Supplier selection under disaster uncertainty with joint procurement

by

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Abstract

Health care organizations must have enough supplies and equipment on hand to adequately respond to events such as terrorist attacks, infectious disease outbreaks, and natural disasters. This is achieved through a robust supply chain system. Nationwide, states are assessing their current supply chains to identify gaps that may present issues during disaster preparedness and response. During an assessment of the Kansas health care supply chain, a number of vulnerabilities were identified, one of which being supplier consolidation. Through mergers and acquisitions, the number of suppliers within the health care field has been decreasing over the years. This can pose problems during disaster response when there is a surge in demand and multiple organizations are relying on the same suppliers to provide equipment and supplies. This thesis explores the potential for joint procurement agreements to encourage supplier diversity by splitting purchasing among multiple suppliers. In joint procurement, two or more customers combine their purchases into one large order so that they can receive quantity discounts from a supplier.

This research makes three important contributions to supplier selection under disaster uncertainty. The first of these is the development of a scenario-based supplier selection model under uncertainty with joint procurement. This optimization model can be used to observe customer purchasing decisions in various scenarios while considering the probability of disaster occurrence. Second, the model is applied to a set of experiments to analyze the results when supplier diversity is increased and when joint procurement is introduced. This leads to the third and final contribution: a set of recommendations for health care organization decision makers regarding ways to increase supplier diversity and decrease the risk of disruption associated with disaster occurrence.

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Chapter 1 - Introduction

In the case of a mass-casualty event or infectious disease outbreak, health care organizations experience a massive surge in demand as the number of patients increases rapidly. These organizations need to have preparedness and response plans in place to adequately respond to the influx of patient needs and requirements. Many preparedness actions focus on the health care preparedness and response supply chain, a critical step of which includes the acquisition of supplies. Significant challenges can present themselves during supplier selection when distributors and providers are planning for disaster response. In supplier selection, customers (hospitals, clinics, and public health departments) choose which suppliers they will purchase supplies from and establish purchasing procedures. Decisions are made regarding purchasing quantities, lead-times, and pricing, to name a few. This step of the process can be the difference between a hospital receiving or not receiving life-saving supplies during a disaster scenario. The research presented in this thesis focuses on supplier selection in the health care field under disaster uncertainty.

1.1 Research Motivation

The U.S. Department of Health and Human Services (HHS) Office of the Assistant Secretary for Preparedness and Response (ASPR) recognizes that all-hazards preparedness plays a significant role in the ability of the health care and public health sectors to respond and adapt to disaster occurrence. ASPR developed the *2017-2022 Health Care Preparedness and Response Capabilities* document to help guide health care organizations in readiness assessment. The first of the four capabilities outlined in this document is "Foundation for Health Care and Medical Readiness" in which health care organizations work together with their stakeholders to identify gaps in the health care supply chain [20]. This is a necessary step in assessing a health care organization's ability to respond when a disaster occurs.

The need to assess all-hazards preparedness was revealed in part by the failures of previous disaster response. During the H1N1 influenza pandemic in 2009, there was a shortage of N95 respirators, masks that help prevent the spread of a virus by blocking entry into the wearer's airways [37]. These respirators are vital for personnel exposed to certain pathogens, but since they are not used on a routine basis and expire after 5 years, the health care sector is less inclined to keep large stocks of them on hand for disaster response. Another example of shortages is within the pharmaceutical field. The U.S. Government Accountability Office (GAO) found that between 2010 and 2015, an average of 420 prescription drugs were in shortage each year. GAO determined that these shortages were due to three main factors, one of which was a decline in the number of suppliers [30]. The GAO goes on to make the claim that shortages could be due to supply disruptions [30]. Supplier selection can help play a role in mitigating these shortages.

Supplier selection involves the customer deciding which suppliers to purchase from and how much to buy from each supplier. In the health care supply chain, customers include distributors and providers, such as hospitals, clinics, and public health departments. These entities purchase supplies and equipment from suppliers and manufacturers. The customers must decide who to purchase from and what quantity to purchase from those suppliers. The customers might work together with the suppliers to create contracts, establish prices in the case of quantity discounts, and create lead-time guarantees. By accounting for disaster uncertainty during supplier selection, both customers and suppliers can find themselves more prepared to handle the increased demand that occurs during a disaster scenario, improving all-hazards preparedness within the supply chain.

1.2 Contributions

Most research in the field of supplier selection is applied outside of the health care environment. The few existing applications of supplier selection in health care focus mainly on selecting suppliers for the pre-positioning of supplies (such as in stockpiles) and efficient post-disaster procurement. This thesis makes valuable contributions to the research field of supplier selection under disaster uncertainty.

The first contribution is a scenario-based deterministic optimization approach that places weighted importance on minimizing costs and limiting supply shortages while considering disaster uncertainty. Existing research into supplier selection outside of the health care environment tends to focus on minimizing costs, and in some cases, maximizing service level, which oftentimes means maximizing filled orders. However, few, if any, place an emphasis on minimizing shortages. In this application, it is more important to minimize shortages of supplies than maximize service level because maximizing service level might lead to recommendations which do not align with the goals of this research, such as filling certain customer orders before others to achieve a higher service level. The optimization approach presented in this thesis also considers customer joint purchasing agreements. In a joint purchasing agreement, two or more customers choose to place one combined order from a supplier to earn quantity pricing discounts. Customer purchasing decisions are altered with these joint purchasing agreements; this is explicitely considered in supplier selection. The model developed in this research is scalable to supplier selection decisions made by health care organizations at a regional or statewide level.

This research also implements a computational study to provide insight into customer behavior during supplier selection. The study looks at customer purchasing decisions with respect to supplier diversity when joint purchasing agreements are and are not used. The results of this study are used to develop recommendations for decision makers within the health care supply chain. There are recommendations for decision makers on both the supplier side and the health care provider, or customer, side alike.

1.3 Outline

The remainder of this thesis is organized as follows. Chapter 2 reviews existing literature regarding health care emergency preparedness and response, supplier selection, and stochastic programming. The literature review also explains the importance of each of these topics and their relevance to the research presented in this thesis. Chapter 3 describes the problem that motivated this research and introduces the optimization model that was developed. The model includes probabilistic scenarios for disaster uncertainty and focuses on the minimization of overall costs and supply shortages. Chapter 4 discusses the application of this model in a computational study. Following the establishment of assumptions and parameter values, a number of experiments are presented to demonstrate the effects of joint procurement on supplier diversity. Finally, Chapter 5 summarizes the results of this research and makes relevant recommendations. This chapter also identifies opportunities for future work.

Chapter 2 - Literature Review

The following chapter introduces relevant literature to this research. The first section relays the importance of emergency preparedness and response in the health care setting. The second section provides existing examples of supplier selection occurring in both commercial and health care environments. The third section provides an overview of the applications of stochastic programming and describes how a stochastic optimization model can be translated into a deterministic optimization model. The fourth and final section focuses on supplier selection models that contain features which can be applied to the research presented in this thesis.

