage inventory through collaborative agreements, establishing a technique based on semi-structured interviews, site visits, and document inspection based on a case study involving a supply chain network of 10 healthcare institutions. Their study demonstrated that several contingent factors impact the selection of pooling type, including product characteristics, spatial configuration, regulatory environment, and the organization's infrastructure.Wu et al. (2015) proposed two simulation models entailing the whole pharmaceutical supply chain, from drug demand to supply – involving patients, hospitals, distributors, and manufacturers, with and without pooling – to examine the possibility of using inventory pooling in China's public hospitals. The results demonstrate that inventory pooling could be a successful method for improving pharmaceutical supply chain performance in China, particularly reducing stockouts. In another study, Zepeda et al. (2016)Zepeda et al. (2016) analyzed possible moderating impacts of affiliation with multi-hospital systems on inventory costs using data from Californian hospitals. They demonstrated that local lateral emergency supply transshipments between hospitals are preferable to vertical supplier integration, particularly under weak logistics service infrastructure.

Other studies tackled inventory pooling problems in healthcare using optimization approaches. Kumar and Tiwari (2013) provided a methodology that incorporates inventory pooling for both safety stock and cycle inventory, as well as calculates facility location and capacity, to reduce supply chain costs. Their findings indicated that a centralized approach may reduce safety stock and running inventory significantly. Guerrero et al. (2013) described a methodology for determining near-optimal joint inventory management policies in a real-world instance entailing a one-warehouse, n-retailer infusion solution distribution system at a university medical center in France. While incorporating service level as a limitation, the study found that stock-on-hand value is reduced by about 45 percent. Hosseinifard and Abbasi (2018) investigated the value of inventory pooling on the second tier of a blood supply chain and concluded that pooling hospitals' inventory is a key element in improving sustainability and resilience in the blood supply chain. In a subsequent study of the Australian healthcare network, Abbasi et al. (2020) proposed a machine-learning-based technique to tackle the resolution of large operational stochastic optimization problems and applied it to the inventory pooling of blood units. These works are summarized in Table 1. Generally, the literature revealed that research tackling inventory pooling in healthcare generally has focused on developed countries (Hosseinifard and Abbasi, 2018; Abbasi et al., 2020; Oeser and Romano, 2021). Indeed, very few inventory pooling studies have examined emerging markets, including China (Wu et al., 2015), Taiwan (Chou et al., 2014), and Iran (Larimi et al., 2019). Emerging countries function under particular conditions regarding budgets with funds allocated for health incentives, the population's spatial distribution, differences in economic impact, and urban network densities (Dwivedi et al., 2018; Henderson and Turner, 2020; El Mokrini and Aouam, 2022).

Based on the literature, the proposed models demonstrate the benefits of inventory pooling in healthcare or other sectors, but few papers have discussed the trade-off between inventory cost savings and increased logistical expenses. We could not find an approach that quantifies pooling costs and integrates them into an inventory pooling optimization model in an actual healthcare setting. Furthermore, the literature revealed a lack of studies on emerging markets' healthcare inventory pooling.

Our literature investigation concluded that few studies quantified inventory pooling costs and integrated them into a tailored aggregation model. This paper contributes to the healthcare inventory pooling literature in three ways. First, we developed an approach to quantify pooling costs to integrate them subsequently into the proposed pooling model. Second, we developed a tailored aggregation model to achieve an optimal cost-efficient scheme that balances inventory pooling costs and savings. Third, the model was applied to a real case study – the pharmaceutical supply chain in Morocco – to investigate how budget constraints and emerging-market conditions that affect pooling decisions. We provided empirical evidence that inventory pooling leads to actual savings while being affected by product type and regional characteristics.

3 A tailored aggregation framework

3.1 Suggested Approach

This section presents the approach used to develop a tailored aggregation framework for decision-makers to design a supply chain inventory pooling scheme that balances inventory pooling costs and savings. Unexpected demand for pharmaceuticals in emergencies could be supported by an information system that can locate the number of required products in other health centers (demand points) within a certain regional perimeter to be delivered to demand points as emergency shipments (transshipments). Using such a tool, a virtual inventory could be formed comprising products stored in all health centers within the sharing perimeter. In this study's case, a centralized information system was used to consolidate products across health centers virtually, although the physical inventory is separate. The three phases of the approach are described below:

- *Phase 1: Pooling cost quantification.* During the first phase, a methodology for calculating pooling costs is developed (Section 3.3). The first step is to determine the annual fixed cost of implementing pooling in a region, which includes the cost of purchasing and setting up the information system required, asset acquisition for warehousing and transportation, and regional human resources management costs. The second step is to determine the fixed costs of implementing pooling at a demand point for a product, including the cost of inventory and transportation management, as well as the cost of local implementation of the information system required for pooling.

Table 1: Summary of papers on inventory pooling

Reference	Pooling cost quantification	Optimization method	Healthcare	Emerging market
Farasyn et al. (2011)		✓		
Villa and Castañeda (2018)		✓		
Jin and Agirbas (2013)			✓	
Oeser and Romano (2021)			✓	
Nicholson et al. (2004)		✓	✓	
Bhakoo et al. (2012)			✓	
Wu et al. (2015)			✓	✓
Zepeda et al. (2016)			✓	
Kumar and Tiwari (2013)		✓	✓	
Guerrero et al. (2013)		✓	✓	
Hosseinifard and Abbasi (2018)	✓	✓		
Abbasi et al. (2020)		✓	✓	
Chou et al. (2014)		✓	✓	✓
Larimi et al. (2019)		✓	✓	✓
Parvin et al. (2018)		✓	✓	
This paper	✓	✓	✓	✓

- *Phase 2: Determining a tailored aggregation strategy (or pooling scheme).* During this phase, we formulated an optimization model that determines tailored aggregation strategies, i.e., efficient pooling schemes that balance between supply chain inventory holding and pooling implementation costs (Section 3.4). An aggregation strategy identifies the regions that implement pooling, as well as the demand points and products to include in a region's pooling scheme. The model allows a decision-maker to allocate a pooling budget efficiently between regions to benefit from the greatest savings in safety stock costs.

- *Phase 3: Analysis of pooling schemes.* By varying pooling budgets, several pooling schemes can be developed. The model in this study was implemented within the Moroccan pharmaceutical distribution network, and key factors were analyzed to obtain managerial insights. Specifically, pooling schemes for varied budgets were investigated concerning emerging market factors, including population density, income per capita, and urbanization rates.

3.2 Notations

The notations used in the rest of the paper are as follows.

Sets

Θ	set of regions indexed by θ
$\mathcal{K}$	set of demand points indexed k
$\mathcal{P}$	set of products indexed by p
$\mathcal{I}$	set of suppliers indexed by i

Parameters

Inventory pooling parameters

IS_θ	information system cost in region θ
FT_θ	fixed cost of transportation asset acquisition in region θ
HR_θ	human resource cost in region θ
DI_θ	average travel distance within region θ
TT_θ	average travel time within region θ
TT_0	effective annual working time
FL_p	fixed cost of a full truck load annual activity for product p
NP_p	number of items of product p per pallet
C_p	number of items of product p per vehicle (vehicle capacity)
α	cycle service level; $z_\alpha = \Phi(\alpha)^{-1}$ the corresponding inverse standard normal c.d.f.
$\mathcal{L}(z_\alpha)$	standard normal loss value corresponding to z_α
B_{kp}	expected backorder of demand point k for product p
L_{kp}	average lead time in for p
T_{kp}	review period in for p
N_{kp}	number of needed vehicles with capacity C_p to satisfy backorders B_{kp}
IS_{kp}	cost of the information system in demand point k for product p
VT_{kp}	cost of transshipment in demand point k for product p
W_{kp}	handling cost in demand point k for product p
UTC_{kp}	cost of transporting one unit of p
V_{labor}	warehousing labor cost per agent= 2.5* direct labor hourly rate
P_{labor}	labor productivity

