Coordinated Network Management for Platelets in Canada

by

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Abstract

The objective of this thesis is to determine whether a simple rule-based policy could be used to reduce the wastage of platelets in a Canadian blood distribution network. The policy we are investigating is a hub and spoke network in which near-outdating units are shipped from spoke sites to a hub. Current regulatory requirements in Canada prevent managed site-to-site transfers. This study looks at the potential value of such a system in terms of wastage and total transportation costs. An optimal transport policy is also applied to the model and used to measure the effectiveness of the rule-based policy. A discrete event simulation of the distribution network is implemented in Microsoft Visual Studio.net and uses transaction level data from Canadian Blood Services to analyze results from a subsection of the blood distribution network in Southwestern Ontario.

List of Abbreviations Used

CBS	Canadian Blood Services
FIFO	First-In-First-Out
IP	Integer Program
KPI	Key Performance Indicators
LP	Linear Program
MIP	Mixed Integer Program

Chapter 1: Introduction

Blood is a crucial resource in any health care system. Blood is used in many medical procedures, such as surgeries or treatments of cancers and diseases. Without an adequate supply of blood products patients can suffer adverse health outcomes, which, in some cases, could result in death. There are four main components of blood: red blood cells, white blood cells, platelets and plasma. Each of these components has a different function along with distinctive characteristics such as shelf-life, differing methods of production, and varying storage and transportation requirements. There are many challenges associated with the supply of blood products. First, blood is collected through voluntary donations. This creates uncertainty in the supply. Because blood is used for many emergency medical procedures, the demand for blood products is also uncertain. In addition to these uncertainties, blood products are also perishable. Shelf lives for blood products range from a day up to a year. When blood products outdate there is a tangible cost to the system as well as the intangible cost of wasting a voluntary donation. Availability is also important as blood products are required in life saving situations and, if the correct product is not available, there could be adverse consequences. The trade-off between shortages and outdates makes perishable inventory policies challenging (Prastacos, 1978).

1.1 Canadian Blood Services

The supply of blood products throughout Canada (except for Quebec) is handled by Canadian Blood Services (CBS). It is a not-for-profit organization that manages the collection, production, testing, and distribution of blood products, as well as running Canada's stem cell registry, public cord blood bank and the national tissues and organ registry. CBS' goal is to provide safe, high quality blood products to all Canadians. CBS is funded primarily by provincial governments within a pre-determined envelope of funds granted annually in advance; the funding formula has several components but is based largely on provincial share of red blood cell demand. Because funding is provided through Provincial governments, hospitals do not directly pay for blood products. This makes determining unit costs for blood products difficult and complicates system management. Furthermore, while blood products are paid for by the provinces, they are regulated by the federal government through Health Canada, which is responsible for ensuring all products meet strict standards (About Us, 2018).

CBS operates both collection sites (clinics) and production/distribution facilities. Seven production/distribution centers, located in Vancouver, Brampton, Calgary, Dartmouth, Ottawa, Winnipeg and St. John's, distribute blood to hospitals in their regional zone. Blood is shipped to production/distribution centres from clinics within a region. Here, whole blood is separated into components and units are tested for both transmissible diseases and bacterial contamination. This typically involves quarantining blood for a prescribed duration and then testing for impurities or the presence of infectious agents. Once products are cleared, they are removed from quarantine, end labeled and are either stored or transported to hospitals; shipments are made regularly from CBS facilities to hospitals. This process is shown in Figure 1 below.

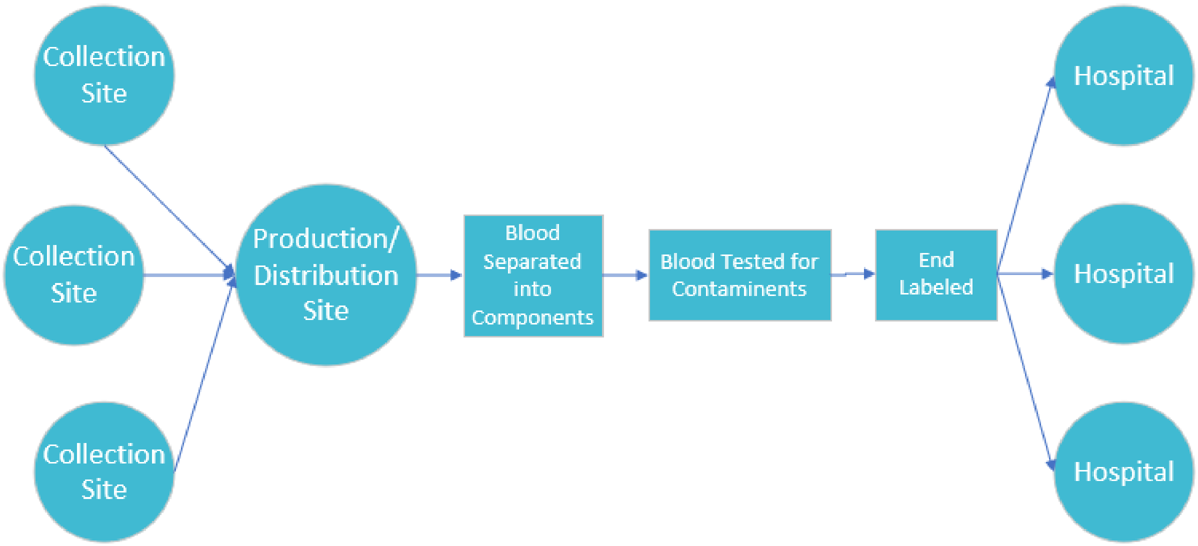

Figure 1: Blood Process Overview

In the 2013 Performance Review, auditors found that in 2011-2012 the CBS system had 46,500 outdates of red blood cells and platelets, costing around $17 million. The majority, approximately 67%, of these outdates occurs at hospitals, while the remaining 33% outdate at CBS facilities (Ernst & Young, 2013).

1.2 Platelets

Platelets are the component of blood which is responsible for clotting. They are used in situations where bleeding must be controlled. Platelets are used in both emergency and planned procedures. They are the smallest element in our blood. They are collected in two ways: apheresis or whole blood donation. Whole blood donation is when whole blood is taken from the donor and later separated into its components; this is the most common method used to collect from donors. Once the platelets are separated, they are combined into pooled platelets. This is done by mixing the platelets of multiple donors (along with one unit of plasma) to produce one transfusable unit. Apheresis involves removing blood from the donor's body, sending it through an apheresis machine, which removes only the platelets from the blood and then returns the remainder to the donor (American Red Cross, 2018). In 2015/2016 CBS collected around 127,000 doses of platelets. Of these, 30% were from apheresis and 70% were pooled platelets (Blake, 2017)

After platelets are collected, they must be screened for transmissible diseases and tested to ensure there is no bacterial contamination. Bacterial testing can take between one to two days and involves holding the units for 24 – 36 hours and then testing for contaminants. Once platelets have been cleared, they can either be stored or shipped to hospitals. Platelets are very sensitive to their environment and must be handled with care to ensure they remain usable after production. Current regulations and clinical practice dictate that they need to be stored between 20 – 24 degrees Celsius and must be gently agitated to prevent clotting. This makes their production and distribution challenging. Platelets also have the shortest shelf-life of all blood components – five to seven days, depending on the bacterial testing regime in place. Determining the cost per unit of platelets is difficult because hospitals don't directly pay for blood units and CBS does not directly cost them. However, depending on the type of product and accounting principles employed, platelets in Canada are believed to be valued between $75 and $450.

Platelets have a high rate of outdates at around 23%. High outdates are to be expected when the shelf-life of products is very short. However, CBS has been researching ways to reduce these outdates. A recent change that CBS has implemented is extending the shelf-life of platelets from five to seven days. This is expected to reduce wastage by 38% (Blake, 2017).

Although this is a significant reduction, there is still room for improvement, but further reductions in wastage are likely to require changes to operational practices.

1.3 Perishable Inventory

Classic inventory models typically assume stock can be held indefinitely. There is a subset of these problems that are specifically formulated for perishable goods. Perishable inventory implies that after a duration of time, the products are no longer usable. This adds complexity to inventory models because state-dependent decisions must be made and as such, realistically-sized problems quickly become too large to solve. Indeed, most problems become too complex to be solved optimality. This results in many of the applications of perishable inventory theory being demonstration through approximations, such as simulation (Nahmias, 1982). Platelets fall under the category of fixed-lifetime perishable goods, meaning it is known in advance how long the platelets will be usable. Like many perishable inventory problems, platelet problems often need to be down-sized to allow realistic run times.

1.4 Hub and Spoke Models

The hub and spoke topology is a specific type of network structure designed to deal with flow of products between sites. Hub sites, as shown in Figure 2, are locations where consolidation, sorting, transshipment and other tasks are performed. They are used to route traffic from one site to another, i.e. between spokes. These types of shipments, which send goods from one site and then to another site, are called transshipments. This type of network reduces direct connections between spokes and replaces them with indirect connections through the hub. This type of network is used in various industries, including airline traffic, data networks, parcel delivery etc. The hub and spoke network takes advantage of economies of scale by consolidating flow through the hub (Elhedhli & Hu, 2005). Network flow models have been developed to allow either single or multiple node to hub assignments, account for restricted flow capacity, and allow shipments to bypass the hub. Most of the research in this field investigates the optimal location of hub sites.

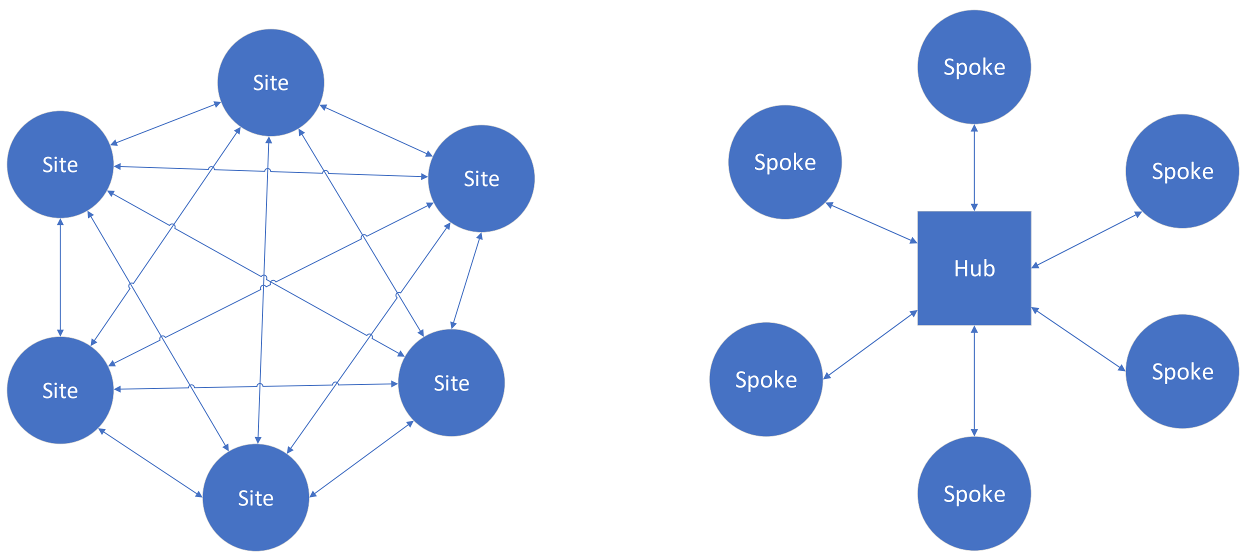

Figure 2: Regular Network (left) Hub and Spoke Network (right)

1.5 Objective

Wastage of platelets is a problem for Canadian Blood Services. Currently, hospitals retain platelets that have been sent to them until they are transfused or become outdated. There are only ad hoc arrangements in place to allow for shipments of platelets between hospitals and regulatory requirements prevent materials from being returned to CBS facilities. The objective of this thesis is to determine whether a simple policy could be put in place to allow products to move between hospitals in a way that reduces outdates and shortages. The policies we are investigating are a hub and spoke model and an s,S ordering model. The hub and spoke model allows spoke sites to send near-outdating platelets to the hub. Experiments are completed to determine the ideal shelf-life at which platelets should be shipped. The s,S model adjusts the ordering policies of hospitals to order quantities based on current inventory levels and desired order up to levels as opposed to fixed order quantities.

To test the value of the hub and spoke policy, a myopic optimal test case will be completed and used as a comparison against a dynamic daily reallocation policy. The myopic policy allows blood to be shipped to and from each facility daily to meet demand by reallocating aging inventory. Experiments will be completed to determine the ideal minimum on hand inventory at hospital sites, between one and two days' demand.

1.6 Outline

This thesis will explore the results of applying different shipping policies to a CBS network. We will first discuss relevant research in the areas of blood supply chain management, perishable inventory management and applicable shipping policies. This review is completed in Chapter 2. Next, we will discuss the simulation framework used to model the CBS network. This includes details on the data used, the simulation process and validation of the model. Chapter 3 also explains three shipping policies, an optimal transportation policy, a rule-based transshipment policy and an s,S ordering policy, which will be tested in the model. Details on how these policies are developed and applied are provided. Chapter 4 analyses the results of each policy and explains differences in wastage, transportation costs and emergency transportation costs. Chapter 4 also provides a discussion on policy characteristics that can impact results and challenges associated with the implementation of each policy. Lastly, Chapter 5 discusses overall conclusions and findings.

Chapter 2: Literature Review

Platelets are a perishable item that are essential to the healthcare system in Canada. They have one of the shortest shelf-lives among blood components, which makes them difficult to manage. Nevertheless, it is important to have enough platelets available to meet the demand from hospitals. If a hospital runs into a shortage, patients can suffer adverse health effects and there are often increased costs for emergency shipments; if hospitals have too many platelets, and they are unused by the date of their expiry, they must be discarded. This leads to wastage costs, including the production and distribution costs of the platelets that were unused. In addition to these measurable costs, there is also an intangible component of wastage, since the blood was made available through voluntary donation, and if donors realized their blood is likely to be wasted they may stop donating. There is also an ethical component of failing to use blood that has been voluntarily donated for the welfare of others. The uncertainty in both supply and demand paired with the short shelf-life make blood distribution a challenging problem (Brodheim and Prastacos).

There has been substantial research on the blood supply chain over the years, with a variety of approaches and conclusions. Most of the existing literature focuses on inventory policies to minimize total costs or to meet service level requirements. There has also been relevant research in other areas, such as perishable goods inventory, and inventory stock movements which we will review.

2.1 Relevant Literature reviews

Several literature reviews have been published that outline the research in the field. A recent review by Beliën and Forcé notes that although there is a growing interest in the blood supply chain, there is significantly less research completed on blood platelets than red blood cells and whole blood (Beliën & Forcé, 2012). They believe the reason for this shortage is due to the complexity of the problem caused by such a limited shelf-life and suggest there is room for further research in this area. Beliën and Forcé also observe that due to the complexity of the research area, a large portion of published papers use simulation as a solution method to provide heuristic solutions. Although simulation cannot guarantee optimality, it can provide results to problems that would otherwise be too large computationally to solve without restrictive assumptions. Other common solution methods include queuing models (Brodheim and Prasracos), linear programming and dynamic programming (Kendall). Commonly, when measuring the performance of supply chain management of blood products, the majority of papers in the literature measure the quantity of outdated units and unit shortages. This review aligns with our research in terms of research methods and performance measures, but in this study we are focusing on platelets, which was identified as an area where further research is needed.

Karaesmen *et al*. review work related to managing perishable and aging inventories for products in various industries, such as the produce sector and pharmaceuticals (Karaesmen, Scheller-Wolf, & Deniz, 2011). They focus on models for finite shelf-life products, where inventory levels must be controlled over a horizon, while accounting for both supply and demand. Karaesmen *et al.* separate research into two main categories, discrete review models and continuous review models. For discrete review models, one of the main differentiators is how outdating costs are handled. For example, Fries (1975) includes outdate costs for an item in the period it expires, while Nahmias (1975) uses an expected outdate cost when items are ordered. Cohen (1976) emphasizes the complexity of state-dependent ordering in these problems and suggests the research shift from optimal to heuristic policies. Continuous review models frequently use queuing theory to understand system behaviour. Karaesmen *et al*. (2011) note that there is a need for continuous review cost minimization models with fixed lead times and fixed shelf-life. Multi-echelon and/or multi-location problems add further complexity to aging products. This is because the age composition of the entire system influences replenishment and allocation decisions and logistics decisions must consider different remaining shelf-life at different locations. Due to this complexity, there is little research on optimal ordering policies for multi-echelon problems involving perishable products. Karaesmen *et al.* (2011) also note the limited research that focuses on transshipment, distribution and collection of perishable goods.

Paterson *et al.* review research on inventory models which use lateral transshipments (Paterson, Kiesmüller, Teunter, & Glazebrook, 2011). They discuss two types of lateral transshipments: proactive and reactive. The former is when shipments are used to redistribute stock at predetermined times. The latter is used to deal with stock outs when they occur or are at risk of occurring. Paterson *et al*. state that periodic review is used as the setting for all research on proactive lateral transshipments. In these models, shipments can be made at the beginning of a period, at the end of a period or at a predetermined time during a period. Agrawal *et al.* suggest that by determining the shipping point dynamically additional cost savings of up to 30% can be made, although this method is computationally challenging (Agrawal, 2004). Research on reactive lateral transshipments has been completed under both periodic and continuous review. Most models are formulated to allow transshipments only after demand for the period has been realized. Another differentiating factor in reactive transshipment research is whether the system uses complete or partial pooling. Complete pooling allows all stock to be shared amongst the system. Partial pooling holds back a portion of stock to handle future demand at individual sites. Systems that use partial pooling require additional decisions to be made around how much inventory to reserve, making them more difficult to optimize and manage.