2.1 Health Care Emergency Preparedness and Response

The health care industry is one of the most important resources for emergency preparedness and response. This is especially true in the case of mass-casualty events including natural disasters, shootings, and terrorist attacks, and infectious disease outbreaks such as H1N1, Ebola, or COVID-19. A robust supply chain is necessary to ensure that organizations are adequately equipped for response to such disasters [19]. Supply chains in the health care system are similar to commercial supply chains in that they include a customer and manufacturer or supplier. However, health care supply chains vary from other supply chains such that the consequences of inefficient operations can be far more serious and devastating. Where a supply shortage in a factory limits the number of completed products, a supply shortage in a hospital limits the number of patients that will receive care. Products cannot be produced when there is a shortage of raw materials in a manufacturing plant, much the same way that patients cannot be treated at the appropriate standard of care when a hospital does not have the correct supplies. The inability to meet product demand in a commercial setting leads to lost revenue, but the inability to meet care needs in a hospital can have life-altering results, and in some cases lead to increased morbidity and mortality. It is necessary to assess and evaluate the effectiveness of emergency preparedness and response within the health care industry.

When analyzing a health care supply chain, gaps are identified between the current and desired states of the supply chain. The identification of these gaps encourages increased focus on those areas so that the gaps can be closed, therefore improving the supply chain. A number of gaps have previously been identified and analyzed. Logistics management, which refers to managing the movement of supplies and equipment, is crucial to the success of a medical organization during disaster response [32]. It is important to create transportation plans for various scenarios prior to the occurrence of a disaster. However, due to the variability of disaster effects and consequences, collaborative communication during disaster response is vital for efficiently delivering supplies and resources. In addition to transporting supplies and equipment to a facility during disaster response, transportation away from an affected area must sometimes be considered, such as post-event evacuation protocols [3]. The demand of traffic flow moving away from a disaster is often highly uncertain and requires pre-planning to determine the best evacuation plans based on when and where a disaster might occur.

An additional way that supply chain gaps can be combatted before a disaster occurs is the use of pre-positioning planning. Most literature focuses on post-disaster actions, in which case supplies are distributed from predetermined locations. The strategic placement and stocking of these stockpiles can improve response times during a disaster and reduce costs for the organization. During pre-positioning planning, an organization needs to consider facility location, stocking quantities for emergency supplies, and how those supplies will be distributed to demand locations, depending on stockpile and transportation network conditions after an event occurs [22]. Stocking quantities can be further broken down into the two categories of storage capacity and initial inventory of supplies [13]. These considerations can also be expanded to include desired service quality to ensure that a certain level of demand is met within a specified amount of time during disaster response [23]. One example focuses on stockpile location and allocation in the state of Kansas [33]. For this model, stockpile locations are preexisting, and decisions are made regarding which locations to stock and how supplies should be distributed from those locations. It was determined that opening multiple stockpiles is more beneficial than one centralized stockpile, and vehicle routing decisions change as demand changes.

Another gap that occurs in health care disaster preparedness and response supply chains is the lack of elasticity. Elasticity refers to a supply chain's ability to expand or contract its operations in response to a change in demand [15]. Due to the uncertainty of demand during disaster response, elasticity is important to consider within the health care supply chain. A network that focuses on minimizing costs by cutting inventory and ordering only as much supply as is needed on a routine basis can become too lean and inelastic, leading to supply shortages during a surge disaster response [15]. Many health care systems practice just-in-time methodology, meaning supplies are ordered only as they are needed. This methodology is highly cost effective during routine situations but limits the ability of an organization to respond in a disaster. One way that organizations combat this inelasticity is through the use of stockpiles [21]. These stockpiles act as an aid during disaster response, providing the additional needed supplies and equipment that are not covered by the routine supply. On the other hand, a highly elastic network can be expensive and wasteful, especially in the case of perishable supplies that could expire before the organization has a chance to use them.

Perishable supplies, such as blood, require additional attention and planning because there are limitations on shelf-life and distribution. There is typically enough blood and blood donors to cover need during a disaster, but inefficient distribution can lead to the underutilization of blood stores and have vastly negative consequences. For example, following the September 11 attacks, blood donations were at least double the normal rate, but a large part of the donated blood could not be utilized because it was not effectively stored or distributed [9]. A model for the timely and efficient distribution of blood during disaster response was developed to avoid situations such as the September 11 failure noted previously. In this instance, supply chain planning can be the difference between someone receiving blood and losing their life. In general, one of the first decisions within supply chain planning involves choosing suppliers.

2.2 Supplier Selection

Supplier selection is the process that a customer completes when selecting one or more suppliers. It is used to determine which suppliers to select, as well as how much supply should be ordered in a given time period [10]. Depending on the problem, supplier selection can improve cost efficiency and increase reliability, both of which are important factors to consider in a health care setting. Supplier selection has been modeled using a number of methods, but most common among them are mixed integer programming and stochastic optimization. The choice of model depends on the decision maker's objectives. The following section considers some applications of supplier selection outside of health care, but which contain concepts that can be applied within the health care field.

Supplier selection and order allocation are often considered simultaneously. When more than one supplier is chosen under supplier selection, it is necessary to determine the amount of supply that will be purchased from each supplier. Breaking up the demand among multiple suppliers is called an order splitting strategy [18]. Using order splitting strategy encourages competition between suppliers, which helps to keep costs reasonable and improve quality. It is also useful in the context of disaster preparedness because under order splitting strategy, if one supplier experiences a disruption, the organization can rely on a different supplier to provide the necessary supplies. However, the benefits of order splitting strategy can sometimes be outweighed by the value of minimizing costs. It is important to consider quantity discounts when looking at whether or not to use multiple suppliers [5]. In some cases, it is more cost effective to stick to fewer suppliers when purchasing supplies in bulk.

For the applications of health care disaster preparedness and response, it is useful to consider supplier selection with respect to supply chain risks. Supply chain risks are typically divided into two categories: operational and disruption [29]. Operational risks refer to uncertainty regarding customer demand and internal failures, whereas disruption risks refer to large-scale disasters. Risks can also be labeled as “superevents” which affect all suppliers, “unique events” which affect individual suppliers, and “semisuperevents” that affect subsets of suppliers [17]. Superevents would fall under the disruption risk category, unique events would be categorized as operational risks, and semisuperevents could be either disruption or operational depending on the scale of the disaster and the event that takes place.

