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Response Strategies for Critical Supply Shortages in Healthcare

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Abstract

The shortage of critical medical supplies in healthcare facilities is of obvious concern to both medical professionals and patients. Specifically, the growing concern in this area is motivated, at least in part, by our dependence on generic pharmaceuticals. In the absence of FDA restrictions on the production of critical generic goods (e.g. morphine), manufacturers possess little financial incentive to produce numerous products whose patents have expired, but remain critical to patient care. Therefore, faced with crippling shortages, hospitals are left seeking ad-hoc solutions for meeting patient demand of these items. This work considers quantitative response strategies to mitigate the impact of these shortages. Specifically, lateral transshipments of supplies amongst cooperative hospitals are analyzed to assess their impact and utility with respect to the amount of met demand and the quality of service. In addition, a multi-objective optimization model is considered that offers insight about how intelligently structured collaboration between hospitals can improve service levels and reduce unmet demand across the system while considering transportation costs. The combination of these analyses provides medical decision-makers with a fundamental level of intuition necessary to guide hospitals in their reaction to supply shortages.

This thesis is approved.

Thesis Advisor:

Thesis Committee:

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1 Introduction

A shortage in healthcare supply chain occurs when a biological product is not commercially available in sufficient quantity to meet patient demand [1]. According to the World Health Organization (WHO), the United States has the highest expenditure on health in the world with \$750 billion spent in the global pharmaceuticals market [2]. The United States pharmaceutical market itself is valued at more than \$306 billion [3], with an annual growth of approximately 5%. However, 10% to 25% of public procurement spending (including pharmaceuticals) are lost to corrupt or inefficient practices. This leads to *shortages and inefficiencies in the delivery of critical healthcare supplies* through the existing pharmaceutical supply chain. In light of these inefficiencies, Landry and Philippe [4] estimated that 48% of the costs in the pharmaceutical supply chain are avoidable. Of these costs, 41% are sustained by healthcare providers, 33% by the manufacturers, and 26% by the distributors. Since much of the healthcare provider cost is passed along to patients, the *PIs believe there are clear opportunities to improve the management of pharmaceuticals to eliminate wasted cost and improve service to patients.*

Beyond the financial implications stemming from inefficient pharmaceutical management are the shortages that result from these poor practices. A total of 1190 shortages were reported between January 2001 and June 2011. Significantly however, from 2006 onwards the shortages grew annually by 200 percent. A record number of shortages (196) were reported in 2010, and 2011 in all likelihood surpassed this number [5]. Drug shortages can cause delay in treatment, inappropriate treatment, medication errors and thus increase in healthcare resource utilization and expenditures. The Food and Drug Administration (FDA) has been involved in addressing the problem of drug shortages. However, despite the fact that it has helped alleviate some of the shortages through its Drug Shortage Program, its authority to regulate the manufacturers is limited. There is no mechanism available to the FDA to require the drug manufacturers to report impending shortages or to require them to take certain actions to avert the situation leading to shortages [5]. On October 31, 2011, the President issued an Executive Order in which he urged the congress to legislate requiring drug companies to report shortages. The executive order directed the FDA to take action to help further prevent and reduce prescription drug shortages [6]. Consequently, a drug shortage bill was introduced in January 2012 in the House of Representatives that would force the FDA to speed up its review of applications from the companies that want to ramp up production to meet the shortages.

The drug shortage problem is a complex phenomenon and stems from legal, regulatory, economic and clinical factors. There are a number of contributing factors towards creating drug shortages. A key contributor to the shortage problems are manufacturers' business decisions in response to economic environment and incentives to earn profits or mitigate losses [7]. This is particularly true of the generic market which has a major share of the drugs that are in short supply. The generic market typically is very competitive and thus has low profit margins, which makes it critical for the manufacturers in the generic industry to constantly allocate and reallocate manufacturing resources and to deploy existing production capacity among products on the basis of conjectures regarding their competitors. The generic market further underwent major transformation in the wake of a series of patent expirations since 2008, in particular chemotherapy drugs, making the problem of shortage worse since it takes several years for the new firms to establish necessary capacity [8]. A survey of 353 pharmacy directors in United States (US) hospitals conducted by American Society of Health-Systems Pharmacists in 2011 revealed that the yearly labor costs to manage drug shortage problems amounted to $216 million nationwide [9]. Another 2011 survey of 820 US hospitals, completed by the American Hospital Association, showed that the hospitals surveyed experienced at least one shortage in the past 6 months. Another survey of 1800 health practitioners, of which 68% were pharmacists, was conducted by the Institute for Safe Medication Practices in 2010. The results of the survey revealed that most of those surveyed encountered shortage problems and that they managed the problems by using less effective and/or more costly alternatives with an increased potential for medication errors and worse patient health outcomes.

Failures in the pharmaceutical drug supply chain, which includes hospitals and outpatient clinics, pose a direct threat to the quality of care received by patients in the United States. Shortages result in patient treatment times being prolonged or procedures (e.g., surgeries) being cancelled. Specific medical examples of critical shortages are readily available [10]. The following are only a subset of those reported.

- *10-fold overdoses of epinephrine (adrenaline) have been reported as a result of staff using an undiluted form of the drug when pre-diluted syringes were unavailable.*
- *The unavailability of succinylcholine, a rapid-acting neuromuscular, threatens hospital abilities to position airway tubes in emergency patients.*
- *Patients with hypertension are at risk in surgery due to the unavailability of ephedria.*

The severe consequences and logistic challenges resulting from ineffective pharmaceutical drug supply chain practices leave hospitals frustrated [10].

In the case that a hospital experiences a drug shortage, several courses of action have historically been performed. Hospitals often choose from borrowing from another institution (e.g., hospital or pharmacy), purchasing off-contract from their current vendor, purchasing from an alternative vendor, purchasing from a secondary vendor, obtaining services from a secondary group purchasing organization (GPO), purchasing a compounded replacement pharmaceutical and using a compound replacement pharmaceutical already in stock [11]. Frustrations regarding shortages have been voiced for the last decade, with key players (e.g., manufacturers and healthcare providers) willing to discuss the issue from varying perspectives [10]. From the discussions amongst practicing professionals, the following key issues have been raised: (i) limitations of federal regulatory to require manufacturers to make certain drugs, (ii) increased risk of drug shortages due to single supplier model and (iii) generic drug product subject to commodity business models.

Solutions to these problems have been brainstormed by the key players. Many of these suggestions offer new qualitative measures to consider. For example, they have suggested: (i) better communication between the FDA, manufacturers and pharmaceutical customers; (ii) reporting tools for drug shortages and (iii) increased inspections of manufacturing facilities to reduce possible production delays. While these solutions merit additional considerations, they are focused more on managerial oversights than improved operational planning. However, the decision makers have also identified tactics that could be evaluated and improved through analytical planning techniques. Specifically, we find the following solution warrants thorough quantitative exploration.