2.2 Rotation Policies to Reduce Outdates

Brodheim and Prastacos describe a prototype blood distribution system to improve the utilization and availability of blood products in Long Island, New York (Brodheim & Prastacos, 1979). They suggest policies that require blood to remain at one location until it is either transfused or outdated result in low utilization and thus high outdating. This is especially true for sites which have low demand, of which there are typically many within a network. Their model allows for fresh blood to move between hospitals and thus ensures near-outdating blood is allocated to high usage sites where the likelihood of transfusion is greater. The model classifies blood as either a rotation unit or a retention unit. Retention units are distributed amongst sites in a way that equalizes utilization rates. After this, rotation units are allocated in a manner to equalize availability at each site. At the end of each period, rotation units are returned to a central blood bank to be redistributed the following period. As the rotation units age, they are reclassified as retention units. This model results in smaller sites receiving fresh rotation units and larger usage sites receiving older retention units. Also included in the model are various delivery schedules, costs and target availability and utilization rates. Brodheim and Prastacos are able to decompose the non-linear problem and use parametric enumeration to determine an optimal solution. The result of a prototype implementation was a reduction in wastage of 80% and decrease in delivery costs of 64%. The concepts of this paper have similarities to our research. However, it only focuses on whole blood and red blood cells; platelets have a fraction of the lifespan of these blood products, making the problem more complex and renders their proposed schedule likely unrealistic.

Although the work of Brodheim and Prastacos is very sophisticated and perhaps one of the best blood rotation algorithms that has been implemented, it does not lend well to implementations in other systems who may not have the same priorities or regulations. In Canada there are regulatory requirements which prevents CBS from redistributing a unit that has been returned because they cannot guarantee the conditions under which the unit has been stored. Kendall and Lee incorporate a goal programing aspect to their rotation policy to allow decision makers to set individual priorities specific to the local system (Kendall & Lee, 1980). They create goal constraints around availability, outdates, overall inventory levels, age of inventory and cost. Decision variables are modelled as a Markov process. Their objective function minimizes the deviations from these targets. By allowing decision makers to set their own targets and rank goals, the model can easily be adapted to comply with the priorities of different regions. It also allows decision makers to see the impact of their decisions and priorities on different feasible rotation policies, while providing insight to help plan collections and distributions. They investigate two model types, one with unlimited rotations and the other with limited rotations.

Their model showed significant improvements could be made within the blood supply system. However, this research is also specific to whole blood and red blood cells rather than platelets.

Denesiuk *et al*. completed a study of red blood cells at remote northern Alberta sites (Denesiuk, Richardson, Nahirniak, & Clarke, 2006). Their objective was to relocate near-outdate units from remote sites to sites with higher usage. By sending units to a location where they were more likely to be used, the overall discard rate is reduced, and availability increased. They were able to show that, in a one-year period, the implementation of their transportation system allowed 92 units to be transfused at a larger site, which would have otherwise outdated. The average reduction in wastage between the four remote sites was about 19%. Denesiuk *et al.* focused on the transportation system to safely allow transshipment and did not go into details on the policy for shipments. This study is a small, specific example with only four remote sites and one larger site within northern Alberta. Expanding this type of system nationwide and determining an optimal redistribution policy could have similar impacts but would require an algorithmic approach to redistribution.

Prastacos analyzes both rotation and retention policies to develop an optimal allocation policy for products with a fixed lifetime (Prastacos, 1978). Although this is a general model for any perishable products, it uses blood products as a specific example. He considers cost-per-unit short, as well as cost per unit outdated. The model generates a solution that minimizes total costs for one period through the allocation of available units. In the rotation policy, all unused products with remaining shelf-life are returned to the distribution center at the end of each period to be re-allocated, along with fresh units, in the following period. Because the model only looks at a single period, Prastacos is able to make two simplifying observations. First, the amount of units that will expire in the next period are independent of the allocation of fresh blood and only depends on the allocation of blood with one period of shelf-life remaining. Second, age is irrelevant when determining the amount of units short, as this depends only on the allocation of all available units. Their model is solved in two steps. First, units that are subject to outdating are allocated such that probability of outdates at each location are equalized and minimized. Then, the remaining available units are allocated such that the probability of shortages at each location are equalized and minimized. The simplicity of this model is ideal for implementation and can be used with a variety of probability distributions. The challenge with this model is that it only considers one period at a time, which is not ideal for planning purposes.

There has also been research on age-based transshipment policies, but with a focus on preventing blood shortage in emergencies. Unlike most models which have quantity-based policies to fill shortages, Ke-Ming Wang and Zu-Jun Ma develop a policy which considers the age of blood, when deciding how to handle the shortage (Wang & Ma, 2015). Their model determines the quantity and age of units to be transshipped for the duration of the shortage using a mixed integer programming model. The model includes constraints for maximum receivable units, maximum age of units transshipped and minimum required inventory at all sites. They recommend a first-in-first-transship policy, to ensure older units are used to fill emergency orders. By applying their age-based policy with a first-in-first-transship selection method, Wang and Ma are able to demonstrate system-wide reductions in wastage during and after a shortage. The model was developed for blood products in general and tested on red blood cells, but could be applied to other specific blood components, such as platelets. This reactive policy may not be feasible for a system-wide policy for continual use as it is based on emergency supplies for shortages which is an expensive technique.

2.3 Platelet Specific Research

Most of the research around platelets focuses on inventory levels at the hospital and tend to recommend different variations of order up to policies. Many of these models do not include options for rotation nor do they consider the age of the unit. Duan and Liao recognize the need for quantitative studies on platelet supply chain and create a model which takes into account both the stock levels and the age distribution of stock (Duan & Liao, 2013). Their model, called the old inventory ratio policy, uses age information to minimize system outdates, while adhering to a set maximum allowable shortage levels. By adding age, the model is able to perform better than quantity-based models. Their model does not however allow for rotation of platelets between sites.

Fontaine *et al.* analyzed the supply chain between a university medical center and a blood center (Fontaine, et al., 2009). One of the improvement areas they identified was the rotation process. At the time of the study, 2016, in the United States 10.9% of apheresis platelets outdate prior to being transfused. In the current state, platelets are distributed to three smaller hospitals where they remain for two days (i.e. have one day of shelf-life remaining). Units that are not used by this time are shipped back to the blood center and then reallocated to the larger medical center. The smaller hospitals and larger medical center have a cost-sharing model that encourages both parties to transfuse older platelets and reduce outdates. Deliveries are made from the blood center to the medical center two to four times daily. Their analysis showed that only 38% of the near-outdated platelets shipped to the larger medical center were actually transfused. To improve this, the rotation policy was changed to allow smaller hospitals to only keep platelets for one day prior to shipping unused units back to the blood center. This allowed more time for the larger medical center to transfuse the blood. The improvement, along with a new collection schedule, reduced the outdate rate from 20% to 11%. This change is important to consider when researching other transshipment models as changes in one day of remaining shelf-life can have significant impacts.

In Australia a program called BloodMove Platelets has been implemented in the Melbourne area. Prior to this program, the policy stated that smaller hospitals would transfer their day five platelets to a larger hospital only if its day five inventory was low. The new policy allows all sites to transfer their day four platelets to the larger hospital, regardless of its stock level (National Blood Authority Australia, 2019). Day five platelets are given a priority for use, above any day three or four platelets. A database is also kept which tracks inventories of day five platelets across all sites. This allows smaller hospitals to pull from this inventory, if they require additional units. The results of this policy show an overall reduction in the average daily discards. Platelet discard rates at smaller hospitals also approached 0%. This model shows that there is significant value in simple transshipment policies, and that policies are realistic for platelets, not just whole blood or red blood cells.

2.4 General Transshipment Policies

Yates *et al.* discuss the drivers of good inventory practices and low wastage in the blood supply chain (Yates, Stranger, Wilding, & Cotton, 2017). They suggest poor management of blood supply chains is due to the complexity of the inventory models available in the research and argue that simple heuristics and approximations are a better way to manage perishable goods.

Yates *et al.* define simple Key Performance Indicators (KPIs) to measure and record waste. They also suggest that techniques from commercial supply chain management, such as lateral transshipments or stock sharing, can be equally as effective in blood supply. Stock sharing is useful in both reducing wastage and increasing availability, both of which are essential for blood supply chains.

Stanger *et al.* conducted a number of case studies to determine the effectiveness of lateral transshipments in the blood supply chain (Stanger, Wilding, Hartmann, Yates, & Cotton, 2013). They compared 18 different hospitals in the United Kingdom, eight of which use lateral transshipments and eight which do not. Both groups agreed that the major benefit of lateral transshipments is reducing time expired wastage. They also agreed that stock sharing allows for an increased availability of more blood types. Hospitals that were not using lateral transshipments had concerns about the safety of shipping blood and a lack of trust among other hospital. This qualitative study shows that hospitals are aware of the benefits of transshipments and given the appropriate safety measures, policies could successfully be implemented in all hospitals.

Nakandala *et al*. study the use of lateral transshipments for the management of perishable produce (Nakandala, Lau, & Shum, 2017). Their model incorporates spoilage costs into the total inventory cost function and optimizes the trade-off between spoilage, the purchase price, and costs for lateral transshipment, backordering and holding. Their goal is to determine whether lateral transshipments can minimize the total cost of perishable inventory in a discrete-time model. Their model assumes that lateral transshipment costs are significantly higher than the regular purchase price from suppliers. They develop a decision rule based on the total inventory cost and when its tangent is negative, increasing the quantity of transshipments decreases the total inventory cost. This rule requires input parameters for lead time, unit purchasing cost, backordering cost, holding cost, lateral transshipment costs and spoilage percentage. Their model shows that as the spoilage percentage increases, lateral transshipments are only justified if they have lower costs. Their model proves that allowing lateral transshipments for perishable inventory management can lower the total inventory cost in certain situations, but not all. This model does have some limitations, including the assumption of zero lead-time for transshipments, no partial orders, and estimates of model parameters such as arrival rates and specific system costs.

In this study a simulation model is used to investigate different shipping and ordering policies. As seen in the literature, simulation is a common method for solving complex limited shelf-life inventory problems. We will measure the success of the models based on system outdates and cost which is also consistent with the literature. This study differs from the literature because it focuses on platelets specifically and investigates the application of different theories for platelet management to a specific area of Canada to see if the application in such a network work be feasible.

Chapter 3: Methodology

To investigate the effects of allowing site-to-site transfers in the Canadian system, a simulation model was built to measure wastage, emergency orders and overall costs for different policies. The model is based on the generic modelling framework for a blood network developed by Blake and Hardy (Blake & Hardy, 2014). This model allows production facilities to collect blood products daily, produce and test it, and ship units to hospitals based on order amounts. Hospitals use blood, as required, to meet their demand and place orders when their inventory on hand falls below their designated order threshold. Each day, all blood products in the system are aged and items whose age exceeds the shelf-life are discarded and counted as waste. The model outputs summary data including key characteristics such as wastage, emergency orders, transportation costs, etc.

A modified transportation model was added to the simulation to determine the optimal distribution of inventory between hospitals each day. The allocation is based on the amount of inventory on hand at a hospital, the age of those products, and the expected demand at each site. Transshipments were included using a hub and spoke model to move near-outdating products from the spoke sites (small hospitals) to the hub site (larger hospital). Different policies specifying when transshipments could occur were tested and results were compared to the benchmark. An s,S order-up-to policy was also included to determine whether changing the current ordering policy without adding additional shipments between hospitals could have similar results. In an s,S policy hospitals set a trigger point, s, and an order-up-to point, S. If the inventory falls below the trigger point an order is placed in return the inventory level back to the desired level. All scenarios investigated are shown in Table 1: Model ScenariosTable 1 below.

Table 1: Model Scenarios

Scenario	Ordering Policy	Shipping Policy	Parameters
1	r,Q	Supplier Only	
2a	r,Q	Optimal Transport	Min Inv = 1 days' demand
2b	r,Q	Optimal Transport	Min Inv = 2 days' demand
3a	r,Q	Hub and Spoke	Remaining shelf life to Transship = 2
3b	r,Q	Hub and Spoke	Remaining shelf life to Transship = 1
3c	r,Q	Hub and Spoke	Remaining shelf life to Transship = 0
4	s,S	Supplier Only	
5a	s,S	Optimal Transport	Min Inv = 1 days' demand
5b	s,S	Optimal Transport	Min Inv = 2 days' demand
6a	s,S	Hub and Spoke	Remaining shelf life to Transship = 2
6b	s,S	Hub and Spoke	Remaining shelf life to Transship = 1
6c	s,S	Hub and Spoke	Remaining shelf life to Transship = 0

3.1 Generic Model

A simulation was developed using Microsoft's Visual Basic.Net to model the supply chain of platelets for Canadian Blood Services. There are three main elements: an input database; the simulation itself; and an output database.

3.1.1 Input and Output Databases

Information is input to the model through a database which contains transaction level information for blood products over a one-year period. This data is then analyzed to determine supplier and hospital characteristic's that are incorporated into the model, usually as input distributions. These characteristics include empirical distributions for arrivals, demand, blood type, etc. See Blake and Hardy (2014; 2017) for details on data preparation methods.

In this study, CBS transaction level data for the 2015/2016 fiscal year was used. Data is separated into standard tables to store specific information relating to distribution centers and hospitals. Tables store information, such as collections and demand by day of week and blood type, imports and exports from distribution sites, transfusion rates at hospitals and ordering characteristics.

3.1.2 Simulation Process

The model has two main objects: the supplier and the consumer. Suppliers are the production/distribution centers that CBS operates across the country. Consumers are the individual hospitals that order blood products; in the CBS network, each hospital is serviced by one supplier.

Both objects have a set of methods which change the state of the object. These methods mimic the collection, distribution and usage of blood throughout the system. At the beginning of each day, all blood that is currently at the supplier is aged by one day. All blood products that are older than their shelf-life are discarded from the system and recorded as waste. Next, inventory arrives at the supplier. In our model, this inventory represents platelets that have been collected through blood donation, have been produced, and have been through the testing process. The number of units to arrive is based on a specific day of week distribution. After units have arrived, they are assigned a blood type and an amount of remaining shelf-life, both drawn from empirical distributions, specific to the supplier. Suppliers also can import and export platelets from one another within the system. If a supplier wishes to import units from other suppliers, they can do so if the amount they are requesting is within an allowable range, which, in our model, is based on historical averages. At this point all the incoming inventory has been received and hospital orders can be filled.

Inventory at hospital sites age in the same way as at the supplier, with units exceeding the shelf-life being discarded from the system and counted as waste. After this, inventory levels are assessed and if they are below their threshold, an order for the desired quantity is placed. If an order needs to be placed for one blood group, it is placed for all blood groups to save transportation costs.

Once all hospitals have placed their orders, the total required units for each blood type is calculated by the regional supplier. This is compared against the inventory available at the supplier, to determine if there is sufficient stock to fill all the orders. If the stock is sufficient, orders are then filled in First-In-First-Out (FIFO) order, starting with hospitals with the highest average daily demand, unless a specific order is indicated. If the stock is insufficient, the supplier will apply a scaling factor to reduce the product delivered to each hospital. The scaling factor is the ratio of units available to units required and is applied to each of the hospital orders to decrease their order quantities evenly. Inventory is then decreased at the supplier and increased at the hospital site to reflect the transfer.

Orders are assumed, by default, to arrive instantaneously at the hospital. After this, demand is realized by hospitals. Total daily demand is drawn from a Poisson distribution based on the specific day of the week for each hospital. It is then assigned a blood type and Rh status from another empirical distribution. Inventory on hand at each hospital is used to fill demand on a FIFO basis. If there is not enough inventory to meet the demand at the hospital, hospitals can request an emergency order from the supplier. The supplier first looks for the exact match and then for possible substitutes. If such units are available, they are instantaneously transferred from the supplier to the hospital. If units are not available, the demand cannot be met, and the order is counted as a shortage.

Finally, suppliers may export remaining units to other suppliers after all customer demand has been met. Exports are made in a similar manner as imports, so long as the quantity exported within the past week does not exceed 7 times the daily average. This ensures system inventory levels remain consistent. After all these tasks are completed, the simulated day is complete. Statistics are gathered at the end of each replication which measure inventory levels throughout the system. After the statistics are recorded, the simulated time is advanced by one day, the statistics reset, and a new cycle begins. The simulation process is shown in Figure 3 below.

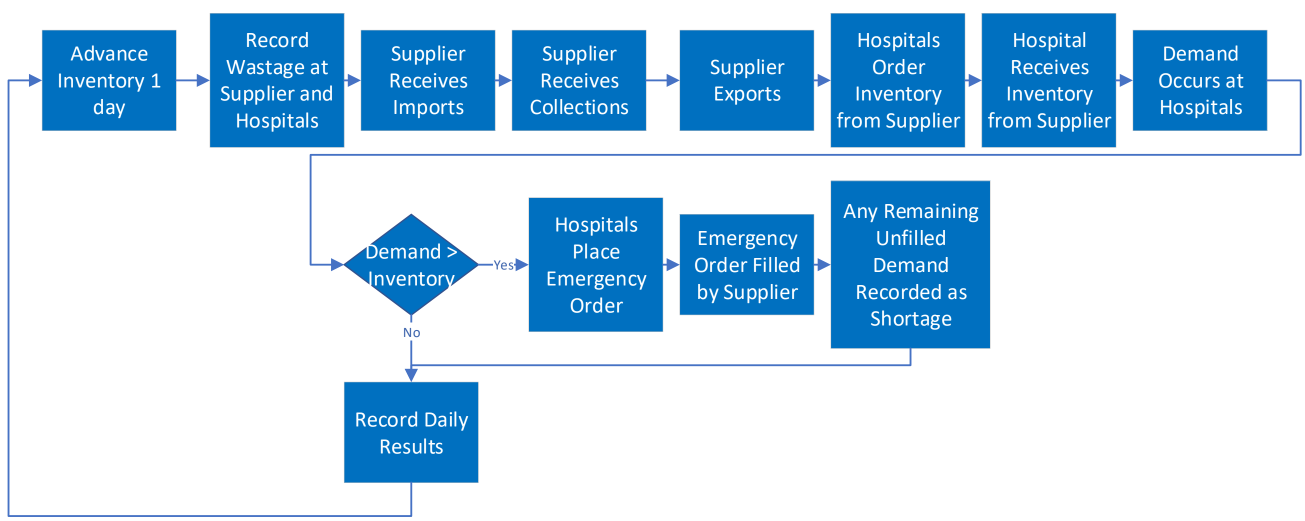

Figure 3: Base Model Process

3.2 Model Validation

In this study, CBS transaction level data for the 2015/2016 fiscal year was used. During this time CBS was using platelets with a 5-day shelf-life. A subsection of the CBS network was chosen to model and test new policies. This study includes the Brampton distribution facility and a network of 16 hospitals in the London area that are within reasonable driving distance of one another of two hours. To account for the demand of all other hospitals supplied by the Brampton site, a consolidated site was created and included in the model with the characteristics of all remaining hospitals. To validate the model, a comparison of means between historical data and the model outputs was applied. This test compared results from ten replications of 365 days with a 95% confidence level. Means for supplier exports and imports, as well as hospital aggregate demand and type specific demand, were analyzed. These tests showed that the mean values from the model for imports, exports and demand were not significantly different from historical data. Prediction interval tables can be seen in Tables 2 – 4 below. Blood type specific demand was also verified and results from the analysis can be found in Appendix A.