Tailored aggregation parameters

D_{kp}	mean demand in k for p
σ_{kp}	standard deviation of demand in k for p
h_p	holding cost of p
b	inventory pooling budget
f_θ	fixed cost of implementing pooling in region θ
$v_{k\theta}$	cost of including demand point k in pooling scheme of region θ
$a_{k\theta}$	equals 1 if demand point k is located in region θ

Decision variables

Y_θ	binary variable equals 1 if pooling is enabled in region θ, 0 otherwise
X_{kp}	binary variable equals 1 if product p in demand point k located in region θ is included in the pooling scheme, 0 otherwise
$Z_{\theta p}$	auxiliary variables, corresponding to the total safety stock of aggregated demand points of product p in region θ

3.3 Quantifying inventory pooling costs

Based on the literature, three main relevant types of costs arise when implementing pooling in a certain location. The first type includes the cost of purchasing, setting up, operating, and maintaining the information system required for pooling (Puga and Tancrez, 2017). The second type deals with the cost of transporting shipments between facilities (Zepeda et al., 2016; Hosseinifard and Abbasi, 2018). The third type represents human resource management costs (Liao and Hsieh, 2009). To quantify inventory pooling costs, we first determined the annual fixed regional cost of implementing pooling, then determined pooling cost implementation at each demand point for each product type.

The annual fixed costs of implementing pooling in the region θ, f_θ, is defined in Equation (1), including the cost of the information system, IS_θ; the transport asset acquisition for transshipments, FT_θ; and the labor cost required to manage pooling operations at the regional level, HR_θ. The fixed transportation cost, FT_θ, is defined in Equations (2 - 4), which were adapted from Ameknassi et al. (2016). It was calculated as the sum of fixed costs; overall demand points, k, within the region ($a_{k\theta} = 1$); and each product, p, required for transshipments within the region, θ. The fixed cost of product p in an individual demand point k was calculated as the fixed cost of one truck, FL_p, multiplied by the number of transshipment trucks, N_{kp}, with a capacity of C_p. The average transshipment inflow of a demand point k is equal to the expected backorder level, B_{kp}, which depends on the target cycle service level, α. Thus, N_{kp} is the number of trucks needed to replenish backorders, B_{kp} , during the annual effective working time, TT_0, as expressed in Equation (3). Also, based on classic inventory theory (see, e.g., Chopra and Meindl (2016)), the expected back-order level, B_{kp}, is provided in Equation (4) for a periodic review of inventory policy, with a review period, T_p, and replenishment lead time, L_p, for each product. Note that in the case of a continuous review, $T_{kp} = 0$. Finally, human resource cost, HR_θ, can be viewed as the cost of annual salaries of regional managers responsible for inventory pooling.

$$f_\theta = IS_\theta + FT_\theta + HR_\theta \qquad \forall\, \theta \in \Theta \tag{1}$$

Where:

$$FT_\theta = \sum_{k\in\mathcal{K}} \sum_{p\in\mathcal{P}} a_{k\theta}.FL_p.N_{kp} \qquad \forall\, \theta \in \Theta \tag{2}$$

$$N_{kp} = \frac{TT_\theta}{TT_0}.\frac{B_{kp}}{C_p} \qquad \forall\, k \in \mathcal{K}, \quad \forall\, p \in \mathcal{P} \tag{3}$$

$$B_{kp} = \mathcal{L}(z_\alpha).\sigma_{kp}.\sqrt{T_p + L_p} \qquad \forall\, k \in \mathcal{K}, \quad \forall\, p \in \mathcal{P} \tag{4}$$

Similarly, we defined the costs of implementing pooling at the level of a demand point k for every product type p, denoted by v_{kp} in Equation (5). v_{kp} is expressed as the summation of the local implementation and operation of the information system cost, IS_{kp}; the cost of transshipments, VT_{kp}; and the handling (labor) cost for the management of warehouse operations, W_{kp}. Based on Ameknassi et al. (2016), we expressed VT_{kp} and W_{kp} in Equations (6) and (7), respectively. The cost of transshipment, VT_{kp}, was computed as the number of annual backorders multiplied by the cost of transportation over an average traveled distance. Handling cost, W_{kp}, is derived by dividing labor cost by labor productivity (assuming 25 pallets per hour inbound and outbound).

$$v_{kp} = IS_{kp} + VT_{kp} + W_{kp} \qquad \forall k \in \mathcal{K}, \quad \forall p \in \mathcal{P} \tag{5}$$

Where:

$$VT_{kp} = a_{k\theta}.B_{kp}.UTC_{kp}.DI_{\theta} \qquad \forall k \in \mathcal{K}, \quad \forall p \in \mathcal{P}, \quad \forall \theta \in \Theta \tag{6}$$

$$W_{kp} = B_{kp}.\frac{V_{labor}}{P_{labor}} \qquad \forall k \in \mathcal{K}, \quad \forall p \in \mathcal{P} \tag{7}$$

$$= B_{kp}.\frac{2.V_{labor}}{25(pallet/hour) * NP_p} \qquad \forall k \in \mathcal{K}, \quad \forall p \in \mathcal{P} \tag{8}$$

3.4 The tailored aggregation model

Although important savings can be achieved trough inventory pooling, the previous section shows that implementing a pooling scheme comes at a cost. To illustrate this, let us compare two extreme cases: one with complete aggregation (maximum pooling) and one with no aggregation (zero or minimum pooling). We assume that demand is independent across locations and products. Under complete aggregation, the total safety stock carrying cost is equal to $\sum_{\theta\in\Theta}\sum_{p\in\mathcal{P}} h_p\Phi^{-1}(\alpha).\sqrt{T_p + L_p}.\sqrt{\sum_{k\in\mathcal{K}} a_{k\theta}.\sigma_{kp}^2}$, while the total cost of implementing pooling is $\sum_{\theta\in\Theta} f_\theta + \sum_{\theta\in\Theta}\sum_{k\in\mathcal{K}}\sum_{p\in\mathcal{P}} a_{k\theta}.v_{kp}$. In this case, pooling is implemented in all regions and all demand points and products are included in the pooling scheme of each region. This results in minimum cost of safety stocks (maximum pooling) and maximum cost of pooling implementation. Under no aggregation, the total holding cost of safety stocks is at its maximum and equals to $\sum_{\theta\in\Theta}\sum_{k\in\mathcal{K}}\sum_{p\in\mathcal{P}} a_{k\theta}.h_p.\Phi^{-1}(\alpha).\sqrt{T_p + L_p}.\sigma_{kp}$, while the pooling implementation cost is equal to zero. Therefore, there is clearly a trade-off between the cost of holing safety stocks in the supply chain and the cost of implementing pooling schemes in the different regions.