- **Hospital collaboration through inventory pooling**. Opportunities exist to make use of collaborative inventory agreements that are more standard in retail logistics. These agreements would make way for portions of individual hospital inventory to be shared amongst participating hospitals. Policies that ensure the equitable distribution of inventory costs and supply amongst partnering healthcare facilities could lead to a drastically reduced number of shortages. These types of institutional collaborations are quite common in healthcare industry for epidemic control in the form of shared services.

Motivated by input from contributors to the pharmaceutical supply chain, as well as a partnership with health services researchers at the University of Arkansas Medical School, our proposed research suggests mathematical models and analysis to intelligently evaluate each of the preceding options. Our work will be divided into two categories: (i) identification of potential service level improvements from collaborative hospital inventory pooling and (ii) exploration of the impact of such sharing on transportation costs. Section 5 will evaluate the possibility of pooling different hospitals' inventory using bi-criteria optimization techniques and analysis. Section 6 considers the transportation costs associated with such service level improvement. With our health services research team and hospital, this work will result in policy recommendations that address the reduction of critical shortages through inventory agreements amongst numerous healthcare institutions.

2 Literature Review

2.1 Healthcare Inventory

Much of the research done in healthcare inventory management has been done with the objective focusing on either minimizing costs [12], [13], [14] or maximizing profits [15], [16]. For example, Yu et al. focused much of their efforts on solving a nonlinear cost function [12]. With a minimization of total costs, they planned on being able to give providers more information for more informed planning and decision making. They considered the multi-echelon flow of the supply chain from manufacturing firms to distribution centers to final destinations [12]. Lapierre et al. have also studied the interaction between suppliers and hospitals but focused on the implications on scheduling management instead of inventory modeling strategies [13]. Work has been done to enable the healthcare industry to make use of more complete data management [17]. Such information would be helpful with any inventory strategy.

Vendor managed inventory (VMI) has been assessed to understand the utility of allowing the manufacturer to control the inventory in each facility [14]. As expected, it has been shown that this strategy reduces the overall costs in the system [14]. Interestingly, it has been shown that VMI can decrease the suppliers profit in the short run. It is expected, though, that it will increase their profit in the long-run [14]. Once again, this study focused on the interaction between manufacturers and the hospitals. It does not consider any interaction between individual hospitals.

Several reviews have been done on the topic of production-distribution models to identify areas of potential future work. One review has highlighted emergency shipments as an area of future study [18]. It is noted that these shipments are not considered in the typical inventory models previously done on this topic. Another review has pointed that many previous models have been completely deterministic and suggests the use of stochastic variables for future work [19]. In a study by Babich [15] that considered the effects of supplier competition, it was noted that companies can benefit by identifying and maintaining alternative supply sources that could be used in the event of an unexpected supply disruption. Such alternative supply sources could potentially also include other consumers of the same product. In other words, these competitors could collaborate to satisfy each of their demands. Work has also been done to understand the potential impact of substitution for shortage products in the retail industry [16]. Such substitution impacts could also be applied to the pharmaceutical supply as well since there are both generic and name-brand drugs to choose from for servicing patients.

2.2 Lateral Transshipments

A comprehensive review has been completed on inventory models that utilize lateral transshipments. In this review, the characteristics have been highlighted of the slightly differing models that have been studied. The identified potential classifications of models are outlined in Table 1 as seen in [16]. As shown in this table, one important characteristic of lateral transshipments is the number of echelons in the network. The number of echelons is the number of levels involved in the network. For example, a two-echelon system may consists of manufacturers and distributors and the interaction within and between echelons. A single-echelon system may consist of only distributors and the interaction within the echelon.

Table 1: Modeling Alternatives

Number of items	1, 2 or any number M
Number of echelons	1, 2 or P
Number of locations (Depots)	2, 3 or any number N
Identical locations?	Yes, (Identical)Costs or No
Unsatisfied demands	Backorder or Lost Sales
Timing of regular orders	Continuous review or Periodic review
Order Policy	(R, Q), (s, S), (S-1, S), General or Other
Type of transshipments	Proactive or Reactive
Pooling	Complete or Partial
Decision making	Centralized or Decentralized
Timing of regular orders	Continuous review or Periodic review

This review shows that lateral transshipments are an important tool to be used in a supply chain as they help to reduce costs or increase service levels. Several proposals have been made for future research relating to lateral transshipments. Two of these relate to the quantity of locations and products. Most previous modeling found optimal policies for small numbers of locations. They also suggest considering multiple products within the system. It is thought that the incorporation of more products will lead to more opportunity in future research. [20]

2.3 Blood Inventory Management

Much work has been done in the area of blood inventory management which is highly relevant to the pharmaceutical industry. Like the pharmaceutical industry, service levels are very important; financial incentives are not the only driving force. There are also numerous hospitals attempting to satisfy similar needs within both systems. Within these systems, it is possible for the hospitals to utilize sharing techniques to improve their service levels. Blood inventory management has typically operated on three levels: hospital, regional, and inter-regional [21]. Blood inventory is unique in that decisions are not primarily cost or profit driven. Ordering policies have been developed that focus more on the amount of demand that is met [21]. Work have been done to understand the impact of collaborative efforts on service levels [21].

It has been shown that as the number of hospitals collaborating on their inventory increases, the percentage of product that outdates decreases [21]. Furthermore, it has been shown that independent hospitals that do not participate in collaborative efforts experience the worst problems with outdating [21]. While the perishability of blood is not particularly relevant to pharmaceuticals, more general lessons can still be learned. For example, if the product is expiring less often, this means that inventory is being better utilized. Crossmatching policies have been developed that attempt to maximize the likelihood of using a product and minimize the expected outdating and shortages [21].

Centralized inventory systems where a Regional Blood Center determines the distribution of resources over the region have been shown to perform better than decentralized systems where individual hospitals determine their own inventory levels [21]. Centralized systems have been studied using a variety of objective functions including minimizing the total regional supply needed to achieve the desired targets as well as minimizing the weighted sum of deviations between the expected and target values of the goals [21]. Work on distribution scheduling for centralized systems has been done in an attempt to develop strategies that stock inventories in hospitals such that each hospital has the same probability of experiencing a shortage [21].

Re-allocation of units in the system has been noted as an option in blood inventory management [21]. Noted incentives for hospitals to participate in regional collaboration include assured supply, increase in availability and utilization of the blood resources, access to more specialize services, and reduction of certain capital investment or operating costs [21]. The disincentive with the largest impact is noted as the requirement that hospitals give up portions of their supply [21].