Table 2: Prediction Intervals - Daily Exports

Daily Exports							
Supplier	**ABORh**	**Historical**	**Model**	**Model Variance**	**Lower Bound**	**Upper Bound**	**Result**
Brampton	A-	0.063	0.061	0.000	0.041	0.081	*Accept*
Brampton	A+	0.603	0.604	0.002	0.511	0.696	*Accept*
Brampton	AB-	0.014	0.010	0.000	-0.004	0.023	*Accept*
Brampton	AB+	0.044	0.046	0.000	0.025	0.067	*Accept*
Brampton	B-	0.008	0.009	0.000	-0.002	0.019	*Accept*
Brampton	B+	0.397	0.405	0.001	0.314	0.496	*Accept*
Brampton	O-	0.099	0.099	0.001	0.041	0.157	*Accept*
Brampton	O+	1.603	1.607	0.004	1.453	1.761	*Accept*

Table 3: Prediction Intervals - Daily Imports

Daily Imports							
Supplier	**ABORh**	**Historical**	**Model**	**Model Variance**	**Lower Bound**	**Upper Bound**	**Result**
Brampton	A-	0.079	0.079	0.000	0.031	0.127	*Accept*
Brampton	A+	0.405	0.412	0.005	0.252	0.571	*Accept*
Brampton	AB-	0.014	0.014	0.000	0.001	0.026	*Accept*
Brampton	AB+	0.014	0.012	0.000	0.006	0.017	*Accept*
Brampton	B-	0.005	0.006	0.000	-0.004	0.016	*Accept*
Brampton	B+	0.093	0.089	0.000	0.059	0.119	*Accept*
Brampton	O-	0.101	0.100	0.000	0.060	0.140	*Accept*
Brampton	O+	0.586	0.594	0.004	0.447	0.741	*Accept*

Table 4: Prediction Intervals - Daily Demand

Daily Demand						
Facility	**Historical**	**Model**	**Model Variance**	**Lower Bound**	**Upper Bound**	**Result**
Alexandra Hospital - Ingersoll	0.022	0.023	0.000	-0.007	0.053	*Accept*
Chatham Kent Health Alliance	0.515	0.516	0.004	0.366	0.667	*Accept*
Chatham Health Alliance	0.011	0.013	0.000	-0.003	0.030	*Accept*
Windsor Regional Hospital Ouelette	0.670	0.673	0.002	0.561	0.785	*Accept*
Leamington District Memorial Hospital	0.020	0.020	0.000	0.000	0.039	*Accept*
South Huron Hospital	0.019	0.023	0.000	-0.001	0.046	*Accept*
Bluewater Health	0.488	0.468	0.002	0.358	0.579	*Accept*
St. Thomas Elgin General Hospital	0.142	0.149	0.001	0.082	0.215	*Accept*
Stratford General Hospital	0.192	0.215	0.001	0.142	0.289	*Accept*
Strathroy Middlesex General Hospital	0.071	0.070	0.000	0.041	0.098	*Accept*
LHSC University Hospital	2.224	2.244	0.017	1.939	2.549	*Accept*
LHSC Victoria Hospital	7.185	7.172	0.027	6.780	7.564	*Accept*
Tillsonburg District Memorial Hospital	0.030	0.024	0.000	-0.016	0.063	*Accept*
Windsor Regional Hospital	2.297	2.285	0.016	1.987	2.583	*Accept*
Woodstock Hospital	0.181	0.192	0.002	0.095	0.290	*Accept*
Norfolk General Hospital	0.062	0.055	0.001	-0.005	0.116	*Accept*
Consolidated Sites	94.637	94.894	0.030	94.486	95.303	*Accept*

To ensure the model was allocating platelets in a similar manner as the current CBS policy, the remaining shelf-life of platelets arriving at hospitals was also analyzed. Two methods were used to adjust the age of platelets received at hospitals. First, the order in which hospital orders are filled from the supplier and second, restrictions on the age of platelets requested at specific hospitals. By adjusting these two inputs the model was able to produce mean values for remaining shelf-life at hospitals which were similar to historical values. The results from two of the 16 hospitals have statistically significant differences compared to historical values, but both differ by less than 0.2 days. This is likely due to the consolidation of all the sites outside of the London area as one hospital in the model. The Brampton supplier services a large area of Ontario but for this study we are only looking at a subset of sites around the London area. To account for the demand that is supplied to other sites within Brampton's catchment area, their demand was consolidated into one hospital. The demand at this consolidated site is much larger than any of the London sites which impacts the order in which remaining hospitals are served. Detailed results from this analysis are shown in Table 5 below.

Table 5: Prediction Intervals - Age of Platelets Received (days)

Age of Platelets Received						
Facility	**Historical**	**Model**	**Model Var**	**Lower Bound**	**Upper Bound**	**Result**
Alexandra Hospital - Ingersoll	2.125	2.129	0.365	0.695	3.562	*Accept*
Chatham Kent Health Alliance	2.212	2.349	0.003	2.226	2.473	*Reject*
Chatham Health Alliance	2.500	2.356	0.842	0.179	4.534	*Accept*
Windsor Regional Hospital Ouelette	2.459	2.641	0.002	2.537	2.745	*Reject*
Leamington District Memorial Hospital	2.375	1.734	0.462	0.122	3.346	*Accept*
South Huron Hospital	0.714	1.256	0.798	-0.864	3.375	*Accept*
Bluewater Health	2.313	2.280	0.007	2.089	2.472	*Accept*
St. Thomas Elgin General Hospital	2.036	1.610	0.041	1.129	2.091	*Accept*
Stratford General Hospital	1.933	1.910	0.002	1.803	2.017	*Accept*
Strathroy Middlesex General Hospital	1.731	1.428	0.146	0.522	2.334	*Accept*
LHSC University Hospital	2.104	2.034	0.003	1.900	2.169	*Accept*
LHSC Victoria Hospital	2.109	2.112	0.003	1.979	2.245	*Accept*
Tillsonburg District Memorial Hospital	1.818	1.643	0.715	-0.363	3.649	*Accept*
Windsor Regional Hospital	2.331	2.295	0.001	2.217	2.373	*Accept*
Woodstock Hospital	1.493	1.413	0.013	1.138	1.687	*Accept*
Norfolk General Hospital	1.792	1.629	0.180	0.622	2.636	*Accept*

The settings used for validation remained unchanged for the experimental policies. After the validation of key metrics, model outputs were further analyzed to determine the resulting wastage, emergency shipments and cost. These results are presented in Chapter 4.

3.3 Base Model

To model the current state of the CBS network an r,Q ordering policy was used. r,Q ordering policies are often used in inventory management systems as they are easy to implement and can have effective results when applied correctly. In this policy there is a reorder point, r, and an order quantity, Q. After all inventory in the system has been advanced by one day and wastage is recorded, hospitals place their orders from the supplier. To determine whether an order will be placed, the current inventory level is measured against the defined reorder point. If the inventory is at or below the reorder point an order is placed for the defined order quantity. If the inventory is not below the reorder point no order is placed. This policy is very easy to implement as order quantities are consistent every time an order is placed, leaving the only decision to be when to place the order. The model was run with values of r and Q ranging from 1 days' demand to 4 days' demand to determine the results under each setting.

3.4 Experimental Overview

To test the impact of shipping policies on wastage, emergency shipments and transportation costs, a set of experiments was performed using the simulation. The first step in this experiment was converting the platelets in the model from a 5-day shelf-life to a 7-day shelf-life. This made the model consistent with CBS's newest policy. Three different shipping policies were then tested. The first was a myopic optimal policy which allows all hospitals to ship platelets to any other hospital. The second shipping policy was a rule-based hub and spoke policy. This policy only allows hospitals to ship platelets to one hub hospital at set ages. The third was an s,S order up to policy which adjusts the order quantity of hospitals from a set amount to the difference between their current inventory level and their desired inventory level. Results from these policies were compared to the base r,Q model in which hospitals place orders for a set quantity whenever their inventory levels fall below their trigger point.

The purpose of these experiments is to determine whether wastage can be reduced with the implementation of a new shipping policy. It then assesses whether similar results from the optimal policy can be achieved through a simple hub and spoke policy or s,S ordering policy. Although an optimal transportation network may result in the greatest reduction in wastage, the implementation of such a policy would be challenging, involving the coordination of all hospitals and the ability to manage shipments of varying sizes and frequencies. A rule-based policy, such as is suggested in our experiments, would be much easier to setup, as shipments are only made to one additional hospital and implementation for employees would be simpler because each day shipments are based solely on remaining shelf-life. The goal of our study was to determine if a simple policy exists which can achieve near optimal wastage and cost values. The simulation model was used to test these experiments and compare results.

3.5 Transshipment Model

In a transshipment model, product can move between hospitals, rather than being shipped solely from the supplier. This allows hospitals to transship near-outdating units to hospitals with a higher demand for these units, thus increasing the likelihood for transfusion. This type of a system typically allows more availability of products and less wastage at smaller hospital sites as unused units can be reallocated prior to outdating. The remaining shelf-life of on-hand inventory at hospital sites who transship is typically high, as fresh units are shipped here from the supplier. Hospitals receiving transshipments tend to have lower remaining shelf-life of on-hand inventory as they are receiving older units from other hospitals. This policy will be used as a rule-based approach to the problem and is shown in Figure 4 below.

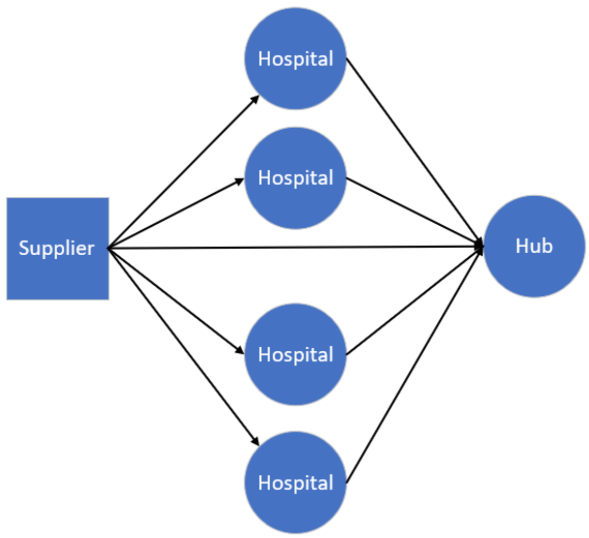

Figure 4: Hub and Spoke network

3.5.1 Hub and Spoke Network

A hub and spoke network was used to design the transshipment model. In this network there are multiple spokes and one hub. Spoke sites are able to send nearly outdating units to the hub. In our experiments with this model, the following hospital characteristics were evaluated to determine whether the site would be an ideal candidate for a hub or spoke location: Hub locations need to have a high daily demand and low variability of demand (large tertiary hospitals in central locations are ideal); spoke locations are smaller hospitals located a reasonable distance from the hub, in our model, within a two-hour drive. Spoke hospitals should have lower demand with a higher variability of demand.

London, Ontario was chosen as the trial location for the model. London was selected due to its size and distribution of hospital customers. London Health Sciences Centre/Victoria Hospital is selected as the hub site. 15 hospitals within Southwestern Ontario represent spoke sites, which met the desired characteristics of proximity to the hub, demand and demand variability. Site details are shown in Table 6 below along with their geographic locations shown in Figure 5. In this map the hub site is displayed in purple and the spoke sites are black.

Table 6: Hospital Sites used in Model

Facility Name	Type	Address
LHSC - Victoria Hospital	*Hub*	*800 Commissioners Rd E, London, ON N6A 5W9, Canada*
Alexandra Hospital	*Spoke*	*29 Noxon St, Ingersoll, ON N5C 3V6, Canada*
Chatham Kent Health Alliance	*Spoke*	*80 Grand Ave W, Chatham, ON N7M 5L9, Canada*
Chatham Health Alliance	*Spoke*	*325 Margaret Ave, Wallaceburg, ON N8A 2A7, Canada*
Windsor Regional Hospital - Ouelette Campus	*Spoke*	*1030 Ouellette Ave, Windsor, ON N9A 1E1, Canada*
Leamington District Memoria Hospital	*Spoke*	*194 Talbot St W, Leamington, ON N8H 1N9, Canada*
South Huron Hospital	*Spoke*	*24 Huron St W, Exeter, ON N0M 1S2, Canada*
Bluewater Health	*Spoke*	*89 Norman St, Sarnia, ON N7T 6S3, Canada*
St. Thomas Elgin General Hospital	*Spoke*	*189 Elm St, St. Thomas, ON N5R 5C4, Canada*
Stratford General Hospital	*Spoke*	*46 General Hospital Dr, Stratford, ON N5A 2Y6, Canada*
Strathroy Middlesex General Hospital	*Spoke*	*395 Carrie St, Strathroy, ON N7G 3J4, Canada*
LHSC - University Hospital	*Spoke*	*339 Windermere Rd, London, ON N6A 5A5, Canada*
Tillsonburg District Memorial Hospital	*Spoke*	*167 Rolph St, Tillsonburg, ON N4G 3Y9, Canada*
Windsor Regional Hospital - Metropolitan	*Spoke*	*1995 Lens Ave, Windsor, ON N8W 1L9, Canada*
Woodstock Hospital	*Spoke*	*310 Juliana Dr, Woodstock, ON N4V 0A4, Canada*
Norfolk General Hospital	*Spoke*	*365 West St, Simcoe, ON N3Y 1T8, Canada*

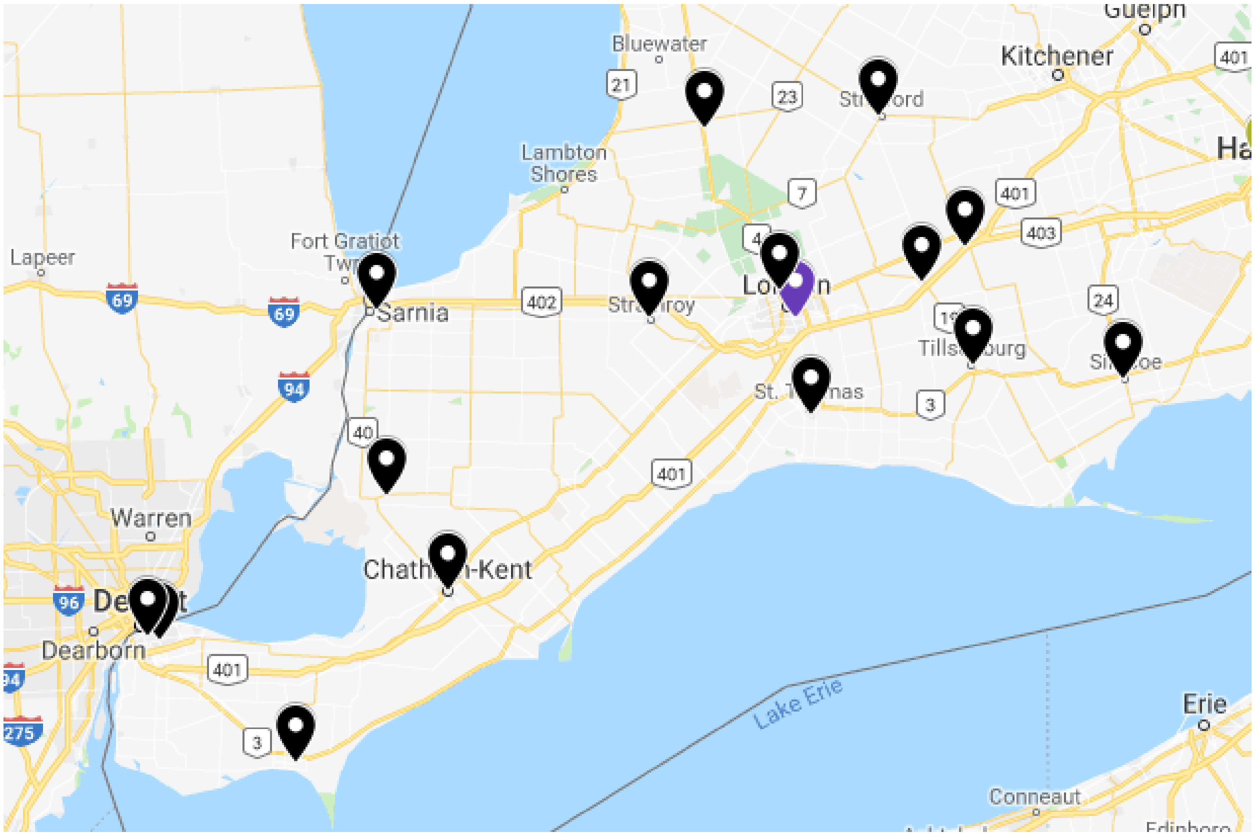

Figure 5: Map of London Network

Variable costs for the shipment of platelets are calculated using the distance between sites. Below, Table 7, is a from-to matrix of distances between each site. These values are multiplied in our experiment by a shipping rate to determine the variable costs.