There are many approaches to incorporating supply chain disruption into supplier selection. Oftentimes, probabilities regarding ability to meet demand are assigned to suppliers. This can be done one of two ways: (1) assigning separate probabilities to each supplier to account for individual supplier disruptions, or (2) assigning one overall probability to all suppliers to represent a large-scale event which disrupts all suppliers [24]. One way to determine how to assign individual probabilities of meeting demand is to use resilience scores [31]. Resilience scores are developed based on a supplier's supply network characteristics. Suppliers whose material flow is likely to be more impacted by a disaster's occurrence will have a lower resilience score than suppliers who are less likely to be impacted. Other research further emphasizes the importance of supplier resilience by mentioning capacity restoration. The research concludes that supply chains with strong pre-disaster plans are not always as reliable as supply chains that possess better restorative capacity, or the ability to recover lost capacity quickly after a disaster occurs [12]. Resilience is based off of a supplier's ability to prepare for and respond to disruptions, so improving restorative capacity would increase a supplier's post-disruption resilience and make them a more desirable choice.

Disruptions can also impact the selection of suppliers based on a disruption's frequency and length. One example looks at varying disruption-management strategies for choosing between two suppliers: the first of which is unreliable, and the second having volume flexibility, which makes it more reliable, but also more expensive [28]. In this example, it was discovered that when disruptions were more frequent and shorter, inventory management was preferred, meaning the customer purchased supplies only from the unreliable supplier and carried extra inventory to mitigate the disruptions. But as disruptions became less frequent and longer, it was in the best interest of the customer to move to a sourcing mitigation strategy, in which they purchased solely from the reliable supplier. The previously described examples model supplier selection in a number of ways. One such way is through the use of stochastic programming.

2.3 Stochastic Programming

During disaster preparedness, organizations are faced with uncertainty regarding when and where a disaster will occur. To model this uncertainty, stochastic programming can be used. Stochastic programming models decision making under uncertainty. It is used to find an optimal solution for multiple sets of input data, or rather, a solution that satisfies a combination of scenarios without favoring any one over the others [6]. Uncertainty can occur within a supply chain, such as uncertain demand or supply. It can also be an external factor that affects the supply chain, such as uncertainty about disaster occurrence. In practical applications, most of the above factors pose uncertainty simultaneously, but for modeling purposes, some uncertain parameters may be given deterministic values while the remaining uncertain parameters are used to develop scenarios. For example, even though demand might be considered uncertain most of the time, it can be given a fixed value when trying to determine the effects of variability in other parts of the calculation, such as disruption uncertainty [26].

Stochastic programming is typically developed as a two-stage optimization model. This allows for the use of two separate objective functions. The first objective function is developed for the overall optimization goals of the model and the second objective function considers any uncertainty within the model, providing the unknown element of the model. For example, decisions regarding supplier selection can be made in the first stage, while post-disaster procurement quantities and transportation decisions are made in the second stage, based on unknown demand quantities [14]. In another example, costs are minimized, and customer service level is maximized under uncertainty due to a set of disruption scenarios [32]. A third example determines facility location and supplier interaction in the first stage, with decisions regarding procurement and transportation quantities occurring in the second stage when uncertainty about facility damages and demand of supplies is considered [13]. These are just three examples of how stochastic programming can be applied to health care operations using two-stage optimization models.

In some cases, a problem facing uncertainty can be developed as a deterministic optimization model by assigning probabilities to the varying scenarios. Each set of inputs is associated with a probability of occurrence, such as three sets of input data with three probability values that sum to one [6]. To understand this connection, we look at a farmer's problem. A farmer is trying to optimize crop planting decisions and introduces scenarios for above- and below-average crop yields. This can be modeled deterministically by assigning probabilities to each scenario (above-average, average, and below-average crop yield). Or it can be modeled stochastically through the use of two-stage modeling in which costs are minimized in the first stage through decisions on how many acres to devote to each crop and sales are maximized in the second stage depending on the crop yield [4]. This is just one example of how a stochastic model can be translated into a deterministic model using probabilities.

2.4 Supplier Selection Under Disruption Risks for Health Care Organizations

The research described in this thesis is at the intersection between the three previous areas. It is most closely related to papers that study supplier selection under disruption risks, especially when applied within a health care setting. This section identifies and explains existing research that falls within that category, emphasizing key aspects of model formulation, results, and conclusions.

The first paper focuses on supplier selection with disruption risks in a centralized supply chain [8]. The research presented in this article is not applied in a health care setting but still makes significant contributions. In this case, a mixed-integer nonlinear programming (MINLP) model is developed to determine optimal supplier selection and order allocation between multiple suppliers with only one customer. The objective of the MINLP model is to minimize total costs of the supply chain. To model disruption, a probability is applied to each supplier regarding whether or not that supplier can deliver product during a given disruption scenario. The model is also extended to look at the differences in results when mitigation strategies are used. One of the strategies is supplier protection, where the decision maker decides ahead of time certain suppliers whose capacity remains unchanged in the event of a disruption. The second strategy is pre-positioned inventory, in which protected suppliers can possess a pre-established emergency stock of products. Two numerical experiments are run to compare the results of the simplified model and the extended model with mitigation strategies. It was discovered that when using the simplified model, purchasing costs plays a bigger role in supplier selection than disruption risk, but in the extended model, suppliers with lower disruption probability are favored. These results are used to support the claim that disruption mitigation strategies are necessary because they both protect the supply chain from disruption risks and increase the overall expected profit within the supply chain.

The second article is similar to the first in the sense that it is centered around supplier selection under disruption risks [17]. In addition, this paper introduces mixed uncertainties for a variety of supply chain elements to provide a more realistic representation of the uncertainties that accompany supplier selection. A deterministic multiobjective programming model (LMOP) is created with the intent to maximize the total profits and minimize the percentage of late and rejected products. This article looks at disruption divided into the three categories discussed previously in Section 2.2: (1) superevents, (2) semisuperevents, and (3) unique events. Individual probabilities are assigned to each supplier to represent the chance of a unique event affecting that supplier, while a probability that affects all suppliers is applied to represent a superevent. A numerical example is given that includes five suppliers and ten customers. Results from this experiment agree with the results of the first paper, that cost is a leading factor in supplier selection. Regarding disruption, it was discovered that unique events have a greater impact on supplier selection than superevents because the customer shows preference to suppliers with a lower probability of disruption risk.

The last paper that will be discussed in this section looks at supplier selection integrated with the disruption management strategy of pre-positioning in humanitarian relief [13]. A two-stage stochastic mixed integer program is formulated where supplier selection decisions are made in the first stage and the second stage includes post-disaster procurement and transportation quantities. In this situation, the disruption risk refers to the possibility that a disaster will destroy facilities and/or suppliers, which in turn limits the amount of inventory and production capacity that can be used following a disaster. The model accounts for this by including a parameter representing how much of the pre-positioned inventory at a supplier or facility location will still be usable after a disaster occurs. The model also includes procurement price discounts for purchasing from suppliers in bulk and commitment quantity, where an organization agrees to purchase a minimum amount of supplies in return for a fixed price. The commitment quantity includes other costs, such as overhead and coordination costs. The model is applied to a set of real data from hurricanes occurring in the Gulf of Mexico region. From the results of this experiment, it was determined that procurement price discounts are taken into account in supplier selection. The researchers also concluded that integrating supplier selection and pre-positioning of supplies can both decrease costs throughout the supply chain and limit the risk of supply shortage.