3 Problem Description

There are several notable differences between the study pursued in this thesis and the work cited in the previous section. For one, financial cost is not taken to be the primary consideration in our model's objective. Since hospitals work in the service industry, costs may not necessarily be the primary driving force in decision making. In fact, there is most certainly inventory strategies which do not minimize costs, but do lead to higher service levels. However, since the amount of money to invest in inventory management is finite, in this work, a budget constraint is used to ensure that reasonable decisions are subject to cost limitations. Alternatively, the objectives proposed in this section focus on the service level that patients experience rather than financial incentives. The purpose of this research is to more fully understand the utility of collaboration between hospitals and develop optimal sharing strategies under different conditions.

The particulars of the modeling done in this study are outlined in the table below. In general, we are attempting to determine how various hospitals should make inventory decisions in order to fulfill critical drug demand. Note that this work can be applied to any number of drugs and any number of hospitals. While in some sense, this work can be thought of as an assignment problem with ordering/stocking considerations, our interest in the impact of collaboration requires that we extend more standard models to allow for models that can incorporate so-called inventory pooling. A major portion of our analysis is is to asses the impact of pooling on a decision-maker's alternatives.

Table 2: Model Classification

Number of items	M
Number of echelons	1
Number of locations (Depots)	N
Identical locations?	Yes
Unsatisfied demands	Lost Sales
Timing of regular orders	Periodic review
Order Policy	Other
Type of transshipments	Reactive
Pooling	Comparison of Complete and Partial
Decision making	Comparison of Centralized and Decentralized
Timing of regular orders	Periodic review

4 Modeling Variations

As the discussion on previous research has noted, there are several ways to approach modeling a hospital inventory system. The models in this study are intended to provide insight into two main system characteristics.

- *the impact of complete pooling compared to partial pooling.*

- *the advantages of centralized decision making over decentralzed decision making.*

In complete pooling, each hospital is willing to share all excess demand. In a centralized system, a single decision maker makes all decisions whereas each hospital would make their own decisions in a decentralized system. In order to quantify these differences, relevant metrics must be used. Focus in this study is on service levels rather than financial incentives. This is done to provide insight into best-case scenarios for service levels when financial aspects are not the driving force. Two primary metrics are used to quantify the service level. The first considers the portion of demand that is satisfied for each drug. This is defined as the fill rate. The second is the total amount of unmet demand for drugs.

The specific objective function is crucial to finding the optimal service levels. If an objective is considered that only attempts to maximize the minimum fill rate, then the model may greedily improve the minimum fill rate and then stop all sharing. There may be more opportunity for sharing improvements, but the model will not implement such decisions because it only cares about the fill rate. An objective with unmet demand, on the other hand, doesn't have this issue. In order to minimize unmet demand, sharing will continue until either there is no excess supply of any drugs to satisfy shortages or the budget has been drained.

Preliminary studies were done to understand the relationship between these two metrics. With these studies, there was no evidence to conclude that they are conflicting. In other words, the optimal solution of maximizing the minimum fill rate is the optimal solution of minimizing unmet demand in many cases. There are no trade-offs between them. The three primary models are shown in Table 3. The specific differences in the models can easily be noticed. These details will be discussed in greater detail later.

Table 3: Model Characteristics

Model	Pooling	Decision Making
1	Partial	Decentralized
2	Partial	Centralized
3	Complete	Centralized

Since one of the primary goals of this study is to provide information to hospital decision makers to help them determine what the best sharing strategy is, four primary metrics were gathered from each model. (For sake of clarity, "our" hospital will be defined as any one specific decision-making hospital). These metrics are: minimum fill rate for our hospital, minimum fill rate for all hospitals, unmet demand for our hospital, and unmet demand for all hospitals. These metrics are used to identify the tradeoffs of differing sharing strategies. This information should allow decision-makers to determine if the potential losses in their hospital′s leves are outweighed by the gains in the service levels in the network of hospitals.

4.1 Notation

In order to understand this problem, a base model formulation was developed. The notation is outlined below. There are two sets: hospitals and drugs. The decision variable is the flow between each hospital.

- **Sets**:

  H: set of hospitals

  H^*: set of hospitals that are not ours

  H^o: set of hospitals that are ours

  D: set of drugs

- **Parameters:**

  i_{dh}: inventory of drug d in hospital h

  n_{dh}: demand of drug d in hospital h

  c_{dh}: cost of ordering one unit of drug d from hospital h

  p_{dh}: price per unit of drug d that hospital h charges

  o_d: holding cost per unit of drug d

  M: allocated budget for each hospital

  T: upper bound on system drug demand

- **Decision variables:**

  $F_{dh_1h_2}$: the number of units of drug d sent from hospital h_1 to hospital h_2

  α : auxiliary decision variable defined as the minimum fill rate of the system

  β : auxiliary decision variable defined as the minimum fill rate of our hospital

  s_{dh}: shortage of drug d in hospital h

  γ : auxiliary decision variable used to sum the drug shortages of the system

  ρ : auxiliary decision variable used to sum the drug shortages of our hospital

4.2 Model Formulation

Three main models are used to understand the differences in sharing decisions. The first model is partial pooling where each hospital only cares about its own service levels. This model is used as the base model to compare the next two models against. The next two models consider the service levels of other hospitals. One of them is used to understand the impact on the system if only one hospital decides to share with other hospitals. The other is used to understand the impact of the situation where all hospitals decide to collaborate within a regional network.

4.2.1 Partial Pooling, Decentralized

The base model discussed here is intended to represent the scenario when there is only one hospital that is willing to share with all other hospitals. It is assumed that the other hospitals are willing tho share their excess inventory with that one hospital, but no others. It is also assumed that this hospital only cares about improving its own service levels. It has no interest in helping other hospitals.

$$\text{maximize } \alpha - \gamma/T + \beta * T - \rho$$

subject to (B)

$$\alpha \leq \frac{i_{dh_1} + \sum_{h_2 \in H}(F_{dh_2h_1} - F_{dh_1h_2})}{n_{dh_1}} \qquad d \in D;\ h_1 \in H \qquad (1)$$

$$\beta \leq \frac{i_{dh_1} + \sum_{h_2 \in H}(F_{dh_2h_1} - F_{dh_1h_2})}{n_{dh_1}} \qquad d \in D;\ h_1 \in H^o \qquad (2)$$

$$s_{dh_1} \geq max(n_{dh_1} - i_{dh_1} - \sum_{h_2 \in H}(F_{dh_2h_1} - F_{dh_1h_2}), 0) \qquad d \in D;\ h_1 \in H \qquad (3)$$

$$\sum_{h \in H}\sum_{d \in D} s_{dh} \leq \gamma \qquad (4)$$

$$\sum_{d \in D} s_{dh} \leq \rho \qquad h \in H^o \qquad (5)$$

$$\sum_{h_2 \in H} F_{dh_1h_2} \leq i_{dh_1} - n_{dh_1} \qquad d \in D;\ h_1 \in H \qquad (6)$$

$$\sum_{h_1 \in H} F_{dh_1h_2} \leq n_{dh_2} - i_{dh_2} \qquad d \in D;\ h_2 \in H \qquad (7)$$