Table 7: Distances Between Hospital Sites

	Distance (km)															
FacilityName	LHSC - Victoria	Alexandra Hospital	Chatham Kent	Chatham Health	Windsor Regional	Leamington District	South Huron	Bluewater Health	St. Thomas	Stratford General	Strathroy Middlesex	LHSC - University	Tillsonburg District	Windsor Regional	Woodstock Hospital	Norfolk General
LHSC - Victoria Hospital	0	36	113	129	188	169	55	109	26	66	50	11	57	185	48	97
Alexandra Hospital	36	0	141	156	215	196	75	136	56	42	77	44	24	212	15	64
Chatham Kent Health	113	140	0	29	82	59	141	74	113	178	91	125	162	79	153	202
Chatham Health Alliance	128	156	29	0	110	87	137	45	128	179	94	119	177	106	168	217
Windsor Regional	188	215	81	109	0	50	230	111	188	252	184	200	237	4	227	276
Leamington District	169	196	59	87	49	0	211	132	169	233	165	181	218	47	208	257
South Huron Hospital	52	75	141	137	230	211	0	97	78	48	53	43	102	227	83	138
Bluewater Health	109	136	74	45	109	132	98	0	115	139	68	95	158	112	148	197
St. Thomas Elgin	26	56	112	128	187	167	78	114	0	93	55	41	44	183	68	86
Stratford General	66	42	184	178	259	239	48	139	99	0	79	58	65	255	41	101
Strathroy Middlesex	50	77	91	94	184	164	55	67	55	79	0	34	98	180	89	138
LHSC - University	9	44	119	119	194	174	43	95	32	58	34	0	66	190	57	106
Tillsonburg District	57	24	162	177	236	217	105	157	45	65	98	65	0	233	34	40
Windsor Regional	184	212	78	105	4	47	227	150	184	249	180	196	233	0	224	273
Woodstock Hospital	49	16	153	169	228	208	83	148	68	40	90	57	34	224	0	72
Norfolk General Hospital	97	64	201	217	276	256	145	197	86	99	138	105	40	273	72	0

3.5.2 Hub and Spoke Policy

There are certain aspects of the hub and spoke policy that must be considered when developing a lateral shipment policy. First, how will the hub site accommodate the additional supply of platelets from the spoke sites? In our model, this is handled by completing any transshipments prior to hospitals placing their orders. This allows both the hub site and the spoke sites to place their orders to the supplier based on their new inventory level after transshipments have been sent or received. The other important characteristic of the transshipment policy is the age at which platelets are shipped from spoke sites to the hub site. Different ages were tested in our experiments to determine the impact on the policy.

3.5.3 Application of the Hub and Spoke Model

The simulation was altered such that at the beginning of each day hospitals send and receive transshipments. The transshipment process occurs after inventory has been advanced one day and before hospitals place orders to the supplier. Inventory at spoke sites is reviewed and any units with a remaining shelf-life within the policy specifications are sent to the hub location. A subroutine removes these units from hospital inventory and adds them to the hub hospital inventory. Units shipped from spoke sites are recorded as exports and units received at the hub hospital are recorded as imports. The cost of transshipments is also recorded based on the quantity shipped and the distance between sites. The fixed and variable costs for transshipping are the same as those used in the transportation problem. The adjusted simulation process for the hub and spoke model is shown in Figure 6 below.

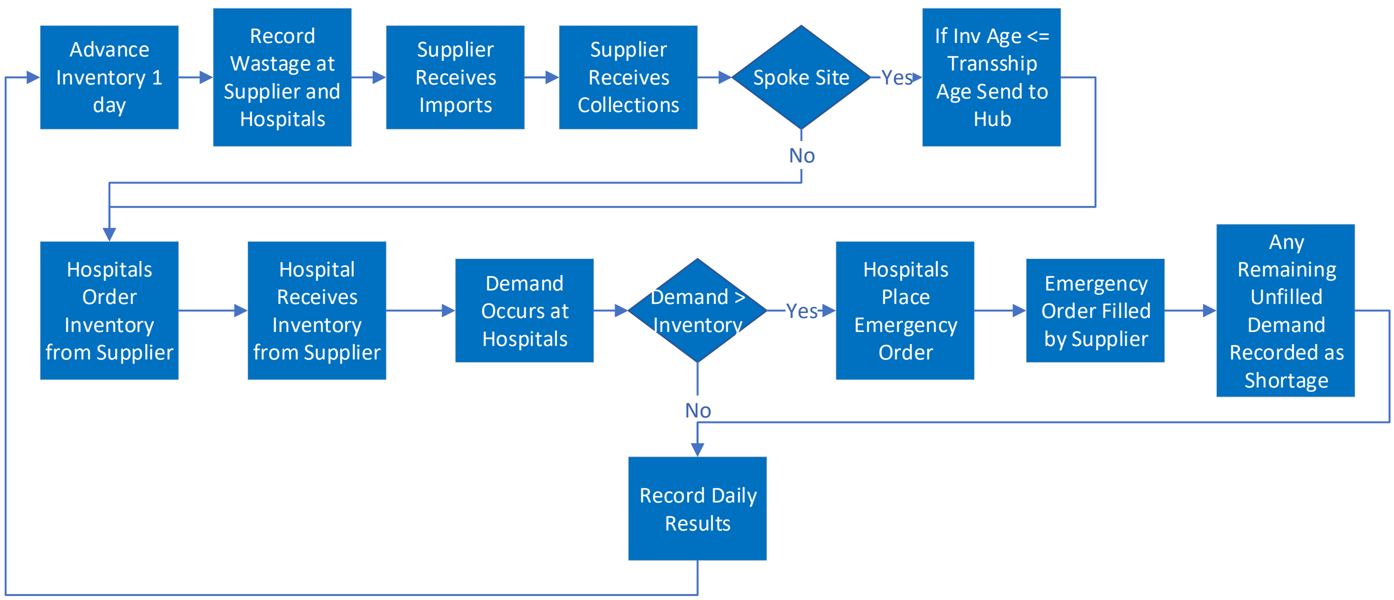

Figure 6: Hub and Spoke Process

3.6 Transportation Problem

A classic application of linear programming is the transportation problem. This type of problem includes *m* different supply facilities who ship units to *n* different demand facilities. There is a cost associated with shipping products from each supply location to each demand location. The goal of the model is to determine the optimal allocation of goods to be shipped from suppliers to hospitals for the minimum cost. Constraints are added to the model to ensure demand is met at each site and supply does not exceed the capacity of each facility. Supply and demand must be equal in transportation problems. If there is an inequality, a dummy location for either supply or demand must be added to the model to account for this. Below is the general formulation for the transportation problem.

Parameters

$C_{i,j}$ = Unit cost of shipping from i to j

S_i = Supply at i

D_i = Demand at j

Decision Variables

$x_{i,j}$ = *Quantity shipped from i to j*

Objective Function

Minimize

$$\sum_{i=1}^{N}\sum_{j=1}^{M} C_{i,j} * x_{i,j}$$

Constraints

Supply Constraint

$$\sum_{j=1}^{M} x_{i,j} \leq S_i \qquad for\ all\ i$$

Demand Constraint

$$\sum_{i=1}^{N} x_{i,j} \geq D_j \qquad for\ all\ j$$

$$x_{i,j} \geq 0$$

The transportation problem is used in our model to determine a benchmark for how the system could perform, if product was able to move freely between distribution centers and hospitals. At present this is likely not a practical solution due to the logistics of non-consistent shipments, as well as regulatory restrictions that prohibit CBS from accepting returning materials from hospital sites. However, it does shed light on the service level that *could* be achievable *if* a globally optimal transportation plan could be executed.

3.6.1 Gurobi Optimization

The canonical transportation problem only includes the variable costs of transportation; fixed costs of setting up a delivery are ignored. In the platelet model, setup costs are not negligible. Thus, the transportation model was converted to a mixed integer program (MIP) with fixed costs included in the objective function and constraints. Thus, solution of the model requires an optimization solver. Accordingly, Gurobi.NET was imported to the simulation framework and referenced to solve an instance of the MIP within the simulation each day. Below is the revised formulation for the MIP which was actually used in our experiments:

Parameters

$VCost_{i,j}$ = Variable unit cost of shipping from facility i to facility j

$FCost_{i,j}$ = Fixed cost of shipping from facility i to facility j

S_i = Supply at facility i

D_i = Demand at facility j

M = Big M

Decision Variables

$x_{i,j}$ = *Quantity of platelets shipped from facility I to facility j*

$$y_{i,j} = \begin{cases} 1 & If\ shipment\ is\ made\ from\ facility\ i\ to\ facility\ j \\ 0 & Otherwise \end{cases}$$

Objective Function

Minimize

$$\sum_{i=1}^{N}\sum_{j=1}^{N} VCost_{i,j} * x_{i,j} + FCost_{i,j} * y_{i,j}$$

Constraints

Supply Constraint

$$\sum_{j=1}^{N} x_{i,j} \leq S_i \qquad\qquad for\ all\ i$$

Demand Constraint

$$\sum_{i=1}^{M} x_{i,j} \geq D_j \qquad\qquad for\ all\ j$$

Supply meets Demand Constraint

$$\sum_{i=1}^{N} S_i \geq \sum_{j=0}^{N} D_j$$

Fixed Cost Constraint

$$x_{i,j} \leq M * y_{i,j} \qquad\qquad for\ all\ i, j$$

$$y_{i,j} \ \epsilon\ Binary$$

$$x_{i,j} \in Positive\ Integer$$

Gurobi.NET provides a framework for setting up an LP/IP with classes for decision variables, model constraints, objective functions, etc. In our implementation, a new object of the GRBModel is created. Decision variables are then defined and added to the model through the GRBVar class object. Two classes of decision variables were included in the model, one, a binary variable, to determine whether a shipment would be made from one location to another, and the other, an integer variable, to determine the quantity of platelets that would be shipped between these locations. The objective function is then defined as a minimization or maximization. This model uses a minimization to optimize the total cost of transportation, including both fixed and variable costs. Next, constraints are defined. There are constraints for supply and demand at each location, as well as the fixed cost constraint to ensure product is only sent through routes for which a set up cost has been included. This information is then used in the optimization subroutine, which calls the Gurobi solver to solve the problem. Decision variable values and the objective function value are then returned to the simulation, where they are used to make shipping decisions for platelets.

3.6.2 Application of Transportation Model

The transportation model is applied to the simulation after each hospital places their order. The demand for each hospital is equal to the quantity they ordered. Supply for each hospital is equal to their total type inventory on hand less a minimum threshold of one- or two-days' demand. These thresholds are experimental parameters chosen to best represent the amount of inventory hospitals' would like retain to deal with their variable demand. If the hospital inventory is below the minimum threshold, their available supply is set to zero. The supplier is also included in the transportation matrix with demand set to zero and supply set to inventory on hand. Total supply and demand values are compared to ensure there is a balanced network. If there is an imbalance in supply and demand a dummy node is created and assigned a supply or demand equal to the difference. Units shipped to and from the dummy node incur a cost of zero in the optimization. These units are not shipped during the simulation.

Using supply, demand, variable costs (distances between hospitals) and fixed costs to set up a route, Gurobi generates an optimal allocation for each platelet type, each day. A total transportation cost is also generated and used for comparison to other scenarios. The allocation matrix is used to transfer units to and from hospitals and the supplier through a subroutine. This subroutine removes inventory from hospitals, or the supplier, based on a first in first out policy and ships them to their destination sites, where they are added to that hospital's inventory. Units shipped from hospital sites are recorded as hospital exports and reported in the output database. Units received from hospital sites are recorded as hospital imports and are also reported in the output database. Inventory is similarly transferred from the supplier to hospitals based on the optimized allocation. After this shipment process, the remainder of the simulation occurs unchanged. The adjusted simulation process is shown in Figure 7 below.

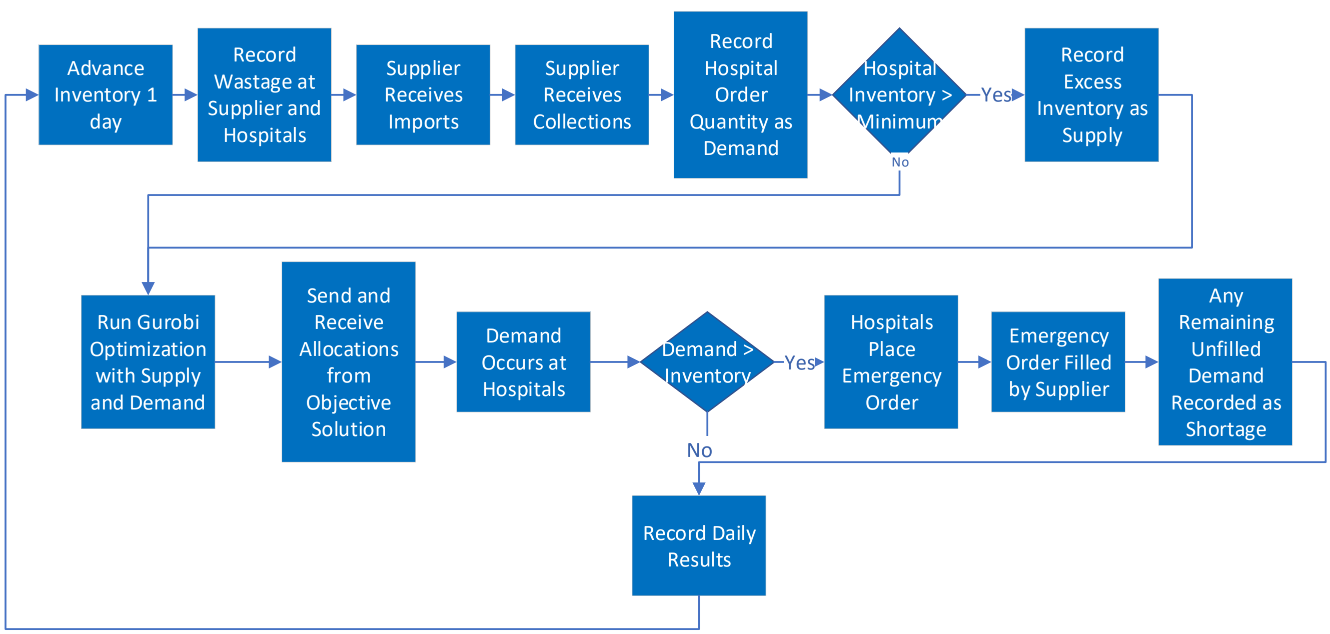

Figure 7: Optimal Transportation Model Process

3.7 s,S Ordering Policy

s,S ordering policies are a slightly more complex inventory model but are easy to implement and are generally known, from the literature, to have improved performance. In the s,S ordering model implemented in our experiments, the ordering process for the hospitals change, but only the supplier can ship platelets. With an s,S ordering policy, each hospital sets a reorder point, *s*, and an order up to quantity, *S*. When hospitals place their orders they first look to see if their current inventory level is at or below the reorder point. If it is, they determine the quantity to order based on their current inventory and their order up to point. This means that their order quantities are not always constant but reflect the amount that is required to return inventory to the order up to point. Practically, an s,S model would require the least amount of changes for the blood distribution system in Southwest Ontario, since it affects only the quantity ordered by hospitals. Accordingly, a set of experiments was conducted, implementing an s,S order policy along with both a rule-based decision policy and an optimal transportation policy

3.8 Shipping Costs

Consistent shipping costs were applied to each policy to allow for direct comparison of policy impact. Each shipment was assigned a variable shipping cost of $1.10 per kilometer per unit. This value is based on the local courier rate provided by CBS from their Logistics Coordination Centre. In addition to the variable cost there are also fixed costs associated with creating a shipment; fixed costs include labour for receiving platelet orders, and a container cost related to the packaging in which platelets are shipped. The labour cost was calculated by multiplying the approximate time to receive a platelet order, 0.25 hrs, by an hourly wage of $20/hr, or $5 per shipment. There is also a fixed cost for the insulated shipping container which must be used when transporting platelets. This container costs $235 and can be reused for 12-18 months. A fraction of this cost, $23, is used in the model as a representation of the container cost. Together there is a fixed cost assigned to each new shipment of $28. Shipments from the supplier to hospitals are not charged the fixed cost for the shipping container as these routes are already established and all required materials have already been purchased.

3.9 Parameter Experiments

All experiments, including r,Q and s,S alone and with a rule-based or optimal transportation policy were tested with varying hospital and supplier ordering policies. Hospital order triggers, hospital order-up-to quantities and supplier inventory levels were tested with one to four days' demand. The three new shipping or ordering policies (transportation, hub and spoke, and s,S) were tested under these parameters, as well as different policy specific parameters to explore the possible solution space:

1. The minimum on hand inventory for hospitals in the transportation policy was tested with one and two days' demand to determine the effects on the solution.
2. The age of platelets for transshipment was tested with zero to two days remaining shelf-life in the hub and spoke policy.
3. The s,S policy was test by itself and with the application of the transportation and hub and spoke policy.

Chapter 4: Results

This section analyzes the results of different ordering and shipping policies. Readers should note that all policies were run for ten replications of 364 days following a two-week warmup period. Warmup was set using Welch's technique (Law, 2014). When comparing policy results, paired t-tests were used to determine if there were any statistically significant differences in the results from each policy across multiple settings. Results from each of the paired t-tests can be found in Appendix B.

In the reported results, wastage is calculated at the beginning of each day when all inventory in the system is advanced by one day. Units with no remaining shelf-life are recorded as wastage and removed from inventory. Blood-type-specific wastage is recorded at each hospital and supplier. The data is aggregated to show total wastage at each hospital as well as total system wastage. However, for clarity of presentation, the results in this section refer only to total system wastage.

4.1 r,Q Ordering Policy

In our experiments, the r,Q ordering policy is used as the base model for comparison to other policies, as it best represents the current state of network logistics in Southwest Ontario. The model was run using a hospital order trigger, r, of 1 to 4 days' demand, a hospital order quantity, Q, of 1 to 4 days' demand and a supplier inventory level, x, of 1 to 4 days' demand. Appendix C shows the detailed results from each of the 40 scenarios tested.