Each of these three articles outlining prior research into supplier selection under disruption risks makes valuable contributions to the research outlined in this thesis. The articles present models for supplier selection under disruption risk that consider disaster mitigation strategies, uncertainty that occurs within the supply chain, varying probabilities of disruption, pricing discounts for bulk purchasing, and overhead costs. However, there are still important aspects of the problem that have not been studied, such as joint procurement and supplier diversity. It is important to consider the effects of joint procurement on customer purchasing decisions, and supplier diversity should be examined in order to make useful recommendations to purchasing decision makers. Each of the three articles uses a different type of optimization strategy: (1) mixed-integer nonlinear programming, (2) deterministic multiobjective programming, and (3) two-stage stochastic mixed integer programming. For the purposes of this research, a deterministic optimization model with multiple scenarios is developed that includes a combination of the above features, adapting them to fit the model's application. This model is then applied in a computational study which examines customer purchasing decisions with the introduction of supplier diversity and joint procurement. This research makes important contributions within the field of supplier selection under disaster probability by answering the following questions. How does increased supplier diversity impact the distribution of purchases among suppliers? Does increased supplier diversity help to mitigate the effects of disaster occurrence? How does the introduction of joint procurement agreements alter customer purchasing decisions?

Chapter 3 - Methods

During disaster response, it is necessary for health care organizations to have plans in place for efficient acquisition and distribution of supplies. An increased number of patients can be helped in a timely manner when improvements are made to this stage of the supply chain. This chapter describes the concerns related to supply acquisition that motivated this research. It also introduces a scenario-based supplier selection model under uncertainty that can be used to solve the problem.

3.1 Problem Definition

When a mass-casualty event or infectious disease outbreak occurs, health care organizations experience a massive surge in need for supplies and equipment. Some organizations mitigate this added demand with stockpiles that are kept on-hand or nearby. However, stockpiles are expensive to maintain and have limited capacity. In addition, it is not possible to stockpile all of the items that might be needed during disaster response. All health care organizations, stockpile or not, must utilize the health care supply chain to order and receive supplies during disaster response. In the health care supply chain, manufacturers and suppliers sell supplies and equipment to distributors and providers, such as hospitals, clinics, and public health departments.

The model proposed here is motivated by evidence of supplier consolidation in health care. Less than five suppliers control over 75% of the market in a number of common medical supply categories [35]. For example, there are three suppliers controlling a majority of the market for medical gowns, two suppliers for surgical gloves, and one supplier for blood collection needles, all of which are needed on a routine basis, and even more so during disaster response. In the pharmaceutical industry especially, there has been a significant increase in mergers and acquisitions, which has led to a decrease in the available number of pharmaceutical suppliers. An article written in 2019 backs up this claim when it states that in 2018 there were 803 mergers and acquisitions within the health care industry [7]. Health care coalition members in Kansas also raised this concern in a recent study examining supply chain integrity for health care preparedness and response in Kansas [36].

In addition to supplier consolidation, facility closures pose a concern. The FDA has been monitoring the effects of closing facilities where ethylene oxide is used to sterilize medical devices. These closures have led to supply shortages across the nation [27]. With fewer suppliers comes an increased risk of supply shortage, as distributors and providers alike must overlap purchasing from the same manufacturers. The use of joint purchasing during this overlap can be beneficial for all parties involved.

Joint procurement occurs when two or more customers join together to place a single order so that they earn quantity discounts from the supplier. Joint procurement can be beneficial for both the customers and the suppliers. In a study of joint procurement within a fresh produce supply chain, it was found that the profit for both suppliers and retailers was greater when the retailers entered joint procurement contracts than when they purchased from the suppliers independently [34]. Another example assesses the results of joint procurement of pharmaceuticals in Jordan. Joint procurement was implemented to combat a number of inefficiencies within the pharmaceutical sector. The results of the assessment showed a significant savings over one year such that it was recommended to continue this joint procurement in future years [2]. The research presented in this thesis analyzes the effects of implementing joint procurement on supplier selection and customer purchasing decisions when disruption uncertainty is considered. The following section outlines a modeling approach that can be used to solve this problem.

3.2 Model

This section describes the scenario-based supplier selection model under uncertainty with joint procurement. This model minimizes purchasing costs while also minimizing supply shortages for each customer. The model notation, parameters, and mathematical formulation are provided below.

3.2.1 Notation and Parameters

The cost parameters for this model include unit costs for individual and joint purchases, as well as a shortage cost associated with the amount of shortage a customer experiences and an overhead cost for customers to enter joint purchasing agreements. The shortage cost is a monetary representation of the loss incurred by supply shortage. Since shortage in the health care context represents potential for increased morbidity and mortality, this parameter captures the social cost, rather than simply the cost of lost sales as may be used in other applications. Accordingly, shortage cost far exceeds unit purchasing costs from any supplier in our study. The parameter specifying the minimum number of suppliers exists to alter the minimum number of suppliers that each customer is required to purchase from. This parameter is important for analyzing the effects of supplier diversity. There are also parameters for customer demand, supplier capacity, and a limit on the amount of supplies that each customer can purchase jointly from a supplier. Regarding disaster scenarios, there is a probability of disaster occurrence and an increase in demand associated with that disaster.

i index of customers

j index of suppliers

s index of scenarios

r shortage cost

Min minimum number of suppliers that each customer must purchase from

D_i demand of customer i

Cap_j capacity of supplier j

c_j unit cost to purchase from supplier j

h_j unit cost to purchase jointly from supplier j

o_i overhead cost for customer i to enter a joint purchasing agreement

m_j maximum number of units each customer can purchase jointly from supplier j

p_s probability of scenario s occurring

n_s increase in demand for scenario s

3.2.2 Decision Variables

The decisions made in this model include customers deciding to enter joint purchasing agreements with other customers, quantities of supply that each customer orders individually and jointly from each supplier, and how much supply shortage will be experienced by each customer.

x_{ij} units of supply that customer i purchases from supplier j

y_{is} units of supply that customer i is short in scenario s

w_{ij} units of supply that customer i purchases jointly from supplier j

z_{ikj} = 1 if customers i and k both choose to purchase jointly from supplier j

0 otherwise

q_{ij} = 1 if customer i purchases jointly from supplier j

0 otherwise

b_{ij} = 1 if customer i purchases from supplier j

0 otherwise

3.2.3 Mathematical Formulation

The complete formulation of the supplier selection model is as follows:

Minimize
$$\sum_{i\in I}\sum_{j\in J} c_j x_{ij} + \sum_{i\in I}\sum_{j\in J} h_j w_{ij} + \sum_{i\in I}\sum_{j\in J} o_i q_{ij} + \sum_{i\in I}\sum_{s\in S} p_s r y_{is} \tag{3.1}$$

Subject to
$$\sum_{i\in I}(x_{ij} + w_{ij}) \leq Cap_j \quad \forall\, j \in J \tag{3.2}$$

$$\sum_{j\in J}\left(x_{ij} + w_{ij}\right) + y_{is} \geq D_i n_s \quad \forall\, i \in I, s \in S \tag{3.3}$$

$$x_{ij} + w_{ij} \leq Cap_j b_{ij} \quad \forall\, i \in I, j \in J \tag{3.4}$$

$$\sum_{j\in J} b_{ij} \geq Min \quad \forall\, i \in I \tag{3.5}$$

$$x_{ij} + w_{ij} \geq 50 b_{ij} \quad \forall\, i \in I, j \in J \tag{3.6}$$

$$z_{ikj} - z_{kij} = 0 \quad \forall\, i \in I, k \in I\colon k \neq i, j \in J \tag{3.7}$$

$$\sum_{k\in I: k\neq i} z_{ikj} \geq q_{ij} \quad \forall\, i \in I, j \in J \tag{3.8}$$

$$q_{ij} \geq z_{ikj} \quad \forall\, i \in I, k \in I: k \neq i, j \in J \tag{3.9}$$

$$q_{ij} \leq w_{ij} \quad \forall\, i \in I, j \in J \tag{3.10}$$

$$w_{ij} \leq q_{ij} m_j \quad \forall\, i \in I, j \in J \tag{3.11}$$

$$z_{ikj} \in \{0,1\} \quad \forall\, i \in I, k \in I, j \in J \tag{3.12}$$

$$b_{ij} \in \{0,1\} \quad \forall\, i \in I, j \in J \tag{3.13}$$

$$q_{ij} \in \{0,1\} \quad \forall\, i \in I, j \in J \tag{3.14}$$

$$x_{ij} \geq 0 \quad \forall\, i \in I, j \in J \tag{3.15}$$

$$w_{ij} \geq 0 \quad \forall\, i \in I, j \in J \tag{3.16}$$

$$y_{is} \geq 0 \quad \forall\, i \in I, s \in S \tag{3.17}$$

OBJECTIVE: The main objective of this model is to minimize costs, which in turn minimizes both purchasing costs and the expected cost of supply shortage because of the high cost associated with shortage. The first term calculates the total individual purchasing cost across all customers. Similarly, the second term calculates the total joint purchasing cost across all customers. To add to the total joint purchasing cost, the third term incorporates the overhead that each customer must pay who enters a joint purchasing agreement. The fourth and final term combines the probability of occurrence and shortage cost to allocate supply shortage to each scenario.

CONSTRAINTS: Constraint (3.2) is a capacity constraint for all suppliers. The sum of supplies purchased from a supplier, including both joint and individual purchases, cannot exceed that supplier's capacity. Constraint (3.3) is a demand constraint for all customers. The amount of supplies that a customer purchases, both jointly and individually, summed with the customer's shortage, must be at least the amount of demand for that customer. The demand fluctuates with each scenario and is multiplied by the increase in demand for a given scenario. For example, demand is multiplied by n_s=1 during the routine scenario, and n_s>1 for surge demand scenarios. Constraints (3.4) and (3.5) are used to ensure that each customer is purchasing from at least the minimum number of required suppliers, whether through individual or joint purchases. These constraints are useful when analyzing the effects of supplier diversity. Constraint (3.5) is used to set the minimum number of suppliers and constraint (3.4) requires purchases to be zero when a customer is not purchasing from a supplier. Constraint (3.6) sets a minimum order quantity of 50 products, which forces the model to display reasonable purchasing amounts, not allowing for a customer to make an unreasonably small purchase to meet the multiple suppliers criteria.

The next five constraints are related to joint purchasing. A customer cannot purchase jointly from a supplier unless at least one other customer is also purchasing jointly from that supplier. Constraint (3.7) ensures that if a customer wants to enter a joint purchasing agreement with another customer, both customers are purchasing jointly from the same supplier. In other words, if customer *i* is entering a joint purchasing agreement with customer *k*, then customer *k* is also entering a joint purchasing agreement with customer *i*. Constraints (3.8) and (3.9) translate a customer's decision to purchase jointly with another customer into that customer purchasing supplies jointly. From there, constraint (3.10) is used to determine how much that customer will be purchasing jointly. In constraint (3.11), a limit is set on the maximum amount of supplies that a customer can purchase jointly from each supplier. The remaining constraints establish binary variables and non-negativity for all decision variables.

Chapter 4 - Analysis

The model developed in Chapter 3 was used to perform a number of experiments to aid in the analysis of customer purchasing decisions under varying scenarios. After establishing a set of model assumptions, parameters were established, and four experiments were run. These experiments were designed with the intention of answering the previously identified questions: (1) How does increased supplier diversity impact the distribution of purchases among suppliers? (2) Does increased supplier diversity help to mitigate the effects of disaster occurrence? (3) How does the introduction of joint procurement agreements alter customer purchasing decisions?

4.1 Model Assumptions

When applying this model, a number of assumptions were established. These assumptions helped with the creation of parameters and, in some instances, set values for those parameters. The assumptions are as follows:

- **Joint purchasing quantity limit** – It is assumed that each supplier sets a limit on the maximum amount of supplies that each individual customer can purchase jointly from them. This parameter is necessary so that customers cannot purchase all supplies at the discounted joint purchasing price. In practice, this limit would be established in the contract for the joint purchasing agreement.
- **Unlimited customer joint agreement** – Another assumption is that there is no limit on the number of customers who can enter a joint purchasing agreement. In other words, any combination of customers can choose to purchase jointly from the same supplier.

- **Minimum order size** – A minimum order size of 50 is set so that customers do not make insignificant purchases from suppliers. This is to ensure that each sale covers the supplier's transactional costs to fulfill an order.
- **Probability of disaster** – Disaster occurrence is modeled based on the probability that a disaster will occur in a year. For example, if the parameter p_s is set to 0.2, then the assumption is that there is a 20% chance a disaster will occur in the scenario being analyzed.
- **Demand increase due to disaster occurrence** – To model the effect of disaster occurrence on customer demand, a parameter was introduced which increases demand in the case of the disaster scenario. This parameter, n_s, is set to 2.5 to show that when a disaster occurs, demand increases to 250% of the baseline which represents a significant spike in demand. In practice, this parameter should be based on expert input and examined with sensitivity analysis.

Each of these assumptions is utilized in the following experiments.