We now present an optimization model that determines tailored aggregation strategies, which lie between the two extreme strategies of complete aggregation and no aggregation and balance inventory holding cost and pooling implementation cost. An aggregation strategy sets the regions that implement pooling ($Y_\theta = 1$) and the demand points and products in the region to be aggregated or included in the pooling scheme of the region, ($X_{kp} = 1$). For a given pooling budget b, problem $\mathbf{TAG}^0$ determines an (optimal) tailored aggregation strategy.

$$\textbf{TAG}^0 \quad \min \quad \sum_{\theta\in\Theta}\sum_{k\in\mathcal{K}}\sum_{p\in\mathcal{P}} a_{k\theta}.h_p.\Phi^{-1}(\alpha).\sqrt{T_p+L_p}.\sigma_{kp}.(1-X_{kp})$$
$$+\sum_{\theta\in\Theta}\sum_{p\in\mathcal{P}} h_p\Phi^{-1}(\alpha).\sqrt{T_p+L_p}.\sqrt{\sum_{k\in\mathcal{K}} a_{k\theta}.\sigma_{kp}^2.X_{kp}}$$
$$+\sum_{\theta\in\Theta} f_\theta.Y_\theta + \sum_{\theta\in\Theta}\sum_{k\in\mathcal{K}}\sum_{p\in\mathcal{P}} a_{k\theta}.v_{kp}.X_{kp} \tag{9}$$

subject to:

$$\sum_{\theta\in\Theta} f_\theta.Y_\theta + \sum_{\theta\in\Theta}\sum_{k\in\mathcal{K}}\sum_{p\in\mathcal{P}} a_{k\theta}.v_{kp}.X_{kp} \leq b \tag{10}$$

$$X_{kp} \leq \sum_{\theta\in\Theta} a_{k\theta}.Y_\theta \qquad \forall\, k\in\mathcal{K},\ \forall\, p\in\mathcal{P} \tag{11}$$

$$X_{kp}, Y_\theta \in \{0,1\} \qquad \forall\theta\in\Theta, \forall k\in\mathcal{K},\ \forall p\in\mathcal{P} \tag{12}$$

The objective is to minimize the total annual cost of an aggregation strategy (Y_θ, X_{kp}) as expressed in (9). The first term is the inventory cost of demand points and products with no pooling (when $X_{kp}=0$) and the second term is the inventory cost for demand points and products that are aggregated (when $X_{kp}=1$). The third and fourth terms express the cost of pooling at the regional level and the demand point level, respectively. The economic interpretation of the objective function is given in the next paragraph. Constraint (10) ensures that the total cost of pooling does not exceed the pooling budget. Constraints (11) impose that product p at demand point k cannot be included in the pooling scheme if the corresponding region θ does not implement pooling. Constraints (12) restrict the decision variables to be binary.

$\textbf{TAG}^0$ allows a decision-maker to efficiently allocate budget b between regions and corresponding demand points and products to benefit from the highest possible reduction in safety stock costs. In fact, from the objective function in (9) one can see that the safety stock of a product p in a demand point k will either be accounted for in the first term if the product is not included in the pooling scheme ($X_{kp}=0$), or in the second term otherwise. When the product is included in the second term, i.e. $X_{kp}=1$, the total holding cost decreases, but the pooling implementation costs v_{kp} and f_θ are consumed from the budget. $\textbf{TAG}^0$ optimizes X_{kp} and Y_θ such that the tailored aggregation strategy balances between inventory holding cost (the first two terms of the objective function) and pooling implementation cost (the last two terms of the objective function) while respecting the pooling budget in constraint (10).

Problem $\textbf{TAG}^0$ is a binary integer nonconvex program due to the square root term in the objective function. These problems are typically difficult to solve even for small problem instances. However, by noticing that X_{kp} are binary variables and thus $X_{kp}^2 = X_{kp}$, we can define auxiliary variables $Z_{\theta p}$ using the following quadratic constraints:

$$Z_{\theta p}^2 \geq (\Phi^{-1}(\alpha))^2.(T_p+L_p).\sum_{k\in\mathcal{K}} a_{k\theta}.\sigma_{kp}^2.X_{kp}^2 \tag{13}$$

Using these new variables, corresponding to the total safety stock of aggregated demand points of a product in a region, the complicating square root terms can be eliminated from the objective function. An alternative formulation of the tailored aggregation problem is given by:

$$
\begin{aligned}
\textbf{TAG} \quad \min \quad & \sum_{\theta\in\Theta}\sum_{k\in\mathcal{K}}\sum_{p\in\mathcal{P}} a_{k\theta}.h_p.\Phi^{-1}(\alpha).\sqrt{T_p+L_p}.\sigma_{kp}.(1-X_{kp}) \\
& + \sum_{\theta\in\Theta}\sum_{p\in\mathcal{P}} h_p Z_{\theta p} + \sum_{\theta\in\Theta} f_\theta.Y_\theta + \sum_{\theta\in\Theta}\sum_{k\in\mathcal{K}}\sum_{p\in\mathcal{P}} a_{k\theta}.v_{kp}.X_{kp} \qquad (14)
\end{aligned}
$$

subject to:

$$
Z_{\theta p}^2 \geq (\Phi^{-1}(\alpha))^2.(T_p+L_p).\sum_{k\in\mathcal{K}} a_{k\theta}.\sigma_{kp}^2.X_{kp}^2 \qquad \forall\, \theta\in\Theta,\ \forall\, p\in\mathcal{P} \qquad (15)
$$

$$
\sum_{\theta\in\Theta} f_\theta.Y_\theta + \sum_{\theta\in\Theta}\sum_{k\in\mathcal{K}}\sum_{p\in\mathcal{P}} a_{k\theta}.v_{kp}.X_{kp} \leq b \qquad (16)
$$

$$
X_{kp} \leq \sum_{\theta\in\Theta} a_{k\theta}.Y_\theta \qquad \forall\, k\in\mathcal{K},\ \forall\, p\in\mathcal{P} \qquad (17)
$$

$$
X_{kp}, Y_\theta \in \{0,1\}, Z_{\theta p} \geq 0 \qquad \forall\theta\in\Theta, \forall k\in\mathcal{K},\ \forall p\in\mathcal{P} \qquad (18)
$$

The tailored aggregation problem reformulation **TAG** is a conic quadratic mixed-integer program (CQMIP) that can be efficiently solved using standard optimization software (Atamtürk et al., 2012).

4 Case study

The present study was motivated by Morocco's public pharmaceutical supply chain. This supply chain involves public and private entities including pharmaceutical laboratories, the ministry of health, and different health establishments as shown in Figure 1.

4.1 Case description

General context. With the generalization of health coverage, a considerable segment of the Moroccan population now has access to free medical treatment and services, which has resulted in a huge growth in product consumption (MOH, 2014). The budget allocated to the purchase of these products has witnessed a 600% increase since 2003. Due to a lack of infrastructure and human resources, it became difficult to properly handle pharmaceuticals. The pharmaceutical supply chain as a whole is hampered by a number of operational challenges. These difficulties include product stockouts that necessitate long lead times to replenish, a high product expiry rate, low responsiveness, and the necessity for an information management system that combines all components of the distribution network.

In order to buffer against uncertainty that emanates from these issues, several alternatives are possible. The first alternative is the decrease in service level. The decrease in safety stocks and related costs will be offset by decreases product availability and an increase in the response time which patients cannot tolerate. The second alternative involves expediting emergency shipments from the centralized national distribution center upon need of local demand centers. However, this option may not be practical because it would be expensive and some demand points are not easily accessible and hence would require high transportation time to serve. The third alternative is concerned with physical inventory pooling. Inventory may be pooled at the national level and would lead to a great decrease in cost, but at the expense of a high response time. Inventory may also be aggregated at the regional level, but this option is not feasible at the moment as it requires building regional warehouses which might be expensive. Finally, virtual pooling emerges then as a practical solution given Morocco's engagement in a digitalization strategy involving the public sector in general, and healthcare specifically. Therefore, the Moroccan ministry of health is interested in investigating this solution approach to buffer against uncertainty and minimize costs whilst keeping the same high level of product availability. It is therefore called upon to demonstrate the feasibility and benefits of the approach in this setting to counter stockouts, high expiry rates, and achieve significant savings. This can be done through a collaborative framework for making procurement decisions that define appropriate levels of safety stocks to maintain at each demand point for each type of product.