Wastage

The r,Q ordering model yielded an average total system wastage of 21.6 units per day across all 40 scenarios. The 95% confidence interval on the average wastage is 21.6 +/- 2.1 units per day; this metric includes the aggregated supplier and hospital wastage. As might be expected, the lowest wastage occurred when the hospital order trigger was 1 days' demand, the hospital order quantity was 1 days' demand and the supplier inventory was also set at 1 days' demand; these settings yielded a daily wastage of 6 units per day. Interestingly, the highest wastage tended to occur when the hospital order trigger was one days' demand, the hospital order quantity was 2 days' demand and the supplier inventory was 4 days' demand. A system wastage of 26 units per day, occurred in all settings with supplier inventory levels of 3 or 4 days' demand, as seen in Figure 8 below.

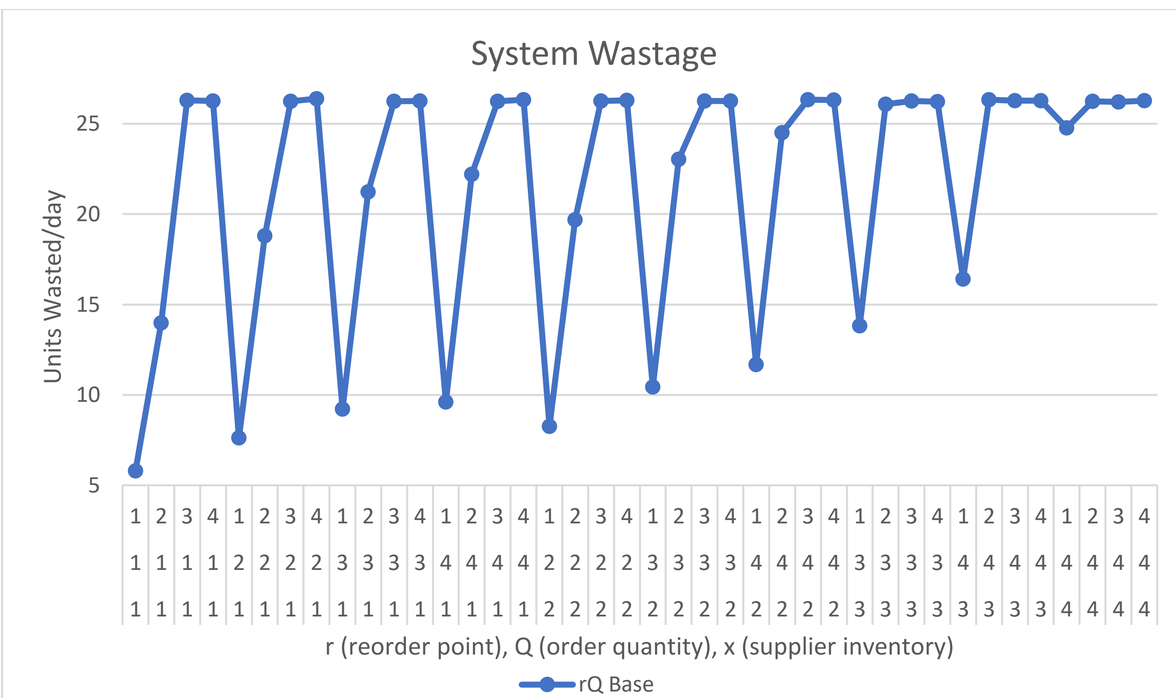

Figure 8: r,Q Model - Wastage

Emergency Orders

When hospitals do not have enough inventory to meet demand, they place an emergency order with the supplier. Emergency orders, therefore, represent instances of local shortage at hospitals and are thus an important metric of system performance. Across all 40 scenarios of the r,Q policy, average emergency orders was observed to be 1.1 +/- 0.2 units per day, with an average yearly emergency transportation cost of $197,440 +/- $34,738. The setting that yielded the lowest emergency orders, 0.6 units per day, corresponding to an emergency transportation cost, $108,782, occurred when the hospital trigger was 2 days' demand, the hospital order quantity was 4 days' demand and the supplier inventory was 2 days' demand. Emergency orders were similar for all scenarios where the hospital order quantity was three- or four-days' demand. The highest emergency orders occurred when the hospital order quantities were only one days' demand, as shown in Figure 9 below.

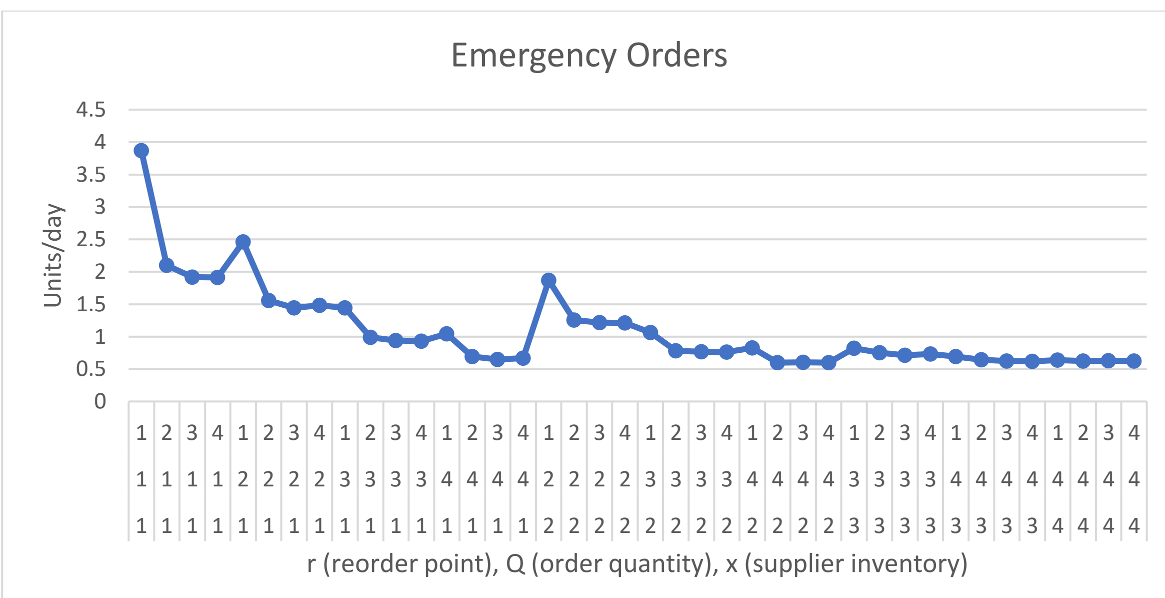

Figure 9: r,Q Model - Emergency Orders

Total Transportation Cost

In our model, the total transportation cost includes the cost of the supplier shipping platelets to each hospital, as well as the emergency orders that hospitals place when they cannot meet demand with locally held stock. The average yearly transportation cost across all 40 scenarios model is $1,907,454 +/- $55,049. The setting that yielded the lowest total transportation cost, $1,578,790, occurred when the hospital order trigger was 2 days' demand, the hospital order quantity was 2 days' demand, and the supplier inventory was set to 1 days' demand. This cost was a combination of $1,237,158 in regular deliveries and $341,632 in emergency shipments. The most expensive transportation cost, $2,167,973, occurred when the hospital order trigger was 1 days' demand, the hospital order quantity was four days' demand and the supplier inventory was set to three days' demand. This cost was a combination of $2,044,830 in regular deliveries and $123,143 in emergency shipments.   Figure 10 below shows the results for all settings.

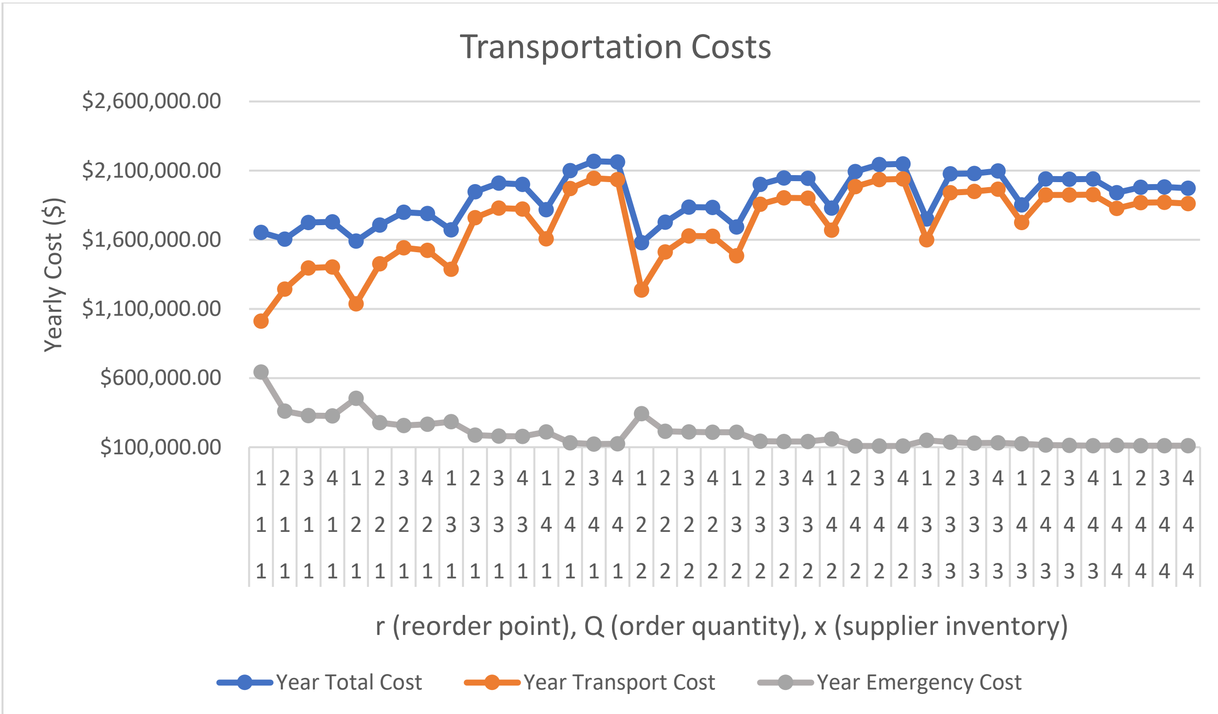

Figure 10: r,Q Model - Total Transportation Cost

4.2 r,Q Ordering Policy with Optimal Shipping Policy

An optimal shipping policy was applied to the r,Q model to determine the effect on results of determining the lowest cost for shipment of platelets between all hospital sites. The optimal shipping policy was tested using a minimum on hand inventory at hospital sites of one- and two-days' demand. Results from the policy with a minimum inventory of two days' demand is described below. Results from other policies tested can be found in Appendix D.

When an optimal assignment is done to determine which sites will ship platelets to other sites, the average wastage was 15.8 +/- 3.1 units per day. This is an average reduction in wastage of 37%, when compared to the base r,Q model. The average total transportation cost of this policy was $1,807,383 +/- $27,673, a decrease of 4% from the base model. This transportation cost consists of $1,332,508 in supplier and hospital transport costs and $474,875 in emergency transport costs. There were no settings in an optimal transportation policy combined with an r,Q ordering policy that yielded increased wastage when compared to the base model. There were, however, some settings that yielded increased total transportation costs. Total transportation costs were higher than the base model when the hospital trigger was one days' demand and the hospital order quantity was one, two, or three days' demand. In the scenarios run, the largest increase in total transportation cost was 19% higher than the base r,Q model. A paired t-test resulted in p-values of 2.66×10^{-6} for wastage and 0.0016 for total transportation cost, indicating changes resulting from implementing an optimal transportation policy are statistically significant at a 95% significance level. Results for both wastage and total cost can be seen in Figure 11 and Figure 12 respectively.

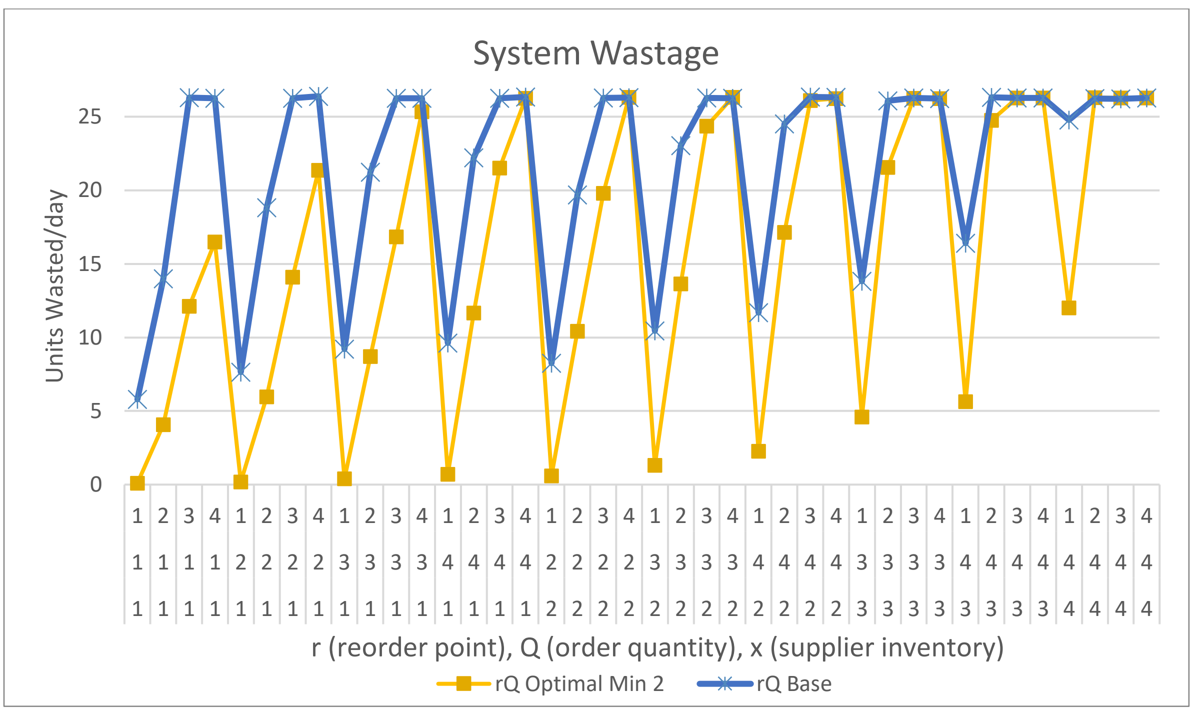

Figure 11: r,Q with Optimal Policy - Wastage

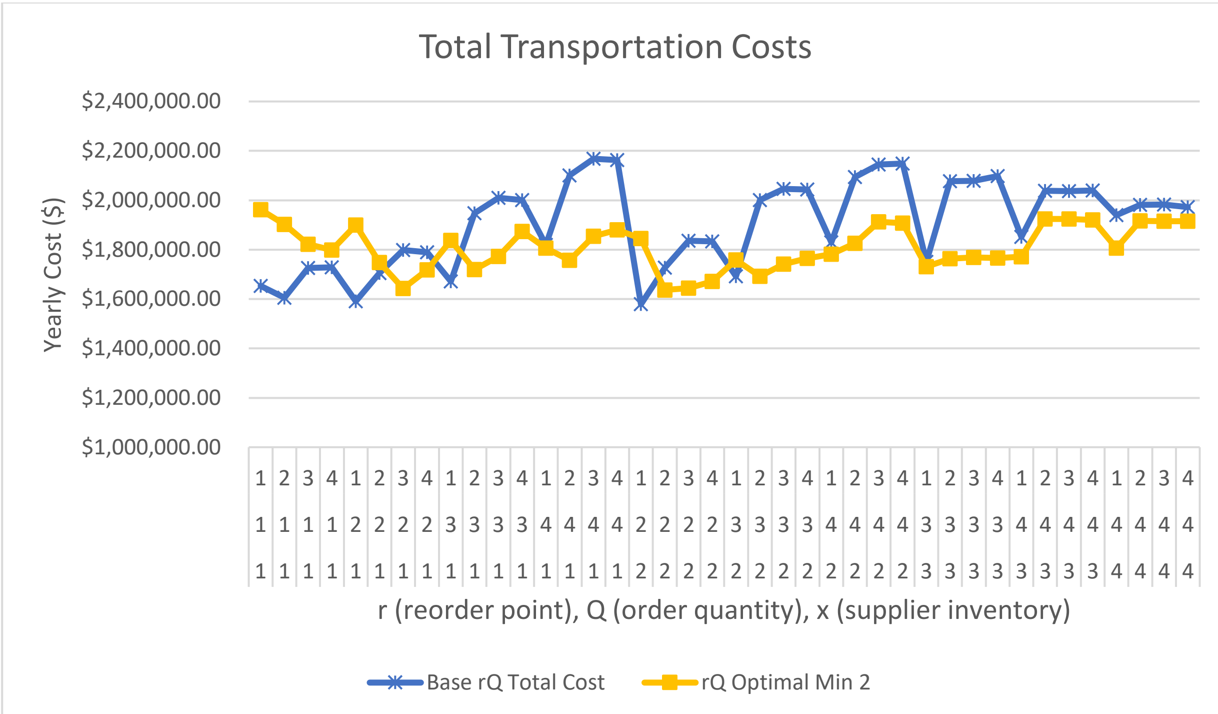

Figure 12: r,Q with Optimal Policy - Total Transportation Cost

4.3 r,Q Ordering Policy with Hub and Spoke Shipping Policy

After completing runs with an optimal transportation policy, a rule-based transshipment policy was applied to the r,Q model to test the impact of a simpler set of shipping rules. In this set of runs, shipments are automatically sent from spoke hospitals to the hub hospital when platelets reach a specific age, regardless of the inventory position of either the spoke hospital or the hub hospital. The rule-based transshipment policy tested in our experiments assumes platelets are shipped from spoke hospitals to hub hospitals when they have a remaining shelf-life of zero, one, or two days. Results for the policy of transshipments with one day remaining shelf-life are described below. The results from the other transshipment policies yielded similar results; detailed results can be found in Appendix E.