$$M \geq \sum_{d \in D}\sum_{h \in H}(c_{dh_1}F_{dh_1h_2} - p_dF_{dh_1h_2} + h_d(i_d - F_{dh_1h_2} + F_{dh_1h_2}))) \qquad h_1 \in H \qquad (8)$$

$$F_{dh_1h_2} = 0 \qquad d \in D;\ h_1, h_2 \in H^* \qquad (9)$$

$$F_{dh_1h_2} \in \mathbb{Z}^+ \qquad d \in D;\ h_1, h_2 \in H \qquad (10)$$

The objective function is to maximize the minimum fill rate of our hospital, β. In order to set the values of the other service levels to be considered in the comparison, they are also included in the objective. The minimum fill rate of the system, the unmet demand of the system, and the unmet demand of our hospital are all weighted in the objective function so that they are significantly less important than the minimum fill rate in our hospital. The value for all values besides β have an upper bound of one. This prevents them from interfering with the primary objective. If these values are not included in the objective function, the solver may return a solution that simply maximizes the minimum fill rate and then ceases to improve the unmet demand with further sharing. Obviously, it is important to see the best values of these metrics at the optimal solution.

Constraints (1) and (2) are used to define the minimum fill rates, within the model. The first sets α for all hospitals in the system. The second sets β for our hospital. Any particular fill rate can be calculated by summing the initial inventory of a drug in a hospital and the net flow at the hospital and dividing by the demand of that drug at that hospital. Constraint (3) determines the unmet demand of particular drugs in each hospital in the system. This constraint can be easily linearized. Constraints (4) and (5) sum up the total unmet demand for all drugs in the system and our hospital respectively. Constraint (6) enforces the idea that a hospital will not give more of a particular drug than it has in excess. It is assumed that a hospital will not willingly give up inventory that it has demand for. In other words, each hospital sets first priority on satisfying its own demand in any particular time period. Constraint (7) prevents a hospital from receiving more of a drug than it has a shortage for. This prevents one hospital from selling a drug to another hospital that has no corresponding unsatisfied demand. Another important aspect of this constraint is that it is assumed that hospitals will not request drugs from hospitals to satisfy future demand. In this modeling, hospitals are only concerned with current demand. The budget constraint is formulated in constraint (8). This constraint consists of sales revenue, purchase costs, and holding costs. The net expenses of each hospital must be no greater than the budget available. It doesnt seem that hospitals are primarily financially driven institutions, so this constraint is not intended to be the primary binding constraint. It is simply to ensure that greedy sharing does not take place that is not within reason. Constraint (9) ensures that no sharing takes place between hospitals where our hospital is not involved. This is enforcing the partial pooling concept. Constraint (10) simply enforces the idea that the quantity of drugs shared between any two hospitals must be integer and nonnegative. Since the flow decision variable goes both ways, all flow can be accounted for with positive values.

4.2.2 Partial Pooling, Centralized

The next model developed examines the impact on the system if a particular hospital decides to make decisions for the betterment of the system rather than just for itself. In order to to this, the objective function is changed to the following.

$$\text{maximize } \alpha * T - \gamma + \beta - \rho/T$$

This means that we are trying to maximize the minimum fill rate of the entire system. This objective simply shifts the emphasis in the objective function to the system's service levels.

4.2.3 Complete Pooling, Centralized

The last model represents the scenario of all hospitals collaborating in for the betterment of the entire system. In order to do this, the new objective proposed in the previous section is used and constraint (9) is removed. This enables all hospitals to participate in the sharing rather than just the sharing that involves our hospital.

5 Computational Study

A computation study was done in order to implement these models and attempt to quantify and compare their solutions.

5.1 Parameter Values

In order to do quantitatively compare the decisions resulting from the various models considered a broad set of experiments were considered. Values specified for the parameters were chosen randomly. These values were generated using the uniform distribution with specified upper and lower bounds shown in Table 4. Importantly, the demand was set such that it exceeded inventory in the range of 0-10%. A broad range between the upper and lower bounds is also used on the inventory and demand. These two parameter characteristics are done so that shortages occur often and the hospitals are forced to make decisions regarding them. Also, the value of the budget parameter was determined by assessing what values would be binding to the budget constraint. The budget parameter used allows all instances for the models to remain feasible. For the purpose of this analysis, five hospitals were assumed initially. For a regional collaboration of hospitals, this seems appropriate. The number of drugs was set initially at ten so that there were a variety of drug sharing opportunities.

Table 4: Parameter Values

Parameter	Lower Bound	Upper Bound
i_{dh}	50	100
n_{dh}	40	130
c_{dh}	5	10
p_{dh}	5	10
o_d	5	10
M	885	885

Each of the three models was run under a variety of conditions to understand the impact of changes in the system and sharing strategies. Each of these studies are outlined below.

5.2 Results

The results of the first study are shown in Figure 1 and Figure 2. Figure 1 shows the different optimal fill rate levels for each model, as well as the case where no sharing is performed (e.g. when a hospital's service level is completely determined by its initial inventory and demand level). Figure 2 shows the different levels of unmet demand for our hospital and the entire system in each of these cases. This study used five hospitals and ten drugs in the network. It is solved for ten different instances which utilize different seeds for their random number generation to give them unique sets of parameter values.

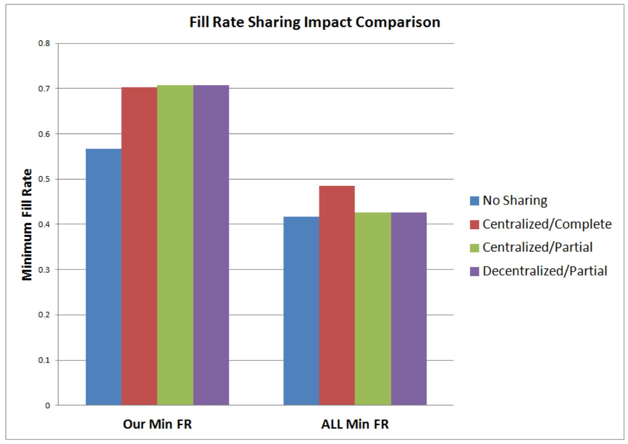

Figure 1: Sharing Impact on Fill Rate

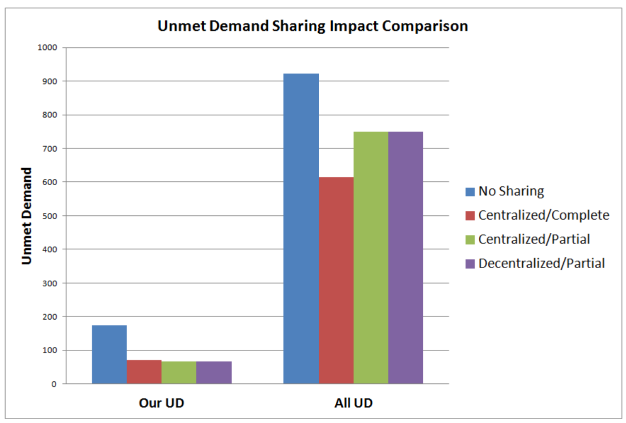

Figure 2: Sharing Impact on Unmet Demand

The numerical values associated with these figures are summarized in Table 5. This table provides the percent improvement gained by each model variant over the case in which no sharing is considered. As expected, all metrics improve from all types of sharing. However, system level metrics improve significantly more with complete sharing. In contrast, our hospital actually experiences higher service levels with decentralized sharing than centralized sharing. In addition, there is no difference in solutions between changing objectives with a decentralized system.