System description. The Procurement division of the Ministry of health acts as a purchasing center for over 40 pharmaceutical laboratories and over 20 other supplier companies, under contracts resulting from calls for tenders. Provincial and regional hospital pharmacies are the primary consumers. They account for 161 and are located at the level of 83 provincial delegations of the Ministry of Health and 78 provincial and regional hospitals. The procurement division also supplies basic healthcare facilities through provincial pharmacies. These establishments, counting more than 2,759 throughout the country, make up the last point in the chain where pharmaceutical products are dispensed to patients. Pharmaceuticals that exist in the public sector supply chain also include several types ranging from expensive drugs to others targeting epidemics, narcotics, anti-cancer products, cold chain products, etc. These products can be classified into the following three categories depending on storage and distribution requirements:

a) *Regular products (P1):* general use pharmaceuticals.

b) *Cold chain products (P2):* pharmaceutical product families that must be kept in controlled temperature and humidity conditions.

c) *Security products (P3):* require strictly secured storage and transportation, such as narcotics and controlled drugs.

Purchasing forecasts of pharmaceuticals are based on annual orders from healthcare establishments. Cycle inventory and transportation management of products from the Ministry of Health takes place in one central distribution center (80% of products) and 3 secondary (20% of products). Supplier deliveries are scheduled in advance according to the tender documents' deadlines and delivery dates. The procurement section is in charge of delivering pharmaceuticals to provincial and hospital pharmacies where safety stock is held. Basic healthcare centers around the country are replenished by regional health delegations. The general schedule of national deliveries is done weekly at the procurement division level. It is generally based on the specifications of the call for tenders, but also takes into account: the delivery rate (percentage of the initial quantity ordered), complaints (stockouts, etc.), distance, and level of inventory. Inventory management at the central distribution center is computerized by batch and by expiration date, periodic inventories are carried out and weekly monitoring of products in stock is ensured. It is important to note that no information system integrates or communicates information about inventory or transportation of pharmaceutical products at either the centralized or regional levels.

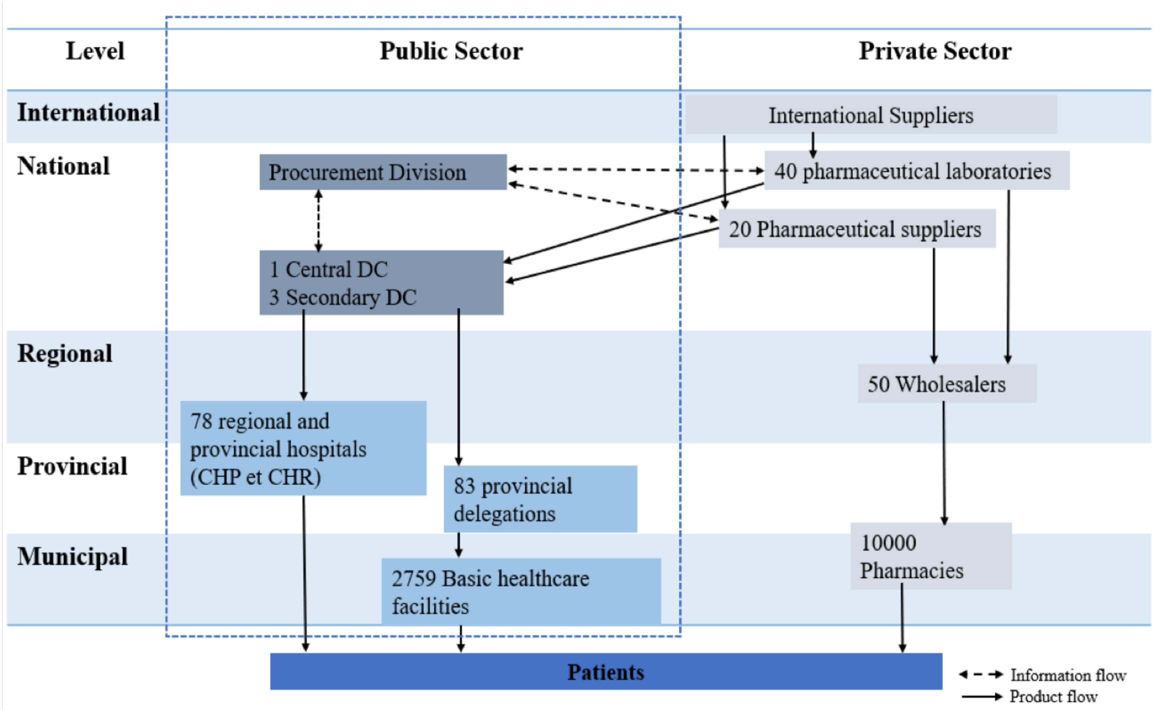

Figure 1: Moroccan public pharmaceutical supply chain

Data preparation. The data needed for applying the framework includes fixed regional and local pooling costs, demand and holding cost data, etc. This data requires the input of decision-makers and experts using questionnaire surveying, interviews, and work sessions. Decision-makers from the Ministry of Health, public-sector pharmaceutical distributors, private-sector pharmaceutical wholesalers, and private-sector third-party logistics providers are among those who helped collect data. Data related to fixed and variable warehousing costs, fixed and variable inbound and outbound transportation costs, and product equipment requirements, was calculated using the input of distributors from both public and private sectors.

The application of the suggested approach starts with the demand for pharmaceuticals for each product of the three categories, for each demand point consisting of hospitals and health centers in the twelve regions of the country. This demand is assumed to be uncertain and normally distributed. Therefore, data includes average demand and its standard deviation, lead time, product availability, price of products, the interest rate for holding costs, etc. Having demand with a mean of D_{kp} and a standard deviation of σ_{kp}, the coefficient of variation is calculated as follows: $CV = \sigma_{kp}/D_{kp}$. For every type of product p of regular, cold-chain, or security product, a coefficient of variation capturing the measure of uncertainty relative to demand is assigned. In the current case study, the coefficient of variation for regular products is higher than for cold-chain and security products. These coefficients

were determined from expert input in the healthcare sector using the Delphi method.
The coefficients of demand variation representing demand variability for each product type P1, P2, and P3 are 0.3, 0.25, and 0.2, respectively. The cycle service level for all products of the Ministry of Health is 95%. The lead-time L in our case is one week, obtained from data gathered from the Ministry of Health. The desired cycle service level (CSL) for the Ministry of Health is 95%, resulting in a $\Phi^{-1}(\alpha)$ score of 1,65. i_p is a measure of the interest rate related to the holding cost of product p, its value includes the cost of capital, taxes, insurance, and warehousing costs. The holding cost per product is calculated as a fraction of the product price: $h_p = i_p.P_p$.

4.1.1 Savings in a pooling scheme without considering pooling costs

The following section presents the results of full inventory pooling for all products and regions without taking into consideration pooling costs quantification. The results show that total safety stock for each type of product in each region is reduced with virtual pooling. In our example, it is clear that aggregating the demand for the three pharmaceutical products can save the supply chain network a reasonable amount of money just by utilizing the pooling inventory system. The supply chain network saves up to 56%, 54%, and 48% on the total inventory holding costs for products P1, P2, and P3, respectively. These values represent the percent decrease in costs when comparing the total holding costs without inventory pooling and those related to the pooling scheme. Besides, the total annual savings on inventory holding costs for all products and regions are 53% compared to the system without pooling which represents 0,59 million USD. The total holding costs per product according to both systems in the supply chain network are shown in Figure 2.

Moreover, significant savings are incurred per pooling region for the three types of products (regular products general use pharmaceuticals (P1), cold chain pharmaceutical products (P2), and security products (P3)). For instance, with inventory pooling, we can notice the highest savings in the region of Casablanca-Settat which includes 15 demand points. In this region, the savings on holding costs amount to 5.86%, 13.46%, and 17,77% for the three types of products P1, P2, and P3, respectively. Besides, savings for security products (P3) are higher than the other two types of products (P1) and (P2) in all regions. All Savings per product and pooling region are shown in Figure 3.