When transshipments occurred with units with 1 days' remaining shelf-life, the average wastage was 21.8 +/- 2.1 units per day, an increase of 1% when compared to the r,Q base model. Similarly, the total cost of shipping was observed to increase; the average total cost for this policy was $2,013,081 +/- $20,582, an increase of 6% from the base model. A paired t-test was applied to compare results from this policy with the base model. It was determined that the results for wastage and total cost differed significantly from the base model with p-values of 0.029 and 3.18×10^{-5} respectively. Although on average, the rule-based policy negatively impacts wastage and shipping costs there are scenarios in which improvements can be seen. When the hospital order trigger was one and the hospital order quantity was one or two, the hub and spoke model resulted in less wastage, by up to 8%, as seen in the figure below. These scenarios did, however, yield the highest transportation costs, by an increase of up to 28%. The scenarios that resulted in reduced transportation costs occurred when the hospital order quantity was 4 and the supplier inventory was 1 or 2. These scenarios resulted in cost reductions of up to 7%. System wastage and total transportation costs are shown in Figure 13 and Figure 14 respectively.

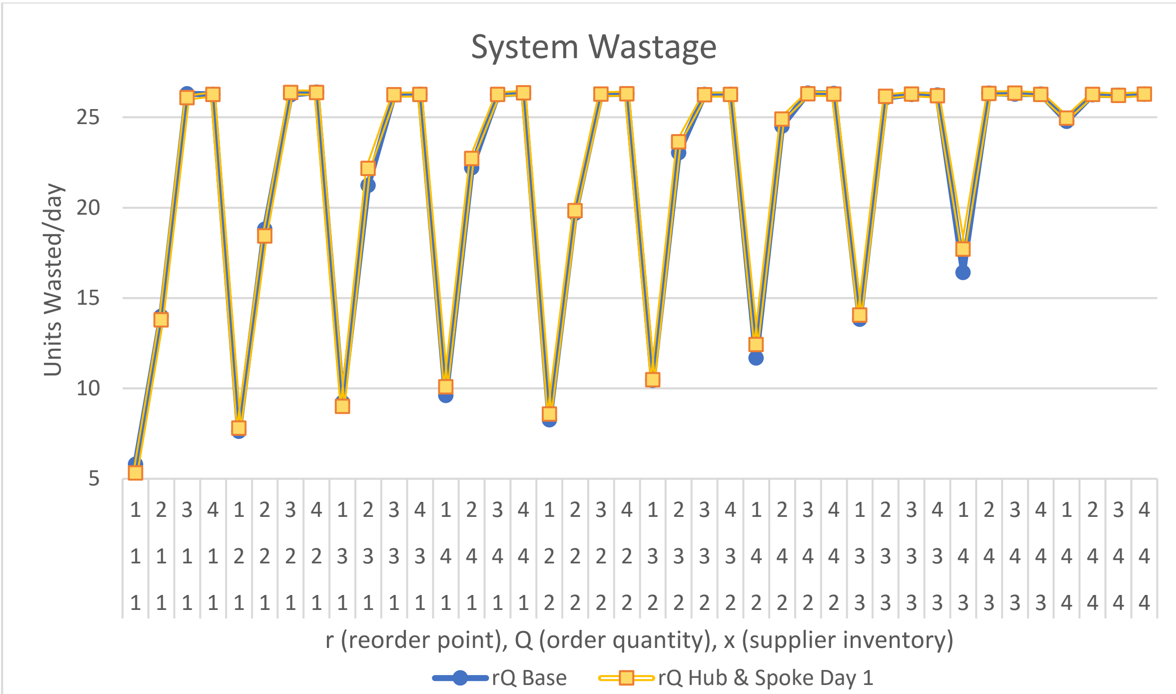

Figure 13: r,Q with Hub and Spoke - System Wastage

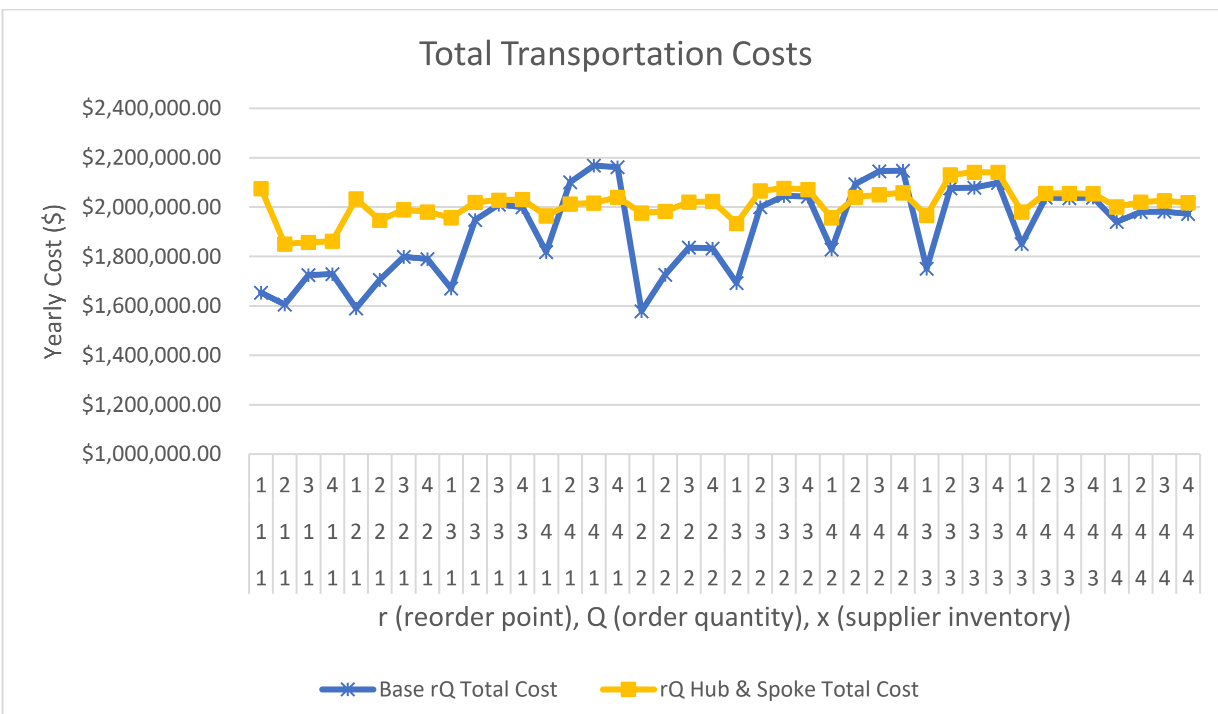

Figure 14: r,Q with Hub and Spoke - Total Transportation Cost

The results from this policy when applied to the same settings as the base r,Q policy did not yield anticipated improvements. Although, when investigating the results further it was determined that in the hub and spoke model wastage at the spoke sites were reduced, but wastage at the hub site was increased significantly. This is likely due to the age of platelets received from both the spoke sites and the supplier. To adjust for the additional inventory with limited remaining shelf-life, the simulation was adjusted to reduce the hub orders from the supplier and to send fresher platelets from the supplier when orders are placed by the hub site. The hub orders were reduced by 60% and the age buckets at the hub were adjusted to preferentially ship newer units (a minimum age of 3 days remaining shelf-life and a maximum age of 5 days remaining shelf-life). These results showed much greater improvements. With these settings the average wastage was reduced to 19.2 +/- 2.5 units per day, an average reduction of 15%. The total transportation cost was also reduced to an average of $1,800,704 +/- $35,069, an average reduction of 4% from the base model. Both results produced p-values that indicate they significantly differ from the base r,Q model. Results for wastage and total transportation cost can be seen in Figure 15 and Figure 16 below.

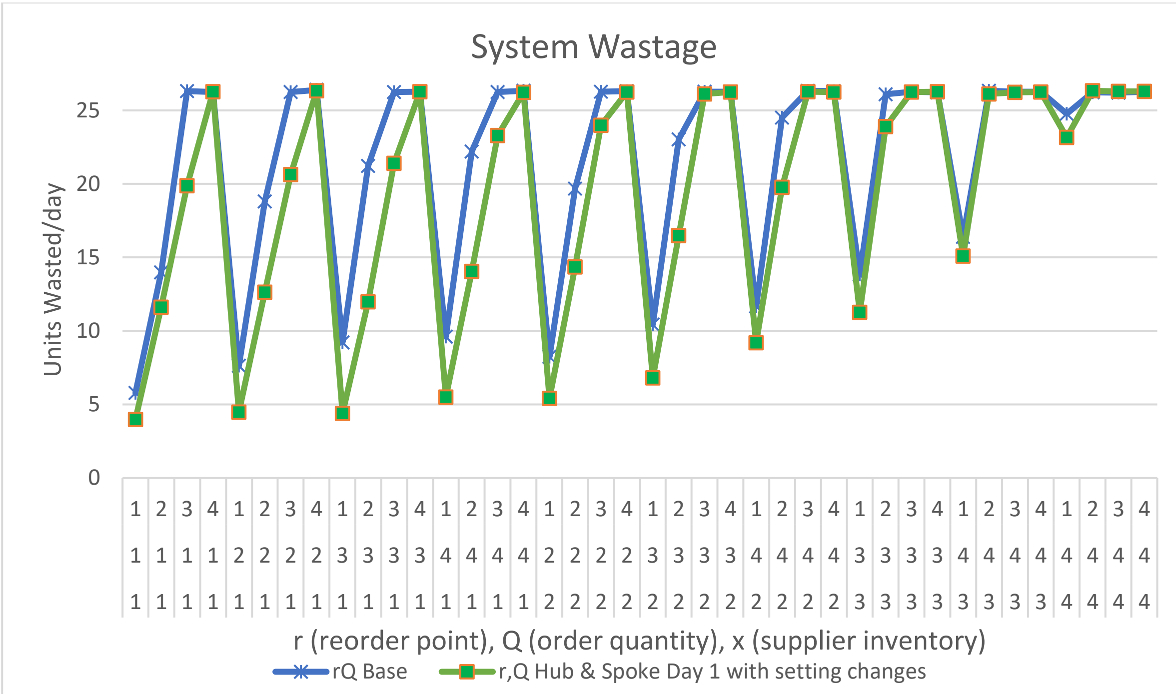

Figure 15: r,Q with Hub and Spoke & Adjusted Hub Ordering - Wastage

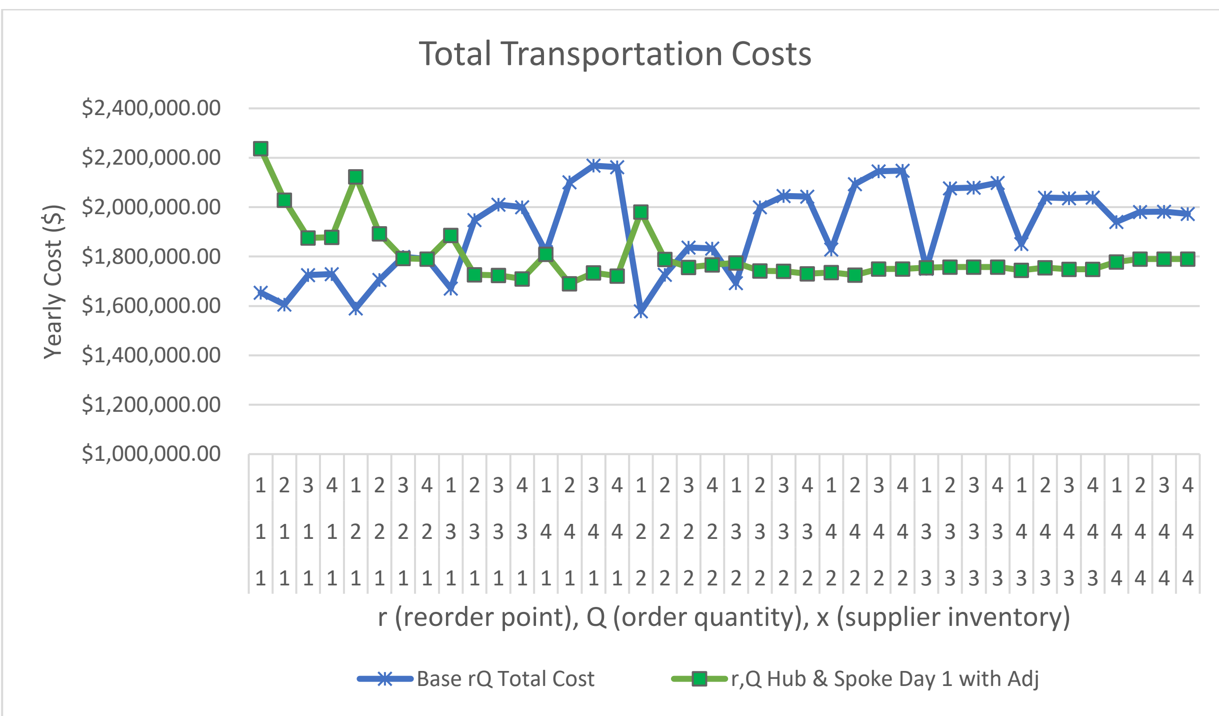

Figure 16: r,Q with Hub and Spoke & Adjusted Hub Ordering – Total Transportation Cost

4.4 s,S Ordering Policy

In addition to testing the r,Q policy, an s,S ordering policy was applied to the model. An s,S policy is similar to the r,Q policy with a trigger point and an order quantity but instead of a fixed order quantity the s,S policy has an order up to quantity. Thus, the quantity ordered depends on the current inventory level. The model was run using a hospital order trigger, s, of 1 to 4 days' demand, a hospital order up to quantity, S, of 1 to 4 days' demand and a supplier inventory level of 1 to 4 days' demand. Appendix F shows the detailed results from each of the scenarios tested. In practice, an s,S policy would be an easily implemented solution, since it involves only minor changes from the current policy and does not need to create new shipping routes with additional regulations.

Wastage

The average total system wastage, over all 40 scenarios, was 18.5 +/- 2.67 units per day. This is a reduction of 18% compared to the base r,Q model. The paired t-test produced a p-value of 1.15x10-5 which indicated the results are statistically significant when compared to the base practice. The lowest wastage occurred when the hospital order trigger was 1 days' demand, the hospital order up to quantity was 3 days' demand and the supplier inventory was 1 days' demand. These settings yielded a daily wastage of 4.9 units per day. There were no scenarios in the s, S policy runs that resulted in higher wastage than the base r,Q model, as seen in Figure 17 below.

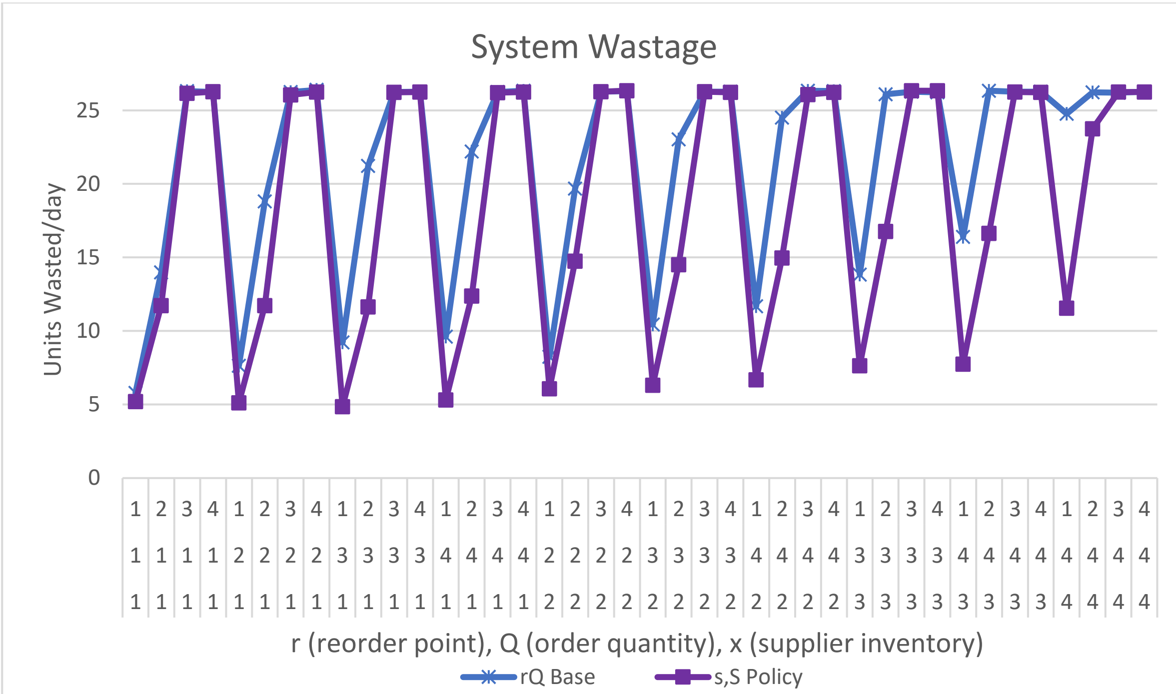

Figure 17: s,S Policy - Wastage

Total Transportation Cost

The average yearly transportation cost over all 40 runs of the s,S policy is $1,847,796 +/- $54,719, a reduction of 3% from the base r,Q model. The p-value from the paired t-test was 0.0079, indicating that the results are statistically significant when compared to the base policy. The setting that yielded the lowest total transportation cost, $1,554,942, occurred when the hospital order trigger was two, the hospital order up to quantity was two, and the supplier inventory was one days' demand. This cost was a combination of $1,192,309 in regular deliveries and $362,634 in emergency shipments. Many of the s,S scenarios resulted in lower total transportation costs than the r,Q model, however, there were some scenarios that resulted in higher total transportation cost, up to a maximum increase of 12%. These results can be seen in Figure 18 below.