Table 5: Improvement Over No Sharing

Model	Our Min FR	System Min FR	Our UD	System UD
Decentralized/Partial	25.0%	2.4%	61.2%	18.8%
Decentralized/Complete	25.0%	2.4%	61.2%	18.8%
Centralized	24.2%	16.4%	58.9%	33.3%

5.2.1 Impact of Budget

In order to understand the impact of the budget constraint on the solutions, the model with complete collaboration was solved with an infinite budget. This change had no impact on the minimum fill rates. This shows that the budget is not the limiting factor to improve fill rates. It is likely that there is no excess supply of the drugs with the lowest fill rates anywhere in the system. Unlike the fill rates, the unmet demand levels, as anticipated, did improve with unlimited supply as shown in Figure 3.

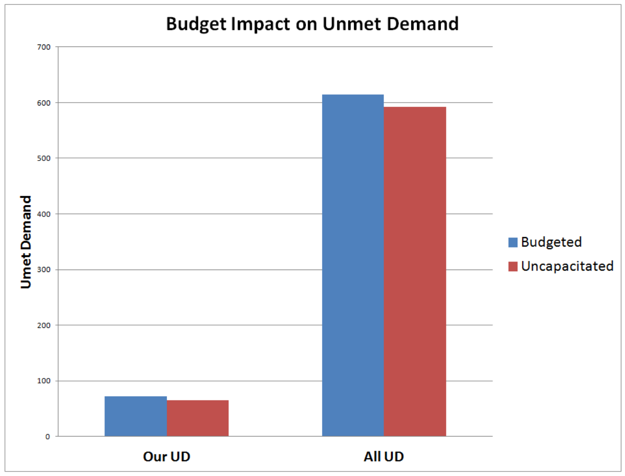

Figure 3: Budget Impact on Unmet Demand

Table 6 shows the improvement of the metrics of the system with infinite budget over the budgeted system. The unmet demand improved by 8.9% and 3.7% for our hospital and the system respectively over the budgeted solution. This improvement is expected; an increase in financial resources leads to the ability to satisfy more demand given that there is excess supply in the system. This improvement verifies that the budget constraint is indeed constraining for the models.

Table 6: Improvement from Infinite Budget

Our Min FR	System Min FR	Our UD	System UD
0.0%	0.0%	8.9%	3.7%

5.2.2 Impact of Network Size

One parameter of the system that can play a large role in the solutions is the number of hospitals involved. So, in order to capture the differences in solutions based on the size of the hospital network some comparisons were made. The system just discussed was compared against systems of 6, 7, 8, 9, and 10 hospitals in their collaboration network. When considering the difference between 5 and 6 hospitals in the network, the 6 hospital network is not simply the same network with an addition of a new hospital. The instances solved in this study were for independent sets of hospitals.

Figure 4 compares the improvements that are seen for each of the metrics as the number of hospitals in the network varies. There is a noticeable upward trend in all of these metrics. The slope of the improvement seen in the minimum fill rate seems to be the steepest. This means that increasing the size of the network has the most impact on the minimum fill rate in the system. It is also very clear from this graphic that the unmet demand of our hospital improves the most proportionally from centralized sharing.

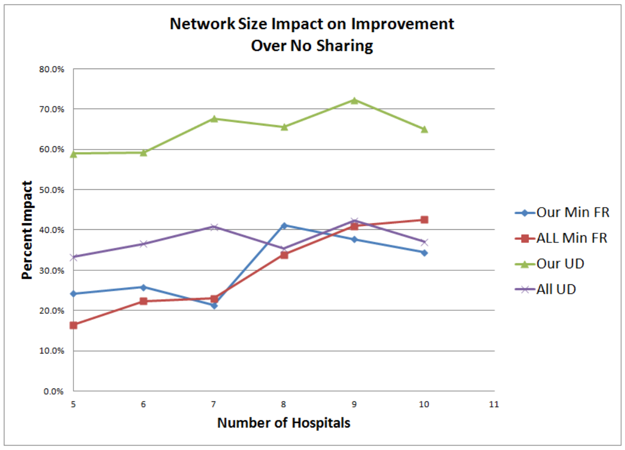

Figure 4: Network Size Impact on Improvement Over No Sharing

Figure 5 compares centralized sharing to the case where all hospitals are willing to help a particular hospital achieve its objective as long as they have excess inventory or demand for the drug that our hospital has excess of. Based on this graph, it seems that as the network size increases the difference between our hospital's best case service levels increases. This observation can be easily explained. An increase in hospitals willing to participate to help our service levels means an increase in our service levels as seen in Figure 4. Therefore, if those additional hospitals are not willing to help our hospital as we desire, the differences are due to the lost potential to help our metrics.

The improvements for the entire system are still present when comparing centralized sharing to the scenario where our hospital utilizes greedy objectives. The system has nothing to gain from such greedy objectives.

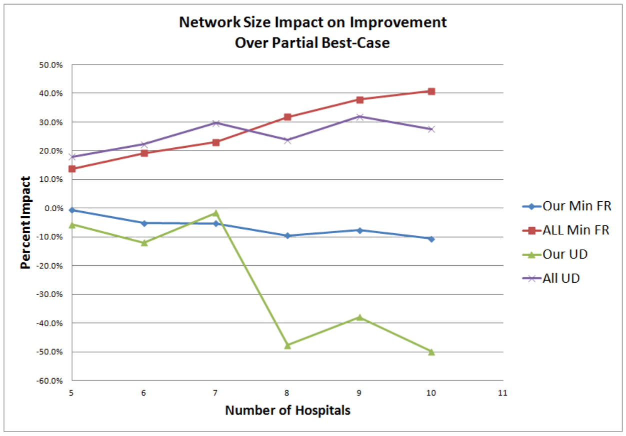

Figure 5: Network Size Impact on Improvement Over Partial Best-Case

5.2.3 Impact of Number of Drugs

Similar to the previous analysis, a comparison was made to determine the impact on the service levels that the number of types of drugs shared has. Here, the number of hospitals in the network was held constant at five. Then the number of drugs was varied at levels of 15, 20, 25, and 30. The instances generated are independent of each other here just as the instances for the varying number of hospitals.