4.2 Computing pooling costs

The first phase of the approach quantifies pooling costs using the provided method in Section 3.3. These costs include f_θ, the annual fixed cost of implementing pooling in the region θ and v_{kp}, the fixed cost of implementing pooling in demand point k for product p. The output of this phase is used as input in the next. f_θ includes the information system cost IS_θ, asset acquisition for transshipments FT_θ, and regional human resources management costs HR_θ. Human resource cost in our case study refers to the annual salary cost of regional managers responsible for pooling (See Equation 1). v_{kp} includes costs of local implementation and operation of the information system required for pooling, cost of transshipments, and labor cost required for pooling (See Equation (5)).

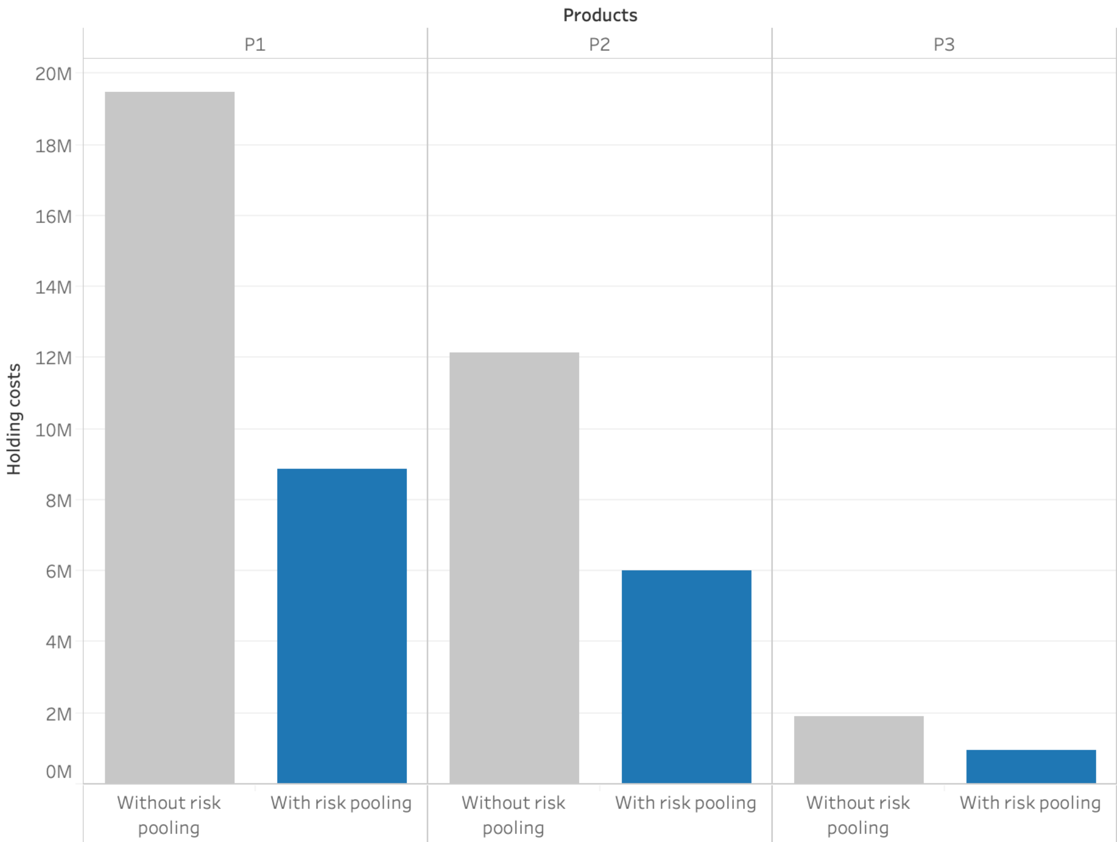

Figure 2: Total holding costs per product with inventory pooling and without inventory pooling in supply chain network

The fixed regional cost is proportional to the number of demand points available for pooling in the region θ. Thus, calculations of f_θ result in values that range from a minimum of 700 \$ to a maximum of 3500 \$, corresponding to regions 12 and 6, which include 15 and 2 demand points, respectively. Table 2 represents a summary of results for v_{kp} depicting the minimum, maximum, and average pooling cost values for each product type. Comparing the minimum, maximum, and average costs of all three products show that regular products (P1) have higher pooling costs than cold-chain (P2), which in turn show higher costs than security products (P3). This difference is due to expected backorder quantities related to each product, which are proportional to their demand. The difference perceived between minimum and maximum for each product is also a consequence of the inherent backorder quantity for a specific demand point. Overall, the cost of transshipment contributes to the greatest proportion of the pooling cost of a product at a demand point, followed by the information system cost. The labor cost presents the smallest contribution to v_{kp}.

4.3 Results and analysis

We use the input pooling costs from Section 4.2 to apply the integrated model developed in Section 3.4 to the case study in this section. CPLEX 12.6 was used to solve the model, which was programmed in OPL studio.

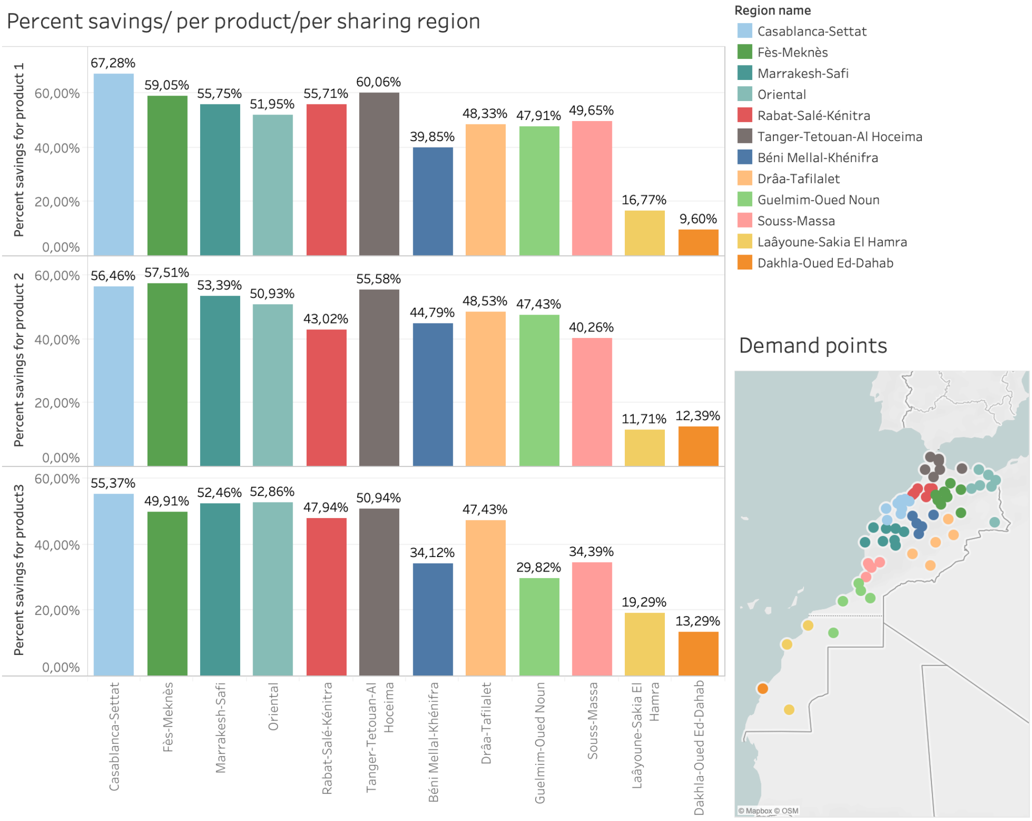

Figure 3: Percent savings of pooling per product and per pooling region

Table 2: Regional cost of implementing pooling per products

Products	Min	Max	Average
P1	158.33	4370.78	1049.80
P2	30.65	196115	36152
P3	3.09	568.41	80.93