4.2 Computational Results

One of the ways that customers can mitigate risk during disaster response is through supplier diversity. Purchasing from a single supplier leaves customers vulnerable to experiencing supply shortage when that supplier cannot fulfill demand. This can occur when the supplier experiences a disruption, either internally or externally, or there is a surge in demand. The experiments outlined in the following sections test the effectiveness of supplier diversity both with and without joint procurement. These experiments were solved using CPLEX version 12.5

run on a desktop PC with 3.1 GHz processor and 8.00 GB RAM, and all instances solved within seconds.

4.2.1 Supplier Diversity without Joint Procurement

To start, the effects of supplier diversity are analyzed without considering additional factors, such as joint procurement. A set of five customers and five suppliers is used for this experiment. Each customer experiences different demand and all customers are given a high overhead cost to force a solution that does not involve joint purchasing. Data regarding customer demand and overhead costs are given in Table 1. Each supplier has the same maximum capacity, with a total maximum capacity exceeding the total customer demand so that no customers experience shortage. The purchasing costs are also the same for every supplier. Data regarding supplier capacity and routine purchasing costs are also given in Table 1. As mentioned in the assumptions, for this experiment there is a 20% probability that a disaster occurs within the year, and a 250% increase in demand when it does.

The base case for this experiment is that every customer must purchase from at least one supplier. The number of suppliers that a customer must order from increases with each trial. In the base case, customers 1, 3, and 5 purchase the entirety of their demand from a single supplier, and customers 2 and 4 split their demand between two suppliers. The distribution of purchases across all five suppliers is shown in the graph of Figure 1. This graph shows that all of the customers are purchasing from suppliers 1, 2, and 3. If something were to happen to any of those suppliers, there would be devastating consequences to any of the customers, especially customers who are purchasing all of their supplies from that supplier.

Table 1 - Experimental data

All Experiments	Customer	1	2	3	4	5
	Demand	300	350	400	450	500
	Supplier	1	2	3	4	5
	Capacity	2000	2000	2000	2000	2000
	Routine Cost	10	10	10	10	10
	Shared Cost	8	8	8	8	8
	Scenario	1	2			
	Probability	0.8	0.2			
	Increase in Demand	1	2.5			
	Shortage Cost	100				
Experiment 1	Customer	1	2	3	4	5
	Overhead	1000	1000	1000	1000	1000
Experiment 2	Customer	1	2	3	4	5
	Overhead	300	300	300	300	300
	Supplier	1	2	3	4	5
	Joint Purchasing Limit per Customer	200	200	200	200	200
Experiment 3	Customer	1	2	3	4	5
	Overhead	300	300	300	300	300
	Supplier	1	2	3	4	5
	Joint Purchasing Limit per Customer	2000	2000	2000	2000	2000
Experiment 4	Customer	1	2	3	4	5
	Overhead	300	300	300	300	300
	Supplier	1	2	3	4	5
	Joint Purchasing Limit per Customer	200	2000	200	200	2000

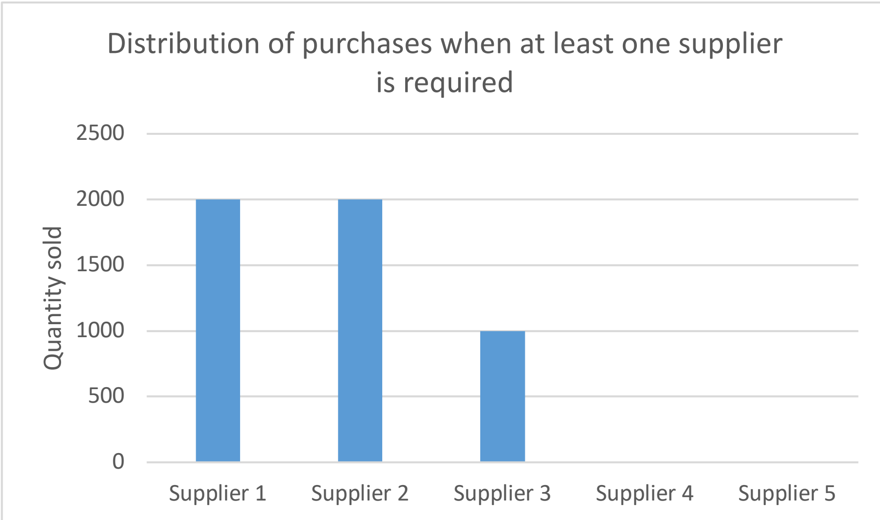

Figure 1 - Base case purchasing distribution

In the second case, the minimum number of required suppliers per customer increases to two. When this scenario is run, every customer purchases from two suppliers. The purchasing distribution for this case is given in Figure 2. This case finds the introduction of supplier 4. The number of suppliers increases, but the distribution is still heavily on the first three suppliers.

Figure 2 - Case 2 purchasing distribution

A third case is tested, where the minimum number of required suppliers is increased to three. In this case, every customer purchases from three suppliers. The purchasing distribution for this case is given in Figure 3. It shows that all five suppliers are being utilized in this scenario. The majority of purchases can still be attributed to the first few suppliers, but the supplier diversity ensures that each customer does not have all of their eggs in one basket. Four out of the five customers purchase most of their supplies from a single supplier, making minimum purchases of 50 from the other two suppliers.

Figure 3 - Case 3 purchasing distribution

As supplier diversity increases, modeled by increasing the minimum number of required suppliers, customer security also increases. As customers purchase from more suppliers, the impact of a supplier not being able to fill demand diminishes. A customer will still be impacted, but less so than if they were purchasing solely from that supplier. That being said, there is still room for improvement. When two suppliers are required, 3/5 of the customers purchase most of their supplies from a single supplier and make the minimum purchase of 50 from the second supplier. When three suppliers are required, 4/5 of the customers purchase most of their supplies from a single supplier and make minimum purchases of 50 from the other two suppliers. Due to the given parameters, there are multiple optimal solutions for these scenarios which would provide the same objective function value with a different distribution of purchases. Introducing varied purchasing costs across suppliers would also lead to varying distributions. Customers would be more likely to purchase as much as they can from cheaper suppliers, but as the required number of suppliers increases, a cost would be incurred for purchasing from other suppliers at a higher cost. The experiment in the following section was motivated by a need to find a more even distribution of purchases across suppliers.

4.2.2 Joint Purchasing

This section discusses supplier selection with the inclusion of joint purchasing. For this experiment, the same set of 5 customers and 5 suppliers is used. For customers, the overhead cost of entering joint purchasing is decreased to a more reasonable amount, so that customers are more inclined to enter joint purchasing agreements. The supplier data is expanded to include values for joint purchasing parameters. The cost of purchasing under joint procurement is discounted compared with routine purchasing costs and a joint purchasing ordering limit is imposed for each customer purchasing jointly from a supplier. The altered customer and supplier data for the second experiment are given in Table 1.