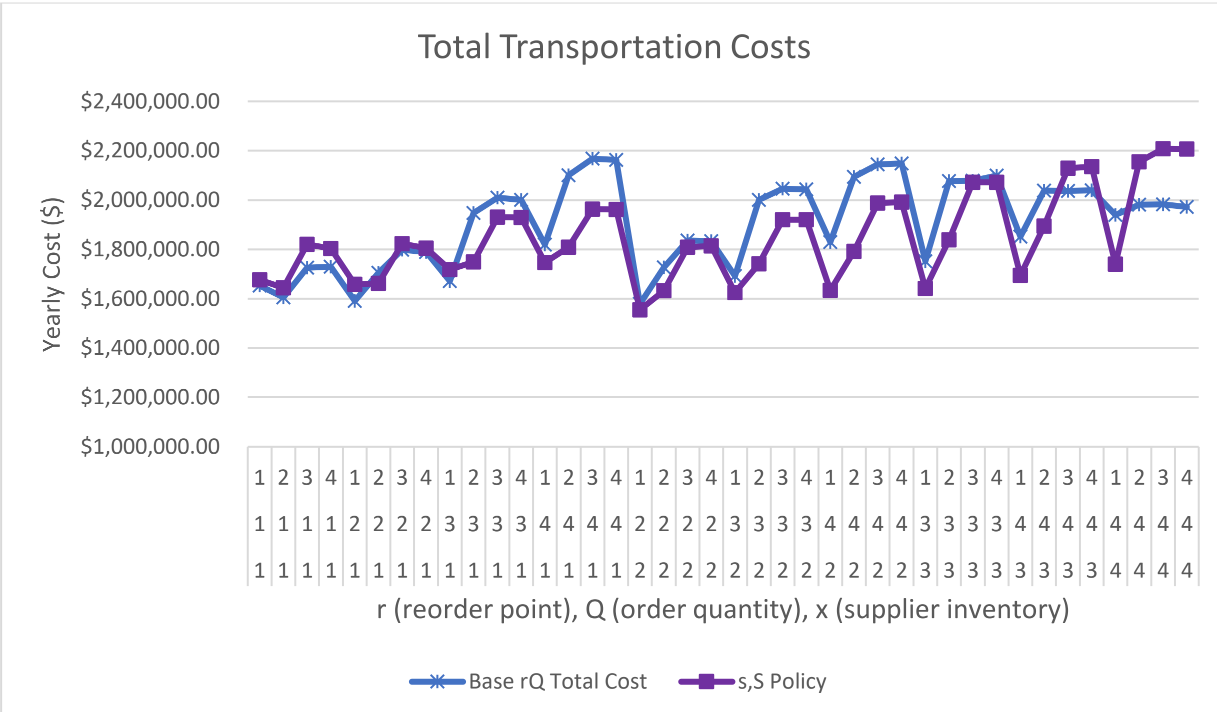

Figure 18: s,S Policy - Total Transportation Cost

4.5 S,s Ordering Policy with Optimal Shipping Policy

In a similar manner to Section 4.2 an optimal shipping policy was applied to the s,S model. The optimal shipping policy was tested using a minimum on hand inventory at hospital sites of one and two days' demand. Results from the policy with a minimum inventory of two days' demand are described below. Detailed results from all policies tested can be found in Appendix G.

When an optimal assignment is done to determine which sites will ship platelets to other sites, the average wastage was 10.6 +/- 2.66 units per day. This is an average reduction in wastage of 58% compared to the base r,Q model. The average total transportation cost of this policy was

$1,835,267 +/- $42,472, a decrease of 3% from the base model. The transportation cost consists of $1,120,350 in supplier and hospital transport costs and $714,916 in emergency transport costs. There were no settings in the s,S policy combined with optimal shipping that yielded increased wastage compared to the base model. There were however some settings that yielded increased total transportation costs. Total transportation costs were higher than the base model when the hospital trigger was one days' demand. The largest increase in total transportation cost was 28% higher than the base r,Q model. The paired t-test resulted in p-values of 3.04×10^{-15} for wastage and 0.072 for total transportation cost, when compared to the r,Q model. This indicates that there is a statistically significant change in wastage but not in total transportation costs. Results for both wastage and total cost can be seen in Figure 19 and Figure 20 below.

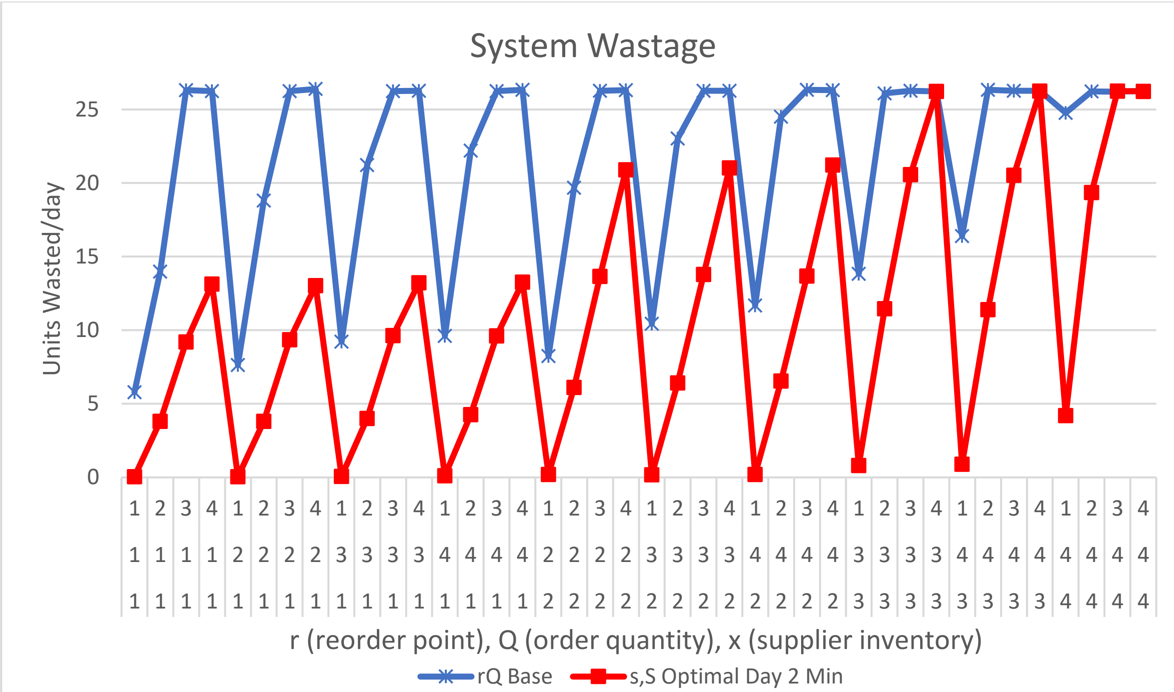

Figure 19: s,S Optimal Policy - Wastage

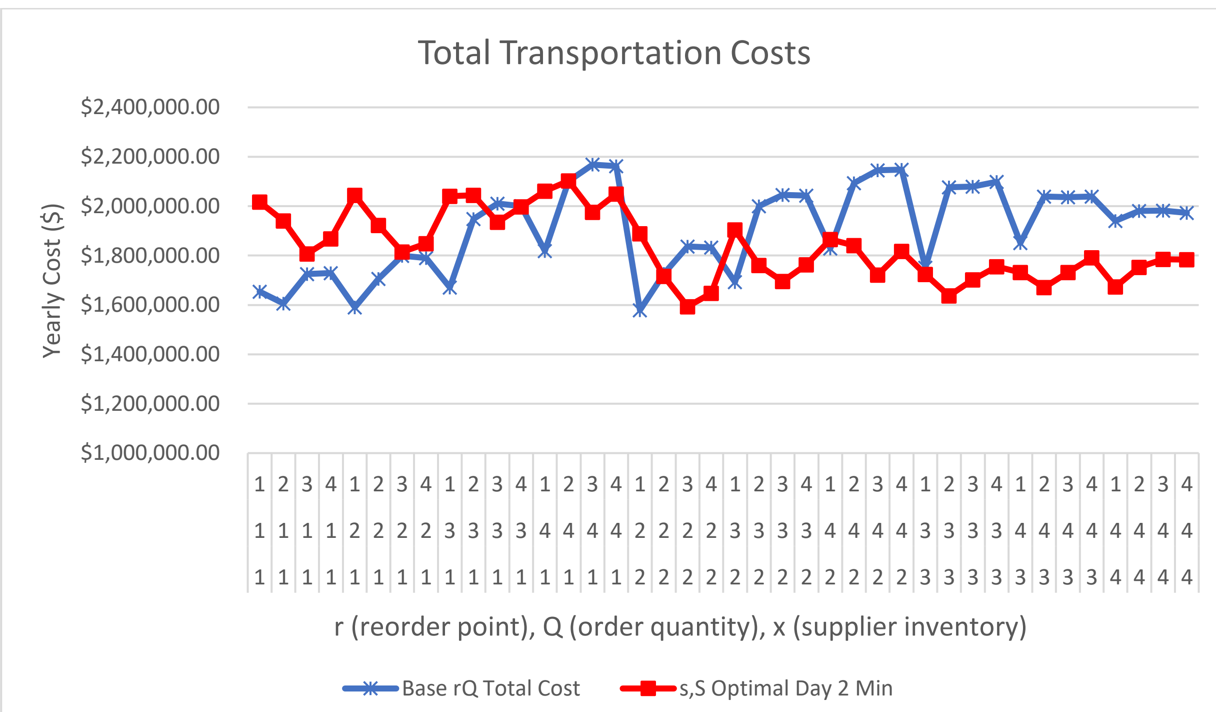

Figure 20: s,S Optimal Policy - Total Transportation Cost

4.6 s,S Ordering Policy with Hub and Spoke Shipping Policy

In a manner similar to Section 4.3, a rule-based shipping policy was applied to the s,S model. The rule-based transshipment policy assumes platelets are shipped from spoke hospitals to hub hospitals when they have a remaining shelf-life of zero, one, or two days. Results for the policy of transshipments with two days remaining shelf-life are described below. The results from the other transshipment policies yielded similar results; detailed results can be found in Appendix H.

When transshipments occurred with units with 2 days' remaining shelf-life, the average wastage was 18.9 +/- 2.6 units per day. This is a decrease of 16% compared to the r,Q base model. The average total cost for this policy was $1,915,251 +/- $21,284, an increase of 1% from the base model. A paired t-test was conducted to compare results from this policy with the base model using 95% significance level. It was determined that the results for wastage were statistically significant with a p-value of 1.42x10-5, but results for total transportation cost, with a p-value of 0.79, were not. This indicates that the wastage was reduced without changing the average total transportation cost in the system. There were no scenarios in this policy that resulted in higher wastage compared to the base r,Q model. The greatest reduction in wastage occurred when the hospital order trigger was one, the order up to quantity was three and the supplier inventory was one. Although there was a slight increase in the average total transportation cost with the s,S policy, there were some settings in which there were reductions in cost. These occurred when the hospital order up to quantities were 4 and they yielded reductions of up to 13%. Results for both wastage and total cost can be seen in Figure 21 and Figure 22 below.

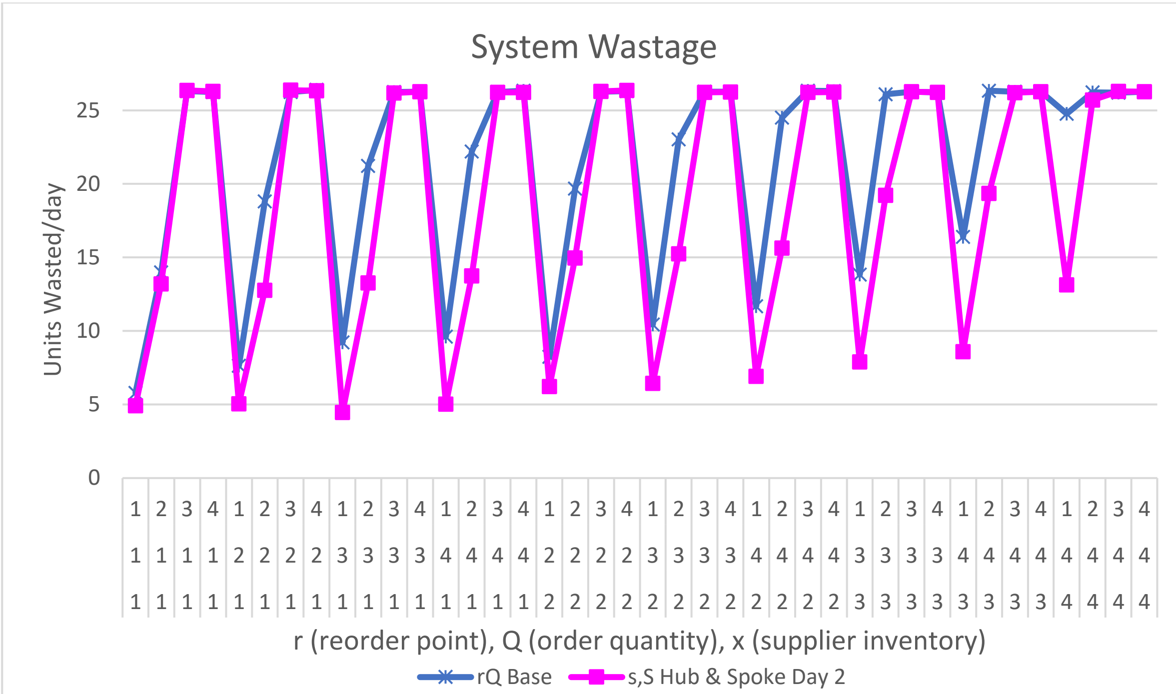

Figure 21: s,S Hub and Spoke - Wastage

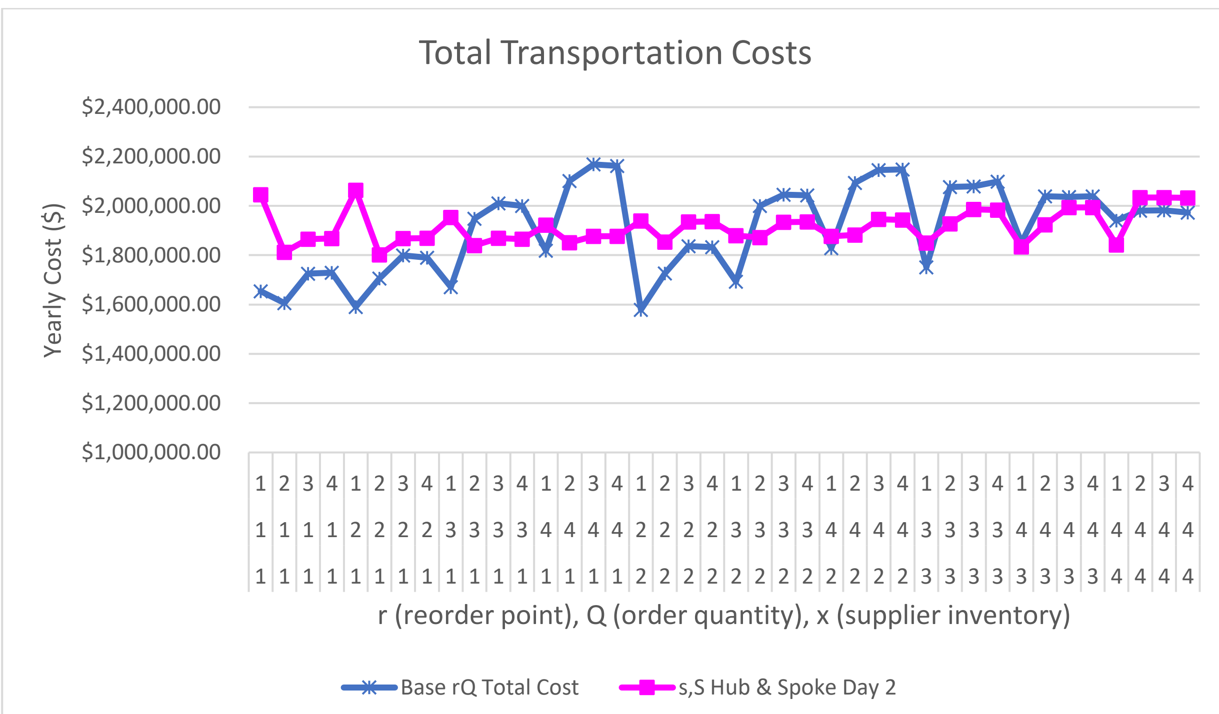

Figure 22: s,S Hub and Spoke - Total Transportation Cost

Similar to the r,Q model, when using the original settings for shipping platelets to the hub site, the rule-based policy did not show anticipated improvements. However, if the settings are adjusted to reduce the orders placed by the hub to the supplier and to adjust the age of platelets received from the supplier, greater improvements can be observed. When hub orders are reduced by 60% and the age buckets at the hub are adjusted (minimum age of 3 days remaining shelf-life and a maximum age of 5 days remaining shelf-life), the results showed decreased wastage and cost. These settings yielded an average wastage of 16.8 +/- 2.7 units per day and an average total transportation cost of $1,806,669 +/- $35,380. These are reductions of 28% and 4% respectively from the base r,Q model and are both statistically significant at the 95% confidence level. Results for wastage and total transportation cost are shown in Figure 23 and Figure 24 respectively.