4.3.1 Base case scenario results

The results of using the proposed approach reveal different pooling schemes that include which regions allow pooling, which demand points are included in the pooling scheme, and for which products. The analysis of the trade-off between pooling and non-pooling is highlighted through case scenarios that are run during experiment testing of different budget allocations. The base case scenario where no pooling budget is applied is first examined and compared to different budget allocations that range from 4000 to 44000 USD including a minimum (4000 USD), medium (24000 USD), high budget (40000 USD), and maximum budget (44000 USD). The base case scenario concludes that with no budget for pooling and no aggregation, total costs of holding safety inventory reach a mean of 11,18 million USD. With full aggregation, taking into account pooling cost, total inventory holding costs are 5,72 million USD, signifying a 49% decrease in total costs. Figure 4 presents efficient curves depicting total supply chain costs and savings. The results confirm that for correspondingly higher pooling budgets, costs decrease and savings increase. By using the efficient curve, decision-makers can select the appropriate pooling scheme based on their available budget.

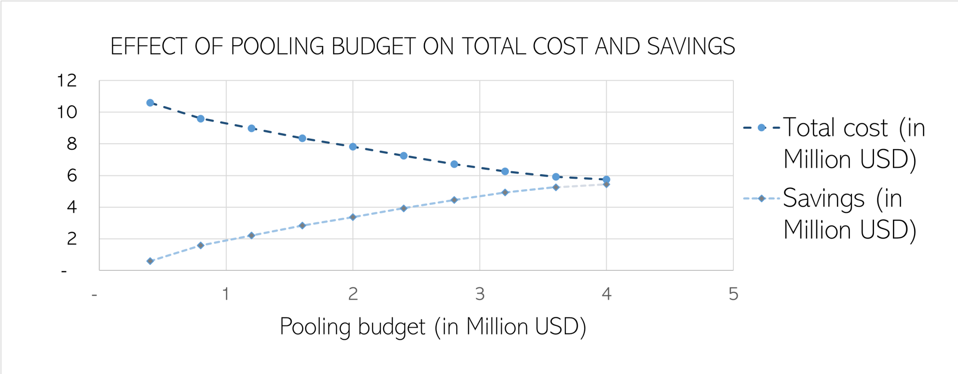

Figure 4: Effect of varying budget on pooling and total inventory costs

Figure 5 presents map pooling configuration for running the four levels of budget allocations: (a) minimum, (b) medium, (c) high, and (d) maximum. The maps show which demand points from regions are included in the pooling scheme. A comparison between the four maps concludes that when the pooling budget increases, the number of aggregated centers increases as well. The first map depicts the scenario where a minimum budget is granted, resulting in the aggregation of 5 demand points in 1 northern region with a high population density. The second map shows the aggregation of 45 demand points from 5 different regions located in the northern region of the country for a medium budget. Given a high budget, the third map (c) shows a scheme where pooling is applied to all regions except 2 southern ones. The fourth scenario (d) shows the case of full aggregation which is feasible starting a maximum budget. In this case, all regions and demand points are included in the pooling scheme. Therefore, it can be realized that though a high budget is allocated to pooling in the third scenario (c), aggregation is never generalized to all regions. The latter can be explained by the fact that the cost of pooling for these demand points exceeds savings since the objective is to minimize total costs. Aggregation in this case is not justified for very few demand points because of high regional fixed costs. We can also conclude that demand points of northern regions are firstly included in the pooling scheme which can be explained by the strong need for public health centers in that region as contrasted to the south, which has a lower population density. These regions are therefore characterized by consequent high pharmaceuticals consumption, which engenders cost savings and therefore justifies fixed costs of pooling. Furthermore, results of the full pooling scheme scenario show that the twelve regions contribute differently to savings achieved. Figure 6 shows that the most significant savings come from Region 6 which is responsible for 28.24% of total savings, followed by Region 3 with 14.45%, and regions 1 and 4 with a close 11.35-11.25%, respectively. Regions that contribute the least are 12, 11, and 10 with less than 1.5%. In the following section, we investigate the impact of regional disparities on pooling schemes to explain these differences.

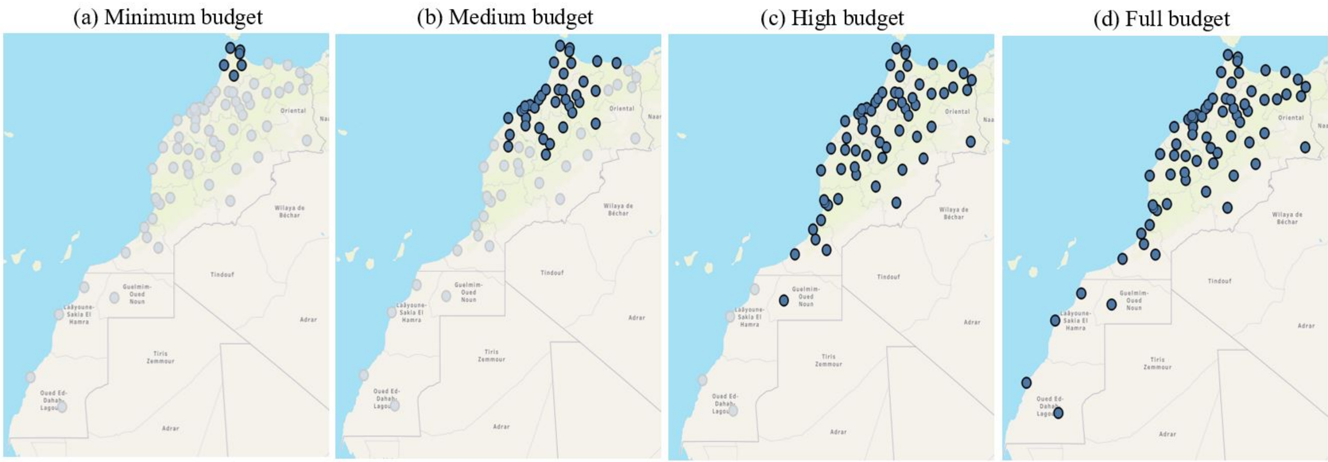

Figure 5: Map pooling configuration showing the effect of varying budget

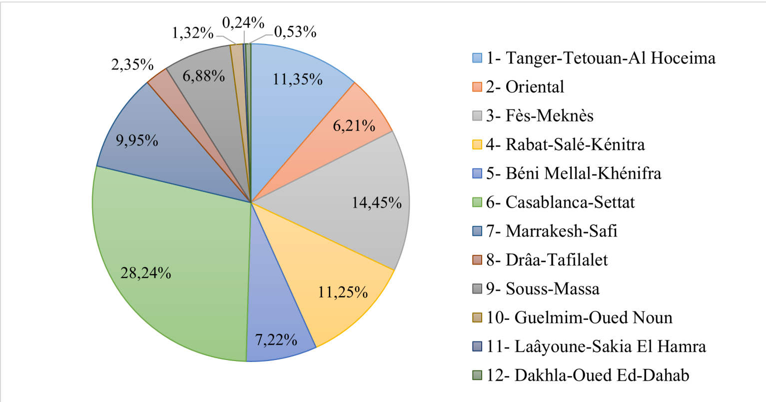

Figure 6: Regional contribution to savings under full aggregation

4.3.2 Impact of regional disparity on pooling decisions

To investigate how regional characteristics and disparity affect pooling decisions, the results are compared based on the following indicators: population density, income per capita, and urbanization rate. Table 3 shows how each region performs for each indicator compared to all other regions on a basis of a 3-point Likert scale (Low, Medium, and high) (HCP, 2019; CESE, 2019).