When joint purchasing is utilized by the model, supplier diversity increases for all five customers, as opposed to the base case from the previous experiment where each customer purchases from only one or two suppliers. With joint purchasing, customers 1 and 2 purchase from four suppliers, and the other three customers purchase from all five suppliers. The distribution of purchases across all suppliers is shown in the chart presented in Figure 4. Compared with the results of the base case, the distribution of purchases is more evenly spread across all suppliers. This is due to the purchasing discounts that joint procurement provides. All of the customers purchase as much as they can at the discounted price, purchasing up to the limit from various suppliers until their demand is filled.

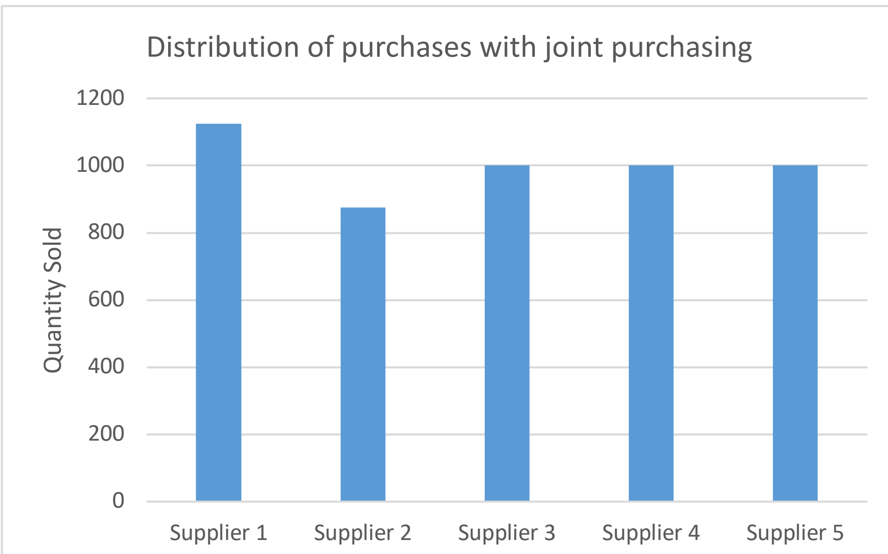

Figure 4 - Experiment 2 purchasing distribution

The results of this experiment show that the use of joint purchasing has benefits for customers and suppliers alike. Customers experience the added security of supplier diversity, spreading their purchases among multiple suppliers to mitigate the effects of supplier disruption. Suppliers share the weight of filling customer demand so that there are not any suppliers with drastically more or less orders to fill. The next section discusses the effects of changing the joint purchasing limit.

4.2.3 Joint Purchasing Ordering Limit

In the previous section, each supplier imposed a joint purchasing order limit of 10% of their capacity on each customer. Any customer that purchased from that supplier could only purchase up to a certain amount under joint procurement. This section emphasizes the importance of setting joint procurement limits. The following experiment uses the same set of 5 customers and 5 suppliers with all of the same values as before, except there is no limit on the amount a customer can purchase jointly from a supplier. The updated customer and supplier data for the third experiment can be found in Table 1.

This experiment shows what happens when organizations do not need to place limits on the amount of product they can sell at a discounted price. This kind of power is often limited to large organizations who have the ability to provide large amounts of product at a cheaper price. In this experiment, all 5 suppliers are represented as these types of organizations. The results are shown in Figure 5. When there is no limit enforced on joint purchasing, customers choose a single supplier to purchase all of their demand from at the discounted rate. There is one customer who purchases from two suppliers so that the purchasing agreements work out between the odd number of 5 customers. In the results, all of the purchasing is limited to suppliers 1, 3, and 5, with zero purchases from suppliers 2 and 4. Not only does this experiment have negative results regarding supplier diversity, but it also shows the poor distribution of purchases among suppliers.

Figure 5 - Experiment 3 purchasing distribution

In a more realistic setting, only 2 or 3 of the suppliers would be large organizations who can forego the joint purchasing limit. This scenario is represented in the following experiment. For this experiment, the same set of customers and suppliers is used as before, however only two of the suppliers (supplier 2 and supplier 4) do not use joint purchasing limits. The updated supplier data for the fourth experiment is given in Table 1.

The results of this experiment are given by Figure 6. This figure is characterized by a very uneven distribution. The suppliers with no limit on joint purchasing sell to capacity, taking over most of the market. The other three suppliers suffer because they are not able to keep up with the other two suppliers' lower costs. Supplier 1 is eliminated from the market altogether and Supplier 4 is close to being edged out. In this scenario, three of the customers purchase from two different suppliers, while the other two purchase their demand from only one supplier each. Again, there is not much supplier diversity in this scenario.

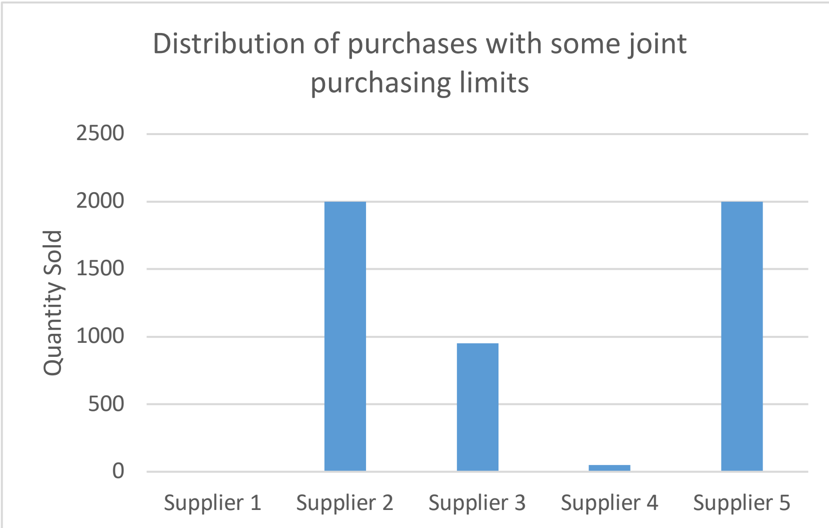

Figure 6 - Experiment 4 purchasing distribution

As mentioned at the start of this section, the joint purchasing limits were established as 10% of a supplier's capacity. In practice, these limits would be determined by the supplier based on how much product the company can sell at a decreased rate or other business goals. It may make sense to set different limits for different customers, such as providing a higher limit to customers with more demand than other customers. The current model can be adapted readily to include those parameters.

4.2.4 Encouraging Supplier Diversity

Based on the experiments outlined in the sections above, supplier diversity can be integrated into the purchasing environment in a few different ways. The first way is to simply increase the number of suppliers a customer is required to buy from. This is shown in the model with the introduction of supplier diversity constraints. In the results, customers purchase from more suppliers, but still purchase as much as they can from a single supplier and do not distribute purchases very well.