The improvement of centralized sharing over no sharing is shown in Figure 6 for each of the metrics. There is no clear trend in this figure. There is no conclusive evidence to suggest that the number of drugs in the system necessarily correlates to a change in the improvement potential by centralized sharing.

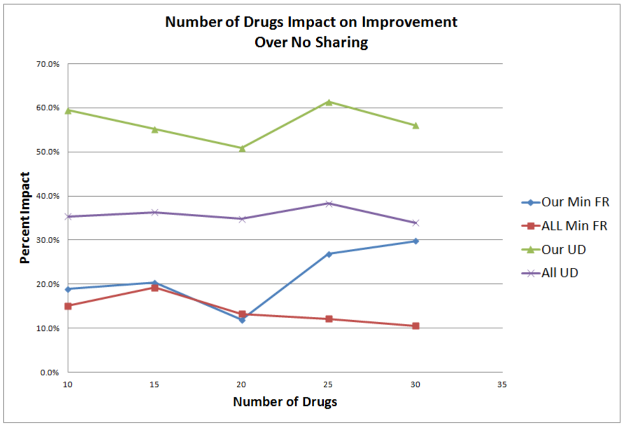

Figure 6: Number of Drugs Impact on Improvement Over No Sharing

As with the network size variation, the improvement for the metrics is compared to the possible greedy objectives of our hospitalin Figure 7. Once again, there does not seem to be any clear evidence to suggest that the number of drugs in the network has an impact on the improvement over the greedy objective.

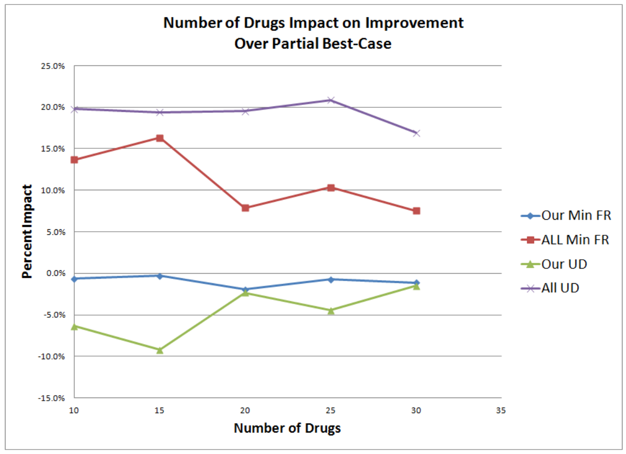

Figure 7: Number of Drugs Impact on Improvement Over Partial Best-Case

5.3 Conclusions From Weighted-Objective Modeling

Several conclusions can be drawn from the analysis discussed in this section. For one, budget plays more of a role bounding unmet demand than fill rate. Still, it doesn't play a huge role on the unmet demand in this model. Considering that the intention of this study is to understand the best service levels independent of budget, this is a positive characteristic of the modeling. Secondly, complete pooling can be beneficial to the network of hospitals as a whole while it may have a negative impact on any one particular hospital. In order to implement complete pooling, it would be important that the hospital decision makers understand that they are helping the whole more than they are being hurt. Thirdly, in order to minimize unmet demand, the hospitals will share as much as their inventory and budget will allow. This is because transportation costs are considered almost negligible. In a sense, the modeling here maximizes transportation costs in order to maximize the minimum fill rate. The next section implements bicriteria optimization to understand the tradeoffs between transportation costs and maximizing the minimum fill rate for the entire system.

6 Transportation Costs

There has been little work done to fully understand the transportation costs associated with service level improvements gained from collaborative sharing amongst hospitals. In an attempt to gain insight into these tradeoffs, a bicriteria optimization model was constructed. To evaluate the bicriteria optimization model, Pareto frontiers were generated through the use of the so-called *Noninferior Set Estimation* (NISE) method. The NISE method, proposed by Cohon et al. [22, 23] is attractive because it is able to generate the exact shape of the noninferior set efficiently. However, much of this efficiency is a result of the fact that the NISE method is applicable only to linear programs (LP) (e.g. no integer/binary restrictions). Therefore, efforts were made to examine how well the LP relaxation of our model approximated the optimal IP solution. Our results, as expected, indicated that the LP relaxation led to an improvement in the service levels of the system. However, these improvements were extraordinarily negligible ($< 1\%$). Therefore, empirical evidence suggests that the NISE method is an appropriate choice to approximate the efficient frontiers of the bicriteria model proposed in this section.

The previous models considered several costs in the form of a budget constraint, but they do not provide any insight into these tradeoffs. In order to develop such a bicriteria model, one change was made to the base model. The objective is changed to the one shown below.

$$\text{maximize } \left\{ \alpha, -\sum_{d=0}^{D} \sum_{h_1=0}^{H} \sum_{h_2=0}^{H} F_{dh_1h_2} \right\}$$

Obviously transportation costs are minimized when there is no sharing between hospitals. However, to reach more attractive fill rate levels, some transportation costs are most likely required.

6.1 Base Scenario Pareto Frontier

By creating a pareto efficient frontier, the tradeoffs can be analyzed for these two conflicting objectives. Figure 8 shows ten frontiers for the base case with five hospitals and ten drugs. Each frontier corresponds to an individual instance generated. Some general trends can be noticed with these graphs. The slope of the frontier decreases with increased transportation costs. This can be easily explained. When improving fill rates, initially there is likely a single drug that has the worst fill rate. Sharing will take place until the fill rate of this drug has improved up to the next lowest fill rate. Then, in order to bring up the minimum fill rate, fill rates on both of these drugs must be improved. In other words, sharing must take place for two drugs instead of one. This will increase the need for transportation costs. This increases the marginal transportation costs for fill rate improvement. It should be noted that each point likely corresponds to the point at which a new drug also has that minimum fill rate. Beyond that point there is an additional drug for which the fill rate must be improved. Each of the graphs in Figure 8 exhibit this decreasing slope characteristic. The last point that is shown on each graph is associated with the minimum transportation cost required to achieve the maximum fill rate. Each graph could be extended further along the horizontal axis with a horizontal line. This would represent that any increase in transportation cost would not achieve any improvement in the fill rate.