Table 4 shows how varying pooling budget affects savings, regions pooled, fixed regional costs, and fixed local costs related to demand points and products. With the minimum budget, only one region located in the North is pooled, characterized by high population density, high income per capita, and high urbanization rate. It results in medium fixed regional costs and enables 5,25% of savings because of its high population density. Region 1 was selected first because it has lower fixed costs compared to regions 4 and 6, which display similar rankings concerning regional indicators. When the budget is increased to 8000 USD, a single different region adheres to the pooling scheme resulting in high savings of 14,14%. Pooled region 6 under this scenario is characterized by high population density with almost 20% of total country demand, high income per capita, and a high urbanization rate compared to other regions. Fixed costs are the highest amongst all regions while variable costs of this pooling are medium. Pooling in region 6 was enabled because the pooling budget was high enough to cover the fixed costs

Table 3: Regional comparison of performance indicators

Region	Population density	Income per capita	Urbanisation rate
1	High	High	High
2	Low	Low	High
3	High	Medium	high
4	High	High	High
5	Medium	Low	High
6	High	High	High
7	Medium	Medium	Medium
8	Low	Low	Low
9	Low	Medium	Medium
10	Low	Low	High
11	Low	Low	High
12	Low	Low	High

Table 4: Results of varying pooling budget

Budget(USD)	%Savings	Regions pooled	Regional costs (USD)	Local costs (USD)
4000	5,25	1	1900	2090
8000	14,14	6	3500	4146
12000	19,74	1,6	5400	6336
16000	25,28	1,4,6	7300	8535
20000	30,13	1,4,6,7	9400	10579
24000	35,13	1,3,4,5,6	11300	12699
28000	39,86	1,3,4,5,6,7	13400	14599
32000	44,09	1,3,4,5,6,7,9	14900	16619
36000	47,04	1,2,3,4,5,6,7,9	16800	18148
40000	48,62	All except 11 & 12	19800	19113
44000	48,80	All	21800	19615

due to investment in the infrastructure and labor required to manage pooling in this region. Local costs on the other hand relate mainly to inventory and transportation management in demand points for the different products.

When the pooling budget is further increased, regions that first adhere to the pooling scheme are 1,6, and 4, all characterized by high population density, income per capita, and urbanization rate. Pooling in these 3 regions results in 25,28% of savings. Given that the maximum percent savings achieved from pooling all regions is 48,80%, pooling the 3 regions, therefore, represents around 52% of possible savings that could be achieved. Although region 3 represents the second-highest savings achieved from

total pooling after region 6 (See Figure 6), this region is not pooled until the 6th budget increase. The latter can be explained by the fact that the region is characterized by high fixed costs.
Regions adhering last to the pooling scheme are 8, 11, and 12. These regions are located further from the center of the country, they are less dynamic economically and have less populated areas. They are therefore characterized by low population density and low income per capita. Pooling these three regions increases savings by solely 1,76% points (from 47,04% to 48,80%). However, they show different urbanization rates, such that regions 11 and 12 are highly urbanized while region 8 has a low urbanization rate. Region 12 has a 74% urbanization rate, significantly higher than the national rate (60.36%); the density is 1.09 inhabitants per km2, much lower compared to the national average (47.6 inhabitants / km2).
We can conclude that population density and income per capita have a higher impact on pooling decisions than the urbanization rate. Population density drives pooling savings up, as it is intuitively correlated with product demand. The income per capita also affects pooling in that fixed and variable costs are high. This can be explained by the fact that operator and driver wages can be higher for regions with high income per capita. On the other hand, local variable costs including transshipment are low for regions with high population density due to the proximity of pooled demand centers.

4.3.3 Impact of product types

In this part, we analyze how different product types impact savings achieved from the virtual pooling of safety stock for the Moroccan healthcare system. This analysis is conducted in light of the differences in demand size, demand variability, holding costs, and average value between products, depicted in Table 5.

Figure 7 presents a graph depicting the savings obtained from the aggregation of products per type (P1-regular, P2-cold-chain, P3-security) under the different budget scenarios presented earlier. It shows that for each product type, savings increase proportionally with the increase of budgets allocated. The curves also show that regular products achieve higher savings than cold-chain products, which in turn are more profitable than security products.

Further investigation of product savings was carried out by representing the contribution of each product type to the overall savings of the full aggregation scenario. Figure 8 shows that regular products contribute to 60% of total savings, cold-chain products to 33%, while security products contribute to 7% of savings incurred. Moreover, closer examination shows that cold-chain and security products have

Table 5: Product comparison of demand attributes

Products	Demand size	Demand variability	Holding cost	Average value
P1	High	High	Low	Low
P2	Medium	Low	High	High
P3	Low	Low	Medium	High

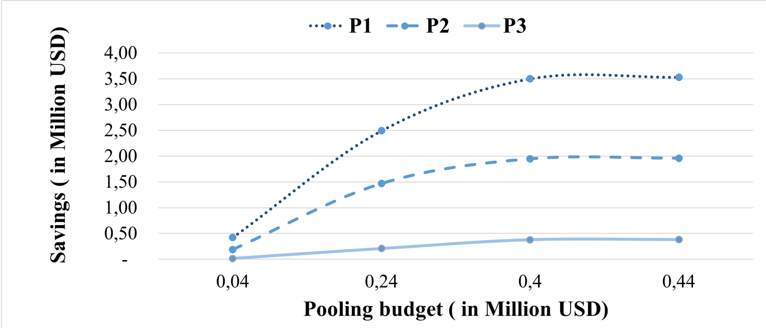

Figure 7: Impact of varying pooling budget on savings per product type

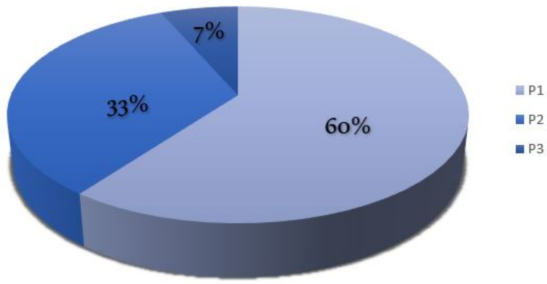

Figure 8: Contribution of each product type to the overall savings

lower demand and low variability but high holding costs required by the infrastructure, compared to regular products. We can conclude that despite having high demand variability and low holding costs, products with high demand contribute to significant savings from pooling compared to high value, low demand products.

Results of experiments also show that when varying pooling budgets, cold-chain products are only included in the pooling scheme when regular products are pooled, and security products are only included when both cold-chain and regular products are included. Figure 9 shows all scenarios occurring when varying the pooling budget regarding the inclusion of a certain product type in the pooling scheme and their respective occurrence. Scenario 1 represents the case where no product type is pooled, scenario 2: product type 1 is pooled, scenario 3: product types 1 and 2 are pooled, and scenario 4: all product types are pooled. We can conclude that the feasibility of pooling for security and cold-chain products in a particular region is conditioned by the pooling of regular products which contributes significantly to the breaking even of fixed regional pooling costs.