The second way is to implement joint purchasing. When customers are allowed to enter joint procurement agreements with other customers, costs are decreased and supplier diversity is increased. However, a limit must be placed on joint purchasing to ensure that certain suppliers are not monopolizing the market. When limits are not used, one or more suppliers might be edged out of the market and customers do not have any supplier diversity. Even though this provides further reduced costs, the tradeoff of decreased costs versus supplier diversity must be taken into consideration. The ideal outcome of these experiments occurs with the highest level of supplier diversity among all customers and when there is a fairly level distribution of purchases among suppliers. This occurred in Experiment 2 when joint purchasing was utilized and a maximum purchasing limit was enforced by all suppliers.

These results can be connected to what is observed in practice. The first experiment shows results that are most likely to lead to supplier consolidation. Customers might choose to limit purchasing to only one or two suppliers for any number of reasons, including but not limited to, customer loyalty, supplier reliability, and bulk purchasing discounts. However, when all customers are purchasing from only one or two suppliers, other suppliers will not get the business they need to remain open, leading to consolidations and acquisitions that further limit the market. In the current market where there are only a few large distributors for some medical supplies, it is important for customers to not only purchase from a variety of those distributors, but also to enter joint purchasing agreements with other customers purchasing from those suppliers. This encourages customers to purchase up to the joint purchasing limit from multiple suppliers to fill their overall demand, as shown in Experiment 2.

The most realistic representation of the current market is shown in Experiment 4, where a couple of suppliers do not place a limit on joint purchases, but the rest do. This can have negative consequences, such as decreased supplier diversity and some suppliers getting edged out of the market. To achieve the ideal results of Experiment 2 rather than the current market, the government could implement regulations or offer incentives to suppliers, encouraging them to enforce a joint procurement limit.

This model can be scaled to a regional or statewide level by adding customers and suppliers to the data spreadsheet and expanding the fields on the model's data sheet in CPLEX. It can also be altered to decrease the number of customers and suppliers, which might be useful for modeling supply categories with fewer available suppliers, such as medical gowns (3 suppliers), surgical gloves (2 suppliers), and blood collection needles (1 suppliers) which were all mentioned previously in Section 3.1.

There are a few limitations of the results of these experiments. One limiting factor is the input data. The number of customers and suppliers is variable depending on the real-life application of this optimization method. Real cost and demand data were unavailable at the time of this research, which led to the development of realistic parameter values. The model itself also presents a few limitations. The model presented in this research assumes that there is a single decision maker optimizing the total cost in the system, but in practice each firm would optimize its own purchases. The model also limits the way that disaster scenarios are considered by combining all disasters into one probability of occurrence.

If disaster probability were to be 0% for the time horizon of interest (meaning there is zero chance of disaster occurrence for that time period), customer demand would not increase for any of the customers and there would not be any shortage because supplier capacity is able to fill routine demand. If disaster probability were increased to 80%, then the purchasing decisions will not change, but the overall costs of the model will be greatly increased if there is any shortage involved. If there is no shortage, then there will not be a change in overall costs. The model increases demand for any single disaster that would occur, so changing the probability of occurrence will not affect purchasing decisions and will only impact the cost of shortage. This points to opportunities to adapt the model to represent opportunities for increasing supplier capacity in periods where there is a higher probability of disaster occurrence.

Chapter 5 - Conclusions and Future Work

At the time of the development of this research, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) which causes coronavirus disease (COVID-19) is sweeping the global community. This pandemic has had major consequences in every nation that it encounters. As of March 25, 2020, there have been 464,683 confirmed cases and 20,942 deaths worldwide from this virus [1]. The health care supply chain has had to adapt to handle the rapid influx of patients as more cases are confirmed each day.

Supply shortages have become quickly apparent as basic equipment and supplies are used up. In South Carolina, hospitals have begun to receive shipments from the Strategic National Stockpile as supplies dwindled to four days' worth of personal protective equipment [16]. In a variety of states including Minnesota, Oregon, and Utah, COVID-19 testing kits are running short, thus forcing the states to limit the people who test for the disease [16]. In Kansas, there are 168 available ventilators across the state, but over half of them are located in Kansas City and Wichita, with expectations for all of them to be in use in the near future [11]. Suppliers are not able to produce faster than orders are coming in, creating a backlog that continues to build upon itself.

These effects are not isolated to the COVID-19 pandemic. Supply shortages presented themselves during the H1N1 influenza outbreak in 2009 as well. In both instances, N95 respirators and face masks could be used to prevent the spread of the disease. However, since N95 respirators are not used on a routine basis, there is a massive surge in demand for this personal protective equipment item during influenza response. Supplier diversity among health care organizations could help to mitigate the issues of filling large amounts of orders in this instance.

As shown in this research, supplier diversity allows for a better distribution of purchases across suppliers as customers are encouraged to purchase from a variety of suppliers. These effects are furthered when joint purchasing agreements are introduced. Previous research into supplier selection under uncertainty explores a number of aspects of disaster response, however, the research presented here combines a number of those aspects, such as pricing discounts for joint procurement, overhead costs, and probabilities of disaster, to analyze the effects of supplier diversity on purchasing decisions in the face of disaster response.

Using the scenario-based supplier selection model developed in this research, the following recommendations were developed for decision makers throughout the health care supply chain:

1. Hospitals and other providers should encourage supplier diversity by purchasing through a variety of suppliers. By diversifying procurement, hospitals can help themselves and suppliers at the same time. Purchasing from multiple suppliers ensures that even if some suppliers are impacted by a disaster, the hospital can rely on other suppliers to fill orders. It helps suppliers by helping to prevent consolidation, as it makes it more difficult for a handful of suppliers to take over the market.
2. Hospitals and health care providers should also enter joint purchasing agreements with other providers to earn discounts and continue to build supplier diversity. The quantity discounts achieved through joint purchasing agreements decrease costs for customers. In addition, it is more cost efficient for the suppliers to fill one larger order, rather than multiple smaller orders.
3. Suppliers should set a limit on the amount of supplies each customer can purchase jointly from them. As shown in this research, when all suppliers enforce joint procurement

ordering limits, customers experience increased supplier diversity and suppliers are not forced out of the market.

This thesis makes useful contributions regarding purchasing decisions within the health care supply chain sector by analyzing the effects of supplier diversity under disaster uncertainty. It also provides a base for future research. There are a number of ways to expand this research, including supplier reliability and demand uncertainty. Incorporating supplier reliability into this model could change purchasing decisions when a customer is trying to decide between purchasing from a reliable versus a non-reliable supplier, especially in disaster situations. This could include adaptations to explore the impacts of superevents, semi-superevents, and unique events. Of particular practical interest are scenarios in which a demand surge occurs simultaneously with a superevent that disrupts multiple suppliers, as has occurred with COVID-19. Altering the model to include demand uncertainty will provide more accurate results when looking at supply shortages during disaster response.

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