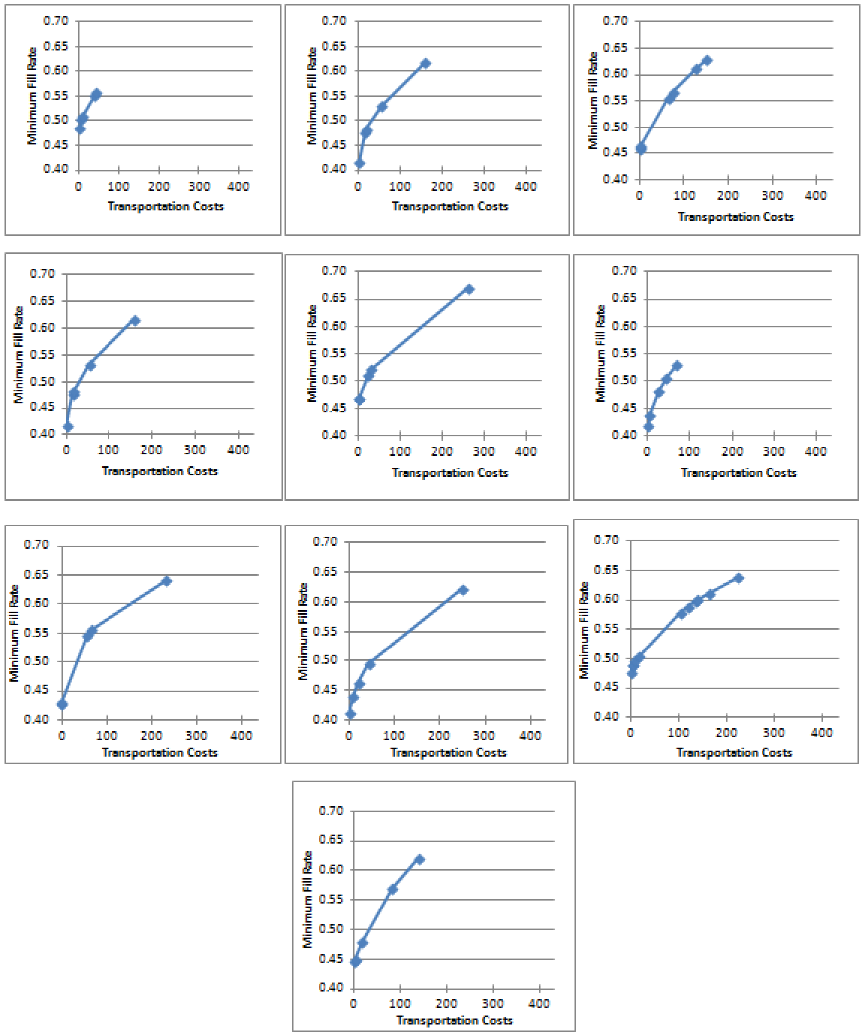

Figure 8: Pareto Frontiers for 5 Hospitals

6.2 Network Size Impact on Pareto Frontier

After drawing these conclusions from these frontiers, frontiers for differing number of hospitals were drawn. Three frontiers for 6, 7, 8, 9, and 10 hospitals are shown in Figures 9-13. Each of the three frontiers for each case corresponds to an individual instance generated for that case. The general characteristics of these frontiers all seem to be very similar to the base case. They all have decreasing slopes with increasing transportation costs. Figure 9 can be used for illustration purposes. The first frontier on this figure contains six points on it. This likely means that the fill rates for six drugs can be improved. However, it is possible that a single point on the frontier can correspond to multiple drugs. The decreasing slope indicates the increasing transportation costs associated with the improvement of the fill rate with each addition of a drug in the set of drugs with the minimum fill rate. The last graph in Figure 9 is notably different from the first. It contains four individual points on the frontier. This means that the marginal return on transportation costs changes four times on the frontier.

The notably different characteristics of the frontiers for the instance shown in Figure 13 can also be used to shed light on the attributes of the frontiers. The first graph has numerous points on it where the rate of required transporation costs changes each time. The continuation of the frontier after each point means that there are excess drugs in the system available to improve the minimum fill rate. In contrast, the third graph on Figure 13 only has three points on the frontier. The end of this frontier corresponds to the point at which the fill rate for at least one drug in the set of drugs with the minimum fill rate can longer be improved. This inability to improve the drug's fill rate is likely due to a shortage in the entire system of a particular drug. At that last point on the frontier, there is no more excess of the drug in any hospitals of the system.