5 Discussion and implications

5.1 Discussion of results

The results obtained from the application of the approach show that pooling configuration differs greatly when varying pooling budgets. It also identifies trade-offs and establishes savings' levels in relation to cost levels. We first show that for the number of regions being pooled, under a given level of variability, the savings of pooling do increase with the number of locations being pooled. If decision-

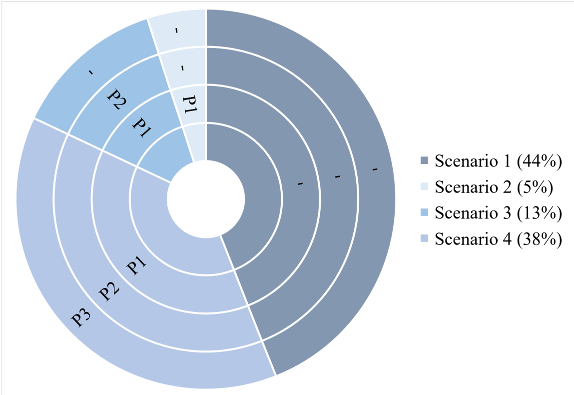

Figure 9: Product inclusion scenarios and their percentage occurrence

makers in healthcare are risk-averse and allocate a minimum budget, then savings will vary between 5 to 10%. If they are willing to affect a large budget to implement pooling at the national level, savings can increase up to 49%. By drawing the efficient curve, decision-makers can define the optimal pooling scheme depending on budget constraints and the requirements of products and regions.

The results also show that the number of demand points pooled depends on the number of locations present in the administrative and geographical regions. This is explained by the fact that administratively assigned regions show a high level of disparity concerning population density, income per capita, and level of urbanization. Since pooling is applied within each region, its application to regions with a high number of demand points is prioritized and results in higher savings. The fixed regional costs of pooling have therefore an important impact on the national pooling scheme, even though these fixed costs are significantly lower for regions with few demand points. Overall, pooling can be interesting in emerging markets or developing countries where the urbanization rate is very high, making the population more condensed and flows of the product easier due to short distances and smaller transportation network.

Further investigation of results shows that savings achieved from pooling depend greatly on products being aggregated. Within pharmaceuticals, regular products achieve higher savings than cold-chain or security products. The intuitive explanation pertains to economies of scale achieved from pooling a larger quantity; however, it is important to note that holding costs for these products are lower than other product types. Cold-chain products have a medium demand and medium value, while security products have low demand but present a high value resulting from the strict and expensive management required. This leads us to conclude that difference in demand quantity between products outweighs the difference in holding costs. Results also show that security products are only pooled in combination with regular and cold-chain products, and cold-chain products on their part are only pooled when regular products are as well. Therefore, pooling low and medium demand items in a region are conditioned by pooling high demand items which contribute greatly to covering the regional fixed pooling cost. Savings achieved from pooling security products are much less significant compared to cold-chain products, which in turn are much less significant than savings of regular products.

5.2 Research implications

In this study, we present a tailored aggregation framework for decision-makers to design a supply chain inventory pooling scheme that balances inventory pooling costs and savings. The proposed framework has significant implications for both researchers and practitioners. The implications of the current investigation are discussed in the sections that follow.

5.2.1 Theoretical implications

The present work is a novel contribution to the existing body of knowledge in healthcare inventory pooling. The current study contributes to the current literature in the field of healthcare inventory pooling in three ways. First, this is the earliest study to identify and present a methodology to quantify pooling costs in healthcare inventory management. Second, The current study is one of the first to attempt to address research gaps between theory and practice by developing a tailored aggregation model to achieve an optimal cost-efficient scheme for healthcare decision-makers in an emerging market. Third, the study successfully demonstrates the application of the approach through empirical evidence by designing pooling strategies that balance inventory pooling costs and savings.

The quantification of inventory pooling costs for solving an inventory pooling problem is worth emphasizing in this work. To address strategic decision-making issues in various fields efficiently, the cost quantification approach can be combined with additional techniques. As a result, the current study makes a substantial addition to the field of operations research and management by developing an integrated quantitative strategy for creating pooling schemes that takes regional and product features into account. The adaptive framework offered may be used to tackle a variety of pooling decision-making problems in different domains, including agri-food, automobile, aeronautic, etc.

5.2.2 Managerial implications

The current study used a real-life instance of the Moroccan pharmaceutical supply chain to demonstrate the implications of the suggested framework. As a result, the current research has important management implications for both public and private sector practitioners and decision-makers. The proposed approach allows the development of a cost-effective supply chain inventory pooling strategy. The proposed methodology for pooling cost calculations can be utilized by practitioners and decision-makers for pooling assessment and decision-making. As a result, the current study effort has four major management implications.

- *Pooling schemes of multiple products and regions:* Real-life supply chain inventories subject to pooling usually involve multiple products that can be characterized by differing demand size, demand variability, holding costs, and average value. Furthermore, pooling can also be impacted by regional factors including population density, income per capita, and urbanization rate. Therefore, taking into consideration these factors when designing a pooling scheme is crucial for decision-makers to optimize costs.

- *Estimating pooling costs:* There are many efforts made in formulating models to optimize inventory pooling, but the least attempts are taken to present a methodology for calculating pooling costs for multiple products and regions. Therefore, practitioners and decision-makers can adopt the proposed approach to calculate pooling costs to evaluate the feasibility of pooling.
- *Designing a new tailored pooling scheme:* The practitioners and decision-makers are encouraged to apply the proposed integrated approach for designing the optimal pooling scheme for their new or existing supply chain network configuration.
- *Assessment of an existing pooling scheme:* The suggested approach can help practitioners and decision-makers assess the existing pooling scheme to evaluate pooling costs and savings achieved and determine whether their strategy is cost-efficient.

6 Conclusion

This study presents a tailored aggregation framework for decision-makers to design a supply chain inventory pooling scheme that balances inventory pooling costs and savings. It incorporates a three-phase approach to determine the optimal safety stock pooling scheme. In the first phase, a method for calculating pooling costs is developed considering the management system required for regions, demand points, and products pooled. The second phase formulates the pooling problem to minimize inventory costs. Given multiple products, regions, and demand points, the problem is defined as a mixed-integer conic quadratic program, which is then transformed into a convex problem. In the third phase, an analysis of the resulting pooling schemes is conducted. By varying the pooling budget and minimizing total costs, several pooling schemes are obtained. Application of the approach is presented for the supply chain of pharmaceuticals in Morocco and analysis is carried out to provide managerial insights. We analyze inventory pooling schemes under different budget allocations to investigate how regional and product disparities affect costs and inventory pooling decisions.

The results indicate that the optimal tailored aggregation differs significantly when varying the pooling budget, and is affected by the product type, the regional population density, the income per capita, and the urbanization rate. They further highlight the trade-offs between costs and savings. We first show that for the number of regions being pooled, under a given level of variability, the savings of pooling do increase with the number of locations being pooled.

This research work is motivated by both theoretical and practical implications. There is a lack of literature from the theoretical standpoint on quantifying pooling costs and integrating them into a pooling optimization in an actual healthcare setting, especially in emerging markets. Practically, the current situation of the supply chain of pharmaceuticals in Morocco calls for an investigation of pooling strategies. By applying this framework, decision-makers can estimate pooling costs, design, and assess pooling schemes based on budget constraints, and the requirements of products and regions.

While we believe that this study can provide a new framework for inventory pooling, we believe that future research could build on our findings in the following ways. The suggested tailored aggregation framework is versatile and can be applied to other country characteristics and adapted to other emerging markets to compare results and derive global insights. It can also be applied to solve different pooling decision-making problems in other industries. Besides considering economic costs, it would be interesting to incorporate environmental and social aspects such as greenhouse gas emissions restrictions, individuals' collaboration, and change management constraints. Furthermore, an ultimate direction of future work is to integrate tactical and operational decisions, especially those related to inventory control and vehicle routing, considering resilience and risks.

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