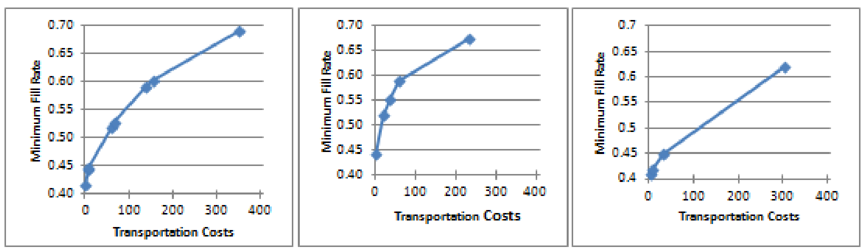

Figure 9: Pareto Frontiers for 6 Hospitals

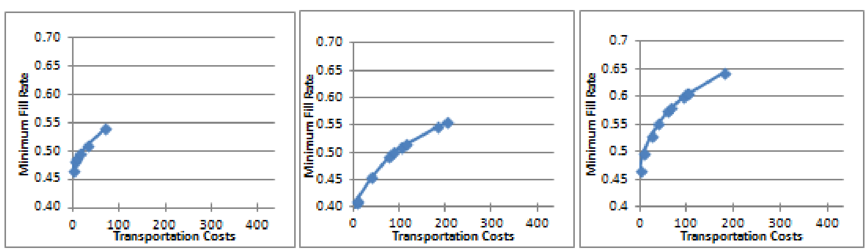

Figure 10: Pareto Frontiers for 7 Hospitals

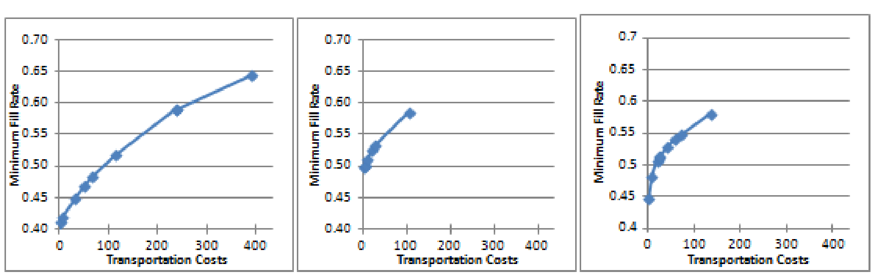

Figure 11: Pareto Frontiers for 8 Hospitals

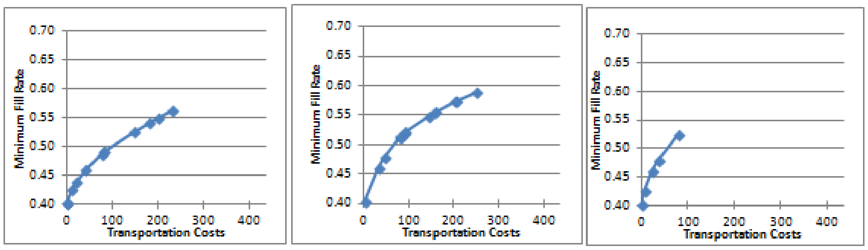

Figure 12: Pareto Frontiers for 9 Hospitals

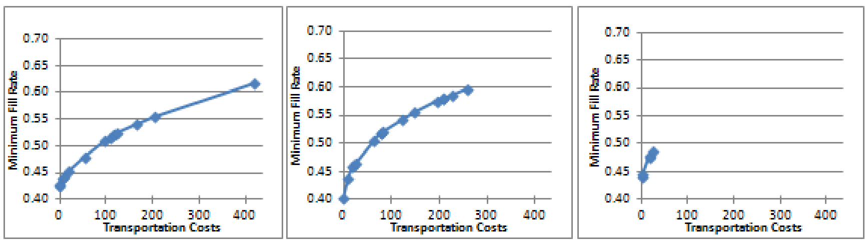

Figure 13: Pareto Frontiers for 10 Hospitals

6.3 Number of Drugs Impact on Pareto Frontier

Similarly, the frontiers for three unique instances were drawn for varying numbers of drugs as shown in Figures 14-17. Since an increase in the number of drugs held leads to a greater need for finances, these frontiers were all drawn for instances that have unlimited budgets. As shown in the previous section, the budget constraint does not have a significant impact on the solutions, so the frontiers drawn here should be a good approximation of the budgeted frontiers. These frontiers all exhibited similar characteristics to each other as well.

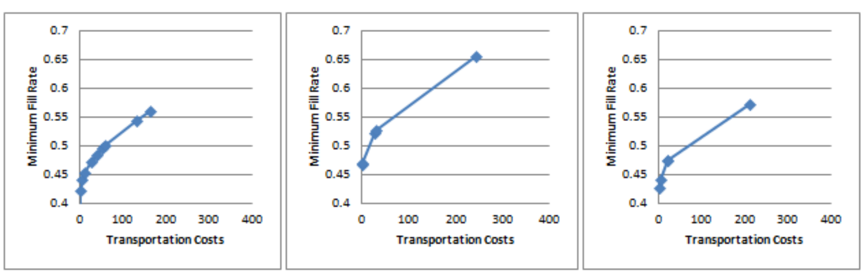

Figure 14: Pareto Frontiers for 15 Drugs

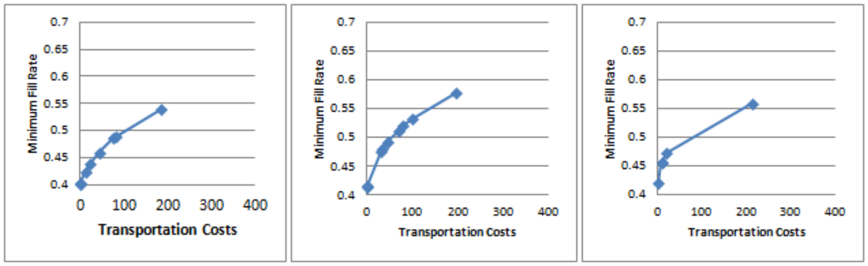

Figure 15: Pareto Frontiers for 20 Drugs

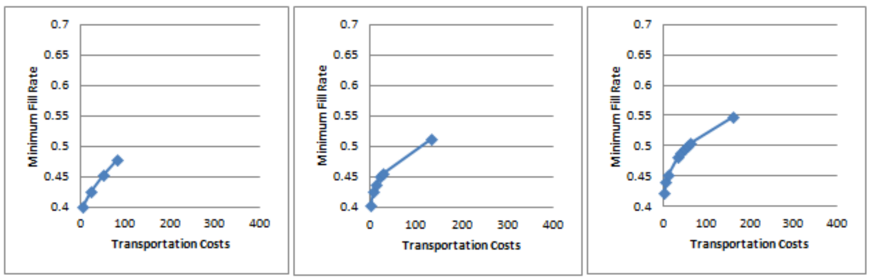

Figure 16: Pareto Frontiers for 25 Drugs

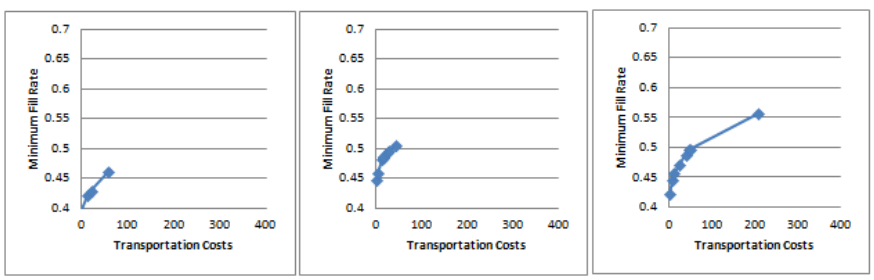

Figure 17: Pareto Frontiers for 30 Drugs

The differences in specific frontiers vary greatly depending on the instance. There doesn't seem to be any clear change in their shape due to the number of hospitals or the number of drugs involved in the system. The parameters generated for each instance likely have a significant impact on each specific frontier. It would be interesting to continue with a similar study that shows frontiers with varying parameters for demand and inventory.

7 Conclusion & Future Work

This study has helped to shed light on many characteristics of collaborative sharing among hospitals in an attempt to maximize service levels. It suggests that a decentralized system has no opportunity for improvement if a single hospital makes decisions in a centralized manner. It requires a collaboration of multiple hospitals. It also suggests that as the number of hospitals within a collaborative network increases, the potential improvement on the system's service levels increases. The impact from differing numbers of drugs seems to suggest that increased numbers of drugs shared in a network decreases the negative impact on an individual hospital and decreases the positive impact on the system. However, this trend is minimal and may be insignificant based on the current study. There does seem to be a negative impact on an individual hospital's service levels if it decides to enter a centralized system. This deterioration of service levels appears to be significantly lower than the improvement felt by the entire system. While this was shown to be the case for the average of the instances studied in the hospital, it is plausible that an individual hospital may benefit from centralized sharing more than the system. This just wasn't the case for the averages of this study. In the case that individual hospitals do suffer from collaborative sharing, they should consider whether they are willing to accept this to benefit the system service levels.

There is a clear trend of increasing marginal transportation costs required to maximize the minimum fill rate. This can be useful for hospitals trying to understand how much of these transportation costs they are willing to incur in order to improve the minimum fill rate. They may be willing to increase this fill rate only to suboptimal levels because of this. Similar conclusions can be drawn based on varying numbers of hospitals and drugs within a collaborative network.

This study only considers a single time period. An interesting extension to this work would be to incorporate multiple time periods in the study. This extension could consider the opportunity costs of sharing with other hospitals when they could potentially have demand later to satisfy. The effects of collaboration with this change could significantly change. In addition, comparison is done in this study between a network where only one participant considers a centralized objective to a network where all participants consider a centralized objective. Further investigation is needed to understand how the proportion of participants in a network with centralized objectives effects the network.

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