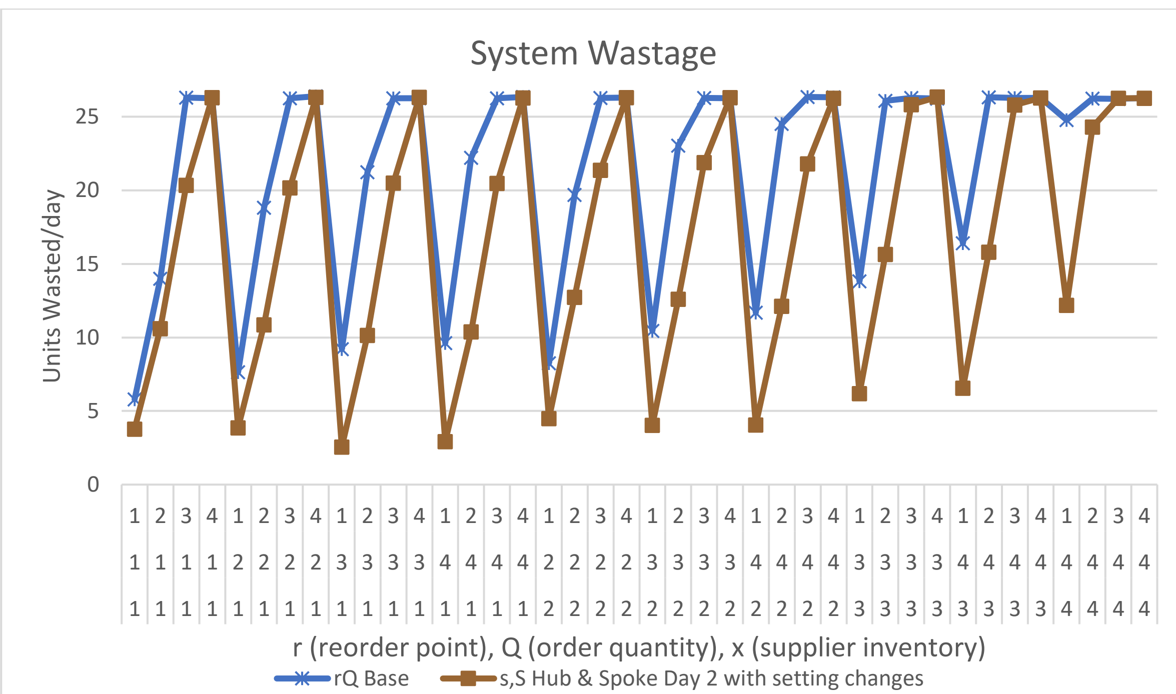

Figure 23: s,S Hub and Spoke with Adjusted Hub Ordering - Wastage

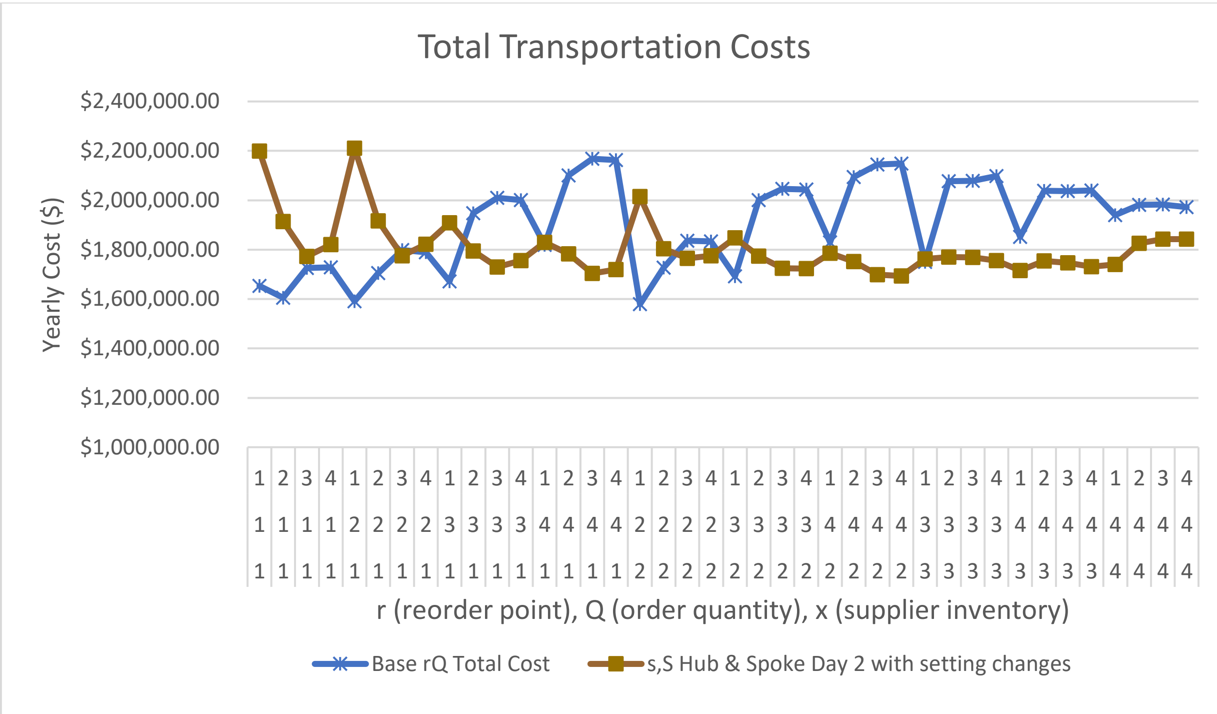

Figure 24: s,S Hub and Spoke with Adjusted Hub Ordering – Total Transportation Cost

When results from the s,S model with a hub and spoke policy were compared against the s,S base model, the results showed a statistically significant reduction in wastage with no statistically significant difference in total transportation costs. This means that implementing the hub and spoke policy with an s,S model further reduced system wastage without increasing the cost of transportation, when compared to the base r,Q policy

4.7 Summary

In summary, each of the policies tested had a statistically significant impact on either wastage, total transportation cost or both. In all policies, there were fluctuations in the amount of improvement or decline, based on the hospital and supplier ordering and inventory settings used.

The optimal transportation policy had the greatest improvements in both wastage and total cost, as might be expected. When applied to both the r,Q model and the s,S model with minimum on hand inventory levels at hospitals of 1 and 2 days' demand, the wastage was reduced by 37% to 59%, depending on the settings of supplier inventory, but in all cases yielded statistically significant change. In addition to a reduction in wastage, the average total transportation cost was reduced in all scenarios by 1% to 4%, although in all cases but one these reductions were not statistically significant. This means that these policies were able to achieve reduced wastage without increasing the transportation costs. Although the optimal policy produced the best results, the implementation of this policy in practice would be challenging.

The rule-based transshipment policy did not yield improvements that were anticipated with the original settings for shipments from the supplier to the hub site. When applied to the r,Q model, the policy did not result in decreases to the average wastage in any of the policies tested. The total transportation cost also did not decrease in any of the policies tested.

However, by adjusting the settings of the model to account for the additional inventory with limited remaining shelf-life at the hub site, statistically significant results were observed. With transshipments made at 1 and 2 days remaining shelf-life, reductions in wastage of 15% were achieved. Average reductions in total transportation costs were 2% to 3%. These policies both showed significant reductions in wastage and the policy with transshipments with 2 days remaining shelf-life, showed a significant reduction in transportation cost.

The s,S model yielded improvements similar in rank as a change to an optimal transportation policy with r,Q ordering. Implementation of an s,S policy is thought to be more practical, since it involves only adjusting the ordering quantity from a fixed amount to an amount based on the current inventory level. An s,S model, even with no additional rule-based or optimal policies, showed a statistically significant reduction in average wastage of 18%, when compared to the base r,Q policy. The s,S model also yielded a statistically significant reduction in average total transportation cost of 3%.

When the s,S model was combined with the hub and spoke policy with ordering adjustments made to the hub site, the observed reductions were even greater. These policies yielded reductions in average wastage compared to the base r,Q model of 28% to 31%, and reductions in total transportation costs of 3% to 4%, depending on the age of transshipments. To determine whether the results from this policy were as good as an optimal policy a paired t-test was conducted to compare results from the r,Q model with an optimal transport policy. This test showed no statistically significant differences in either wastage or total transportation cost. This means that through the implementation of a simple rule-based policy near optimal results were achieved but with much lower computational overhead.

Figure 25 highlights the achievable reductions in wastage with simple rule-based policies compared to the optimal transport policies under both r,Q and s,S ordering policies. This graph includes both system wastage and total transportation costs from each policy. A summary of all results can be seen in Table 8 below and t-test results for all policies tested can be found in

Appendix B.

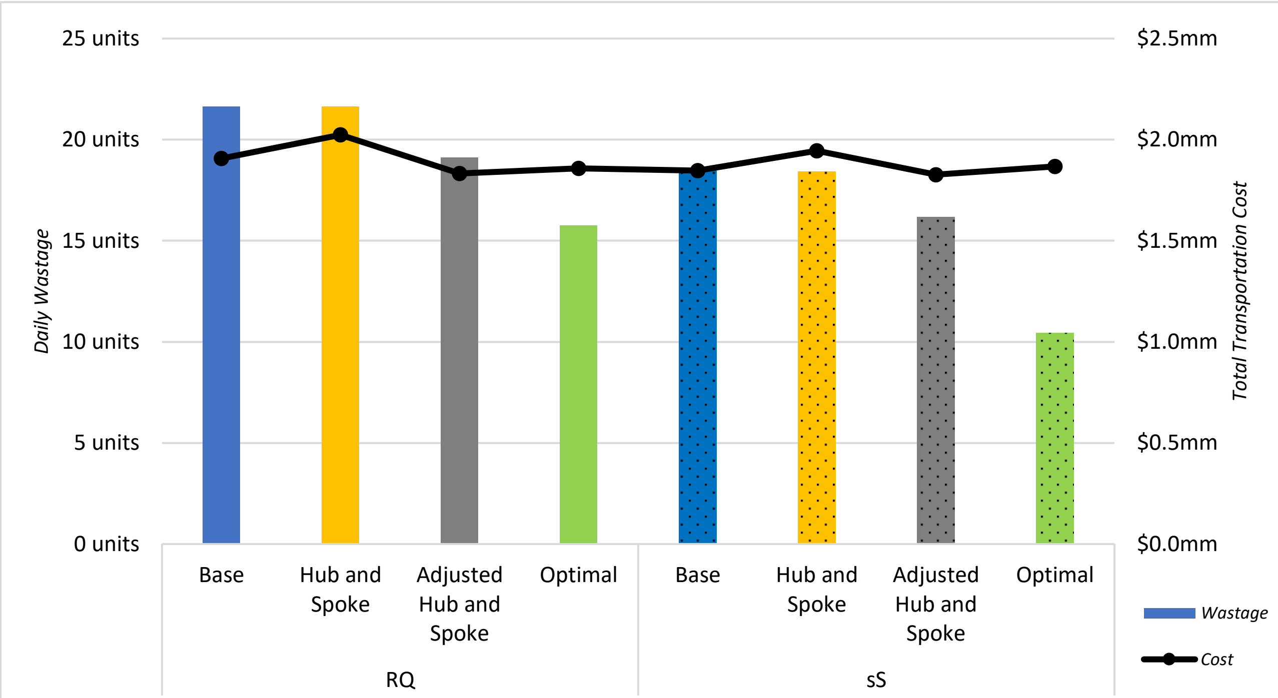

Figure 25: Results from Policies Tested – Wastage and Transportation Cost

Table 8: Summary of Results

		Wastage				Total Transportation Cost			
Model	Parameter	Average	Average Change	Scenarios with Improvements	Significant	Average	Average Change	Scenarios with Improvements	Significant
RQ Base		21.634				$1,907,454			
RQ Optimal	Min Inv = 2 days'	15.820	-37%	34	Yes	$1,807,383	-4%	31	Yes
RQ Hub and Spoke	Remaining shelf life to Transship = 1	21.753	1%	15	Yes	$2,013,081	6%	6	Yes
sS Base		18.501	-18%	33	Yes	$1,847,796	-3%	27	Yes
sS Optimal	Min Inv = 2 days'	10.620	-58%	38	Yes	$1,835,267	-3%	25	No
sS Hub and Spoke	Remaining shelf life to Transship = 2	18.932	-16%	32	Yes	$1,915,251	1%	20	No
RQ Adjusted Hub and Spoke	Remaining shelf life to Transship = 1	19.239	-15%	34	Yes	$1,800,704	-4%	28	Yes
sS Adjusted Hub and Spoke	Remaining shelf life to Transship = 2	16.826	-28%	34	Yes	$1,806,669	-4%	27	Yes

4.8 Additional Considerations

One proviso to these results is the cost of transporting platelets. This was estimated using current values supplied by CBS. If there were significant changes in fixed or variable transportation costs, the outcomes of these policies would likely change. A sensitivity analysis could be completed around price changes, but this was not done since it is believed the costs used accurately reflect those of the current system.

As a future research project, it would be interesting to adjust the size of the network to see if there would be impacts to the effectiveness of these policies. This would include looking at different amounts of hub and spoke sites used in the network. It would also be interesting to investigate whether the scale of the problem is a factor. For example, it is possible that significant changes in performance could be observed if the overall flow through the network was larger than that of the tested network.

Chapter 5: Conclusion

Through this project the effects of different ordering and shipping policies were analyzed when applied to a subsection of the blood distribution network in Southwestern Ontario. All the policies were built into a discrete event simulation of the distribution network implemented in Microsoft Visual Studio.net. The objective of this research was to determine whether a simple rule-based policy could be used to reduce the wastage of platelets in a blood distribution network. Policies were tested under a variety of settings and results were compared to a base case r,Q model to determine whether there were statistically significant changes.

The expectation, based on general considerations of inventory theory was that an s,S ordering policy would perform better than the base r,Q model. It was also expected that the optimal transport policy would yield the greatest improvements when applied to both the r,Q and s,S ordering policies. The anticipated results from the rule-based policy was that it would perform better than the base r,Q but not as well as the optimal. The results from these policies yielded slightly different outcomes than expected.

Significant improvements were indeed achieved through the s,S ordering policy. The metrics from this policy were significantly better than the base r,Q model in and of themselves. Further improvements were achieved through the application of the hub and spoke and optimal transportation policies to the s,S model.

The results from the experiments with an optimal transportation model also performed as expected. The outcomes of these runs performed best in terms of both wastage and total transportation cost reductions. The implementation of such a policy would likely be too difficult; however, it can be used as a good baseline for what is possible within the system.

The hub and spoke policy did not perform as expected as the results from this policy were not substantially better than their comparative base ordering models (s,S base vs s,S with hub and spoke; r,Q base vs. r,Q with hub and spoke). Improvements were observed in certain settings but, on average, the policy did not show overall improvements. The wastage across the system was similar to the base when applying the hub and spoke policies; however, wastage increased significantly at the hub site. This was caused by the increase of near-outdating platelets received at the hub from the spokes, in addition to the aging units in inventory received from the supplier. With the same ordering routines as the base model, the hub site was wasting units that would have expired at the spoke sites in addition to unused units within its inventory. The application of the same ordering routines across all hospitals, as is done in the base model, is not reasonable in the hub and spoke policy, because the hub site functions much differently than the spoke sites. Because of this, the routines should be adjusted to allow differing policies at the hub versus the spoke sites.

When a modified ordering policy is applied to reduce the hub site orders and prioritize fresher units being shipped from the supplier, the rule-based hub and spoke policy yielded significant reductions in both wastage and total transportation cost. In fact, the results from the s,S ordering model with the hub and spoke shipping policy achieved comparable results to the r,Q model with an optimal shipping policy. The s,S model with a hub and spoke policy showed no significant differences in either wastage or total transportation costs compared to the r,Q model with optimal transportation policy, which indicates that the rule-based hub and spoke policy can yield improvements similar to optimal transportation policies if appropriate adjustments are made to ordering parameters at the hub site. This is important because it shows that a simple rule-based policy can perform at near-optimal levels despite being relatively simple to implement.

Overall, this study was able to demonstrate that wastage of platelets in a blood distribution network can be reduced using a rule-based policy. This was successfully demonstrated through the application of a hub and spoke policy with adjusted ordering routines at the hub site. The ability to achieve significant and near optimal reductions in wastage and transportation costs without the complex computational challenges of an optimal model makes the application of such a policy highly desirable. These results provide evidence that allowing site-to-site transfers within the Canadian blood distribution network could results in significant improvements and should, therefore, be considered.

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Appendix A: Blood Type Specific Daily Demand Verification

ABORh Specific Daily Demand							
Facility	ABORh	Historical	Model	Model Var	Lower Bound	Upper Bound	Result
Chatham Kent Health Alliance	B-	0.003	0.003	0.000	-0.004	0.010	*Accept*
Chatham Kent Health Alliance	B+	0.014	0.010	0.000	-0.003	0.024	*Accept*
Chatham Kent Health Alliance	O-	0.093	0.101	0.000	0.052	0.151	*Accept*
Chatham Kent Health Alliance	O+	0.104	0.100	0.000	0.047	0.153	*Accept*
Chatham Health Alliance	O-	0.008	0.011	0.000	-0.006	0.028	*Accept*
Chatham Health Alliance	O+	0.003	0.002	0.000	-0.004	0.009	*Accept*
Windsor Regional Hospital Ouelette Campus	A-	0.002	0.002	0.000	-0.003	0.007	*Accept*
Windsor Regional Hospital Ouelette Campus	A+	0.581	0.582	0.002	0.488	0.676	*Accept*
Windsor Regional Hospital Ouelette Campus	AB+	0.002	0.002	0.000	-0.003	0.007	*Accept*
Windsor Regional Hospital Ouelette Campus	B+	0.064	0.063	0.000	0.027	0.099	*Accept*
Windsor Regional Hospital Ouelette Campus	O+	0.021	0.024	0.000	0.004	0.044	*Accept*

Leamington District Memorial Hospital	A+	0.003	0.002	0.000	-0.003	0.007	*Accept*
Leamington District Memorial Hospital	O-	0.005	0.007	0.000	-0.004	0.017	*Accept*
Leamington District Memorial Hospital	O+	0.013	0.011	0.000	-0.005	0.026	*Accept*
South Huron Hospital	B+	0.005	0.005	0.000	-0.003	0.013	*Accept*
South Huron Hospital	O-	0.003	0.003	0.000	-0.003	0.009	*Accept*
South Huron Hospital	O+	0.011	0.014	0.000	-0.001	0.030	*Accept*
Bluewater Health	A-	0.008	0.007	0.000	-0.004	0.018	*Accept*
Bluewater Health	A+	0.293	0.286	0.002	0.188	0.384	*Accept*
Bluewater Health	AB+	0.002	0.002	0.000	-0.004	0.009	*Accept*
Bluewater Health	B-	0.004	0.002	0.000	-0.003	0.007	*Accept*
Bluewater Health	B+	0.023	0.019	0.000	0.003	0.035	*Accept*
Bluewater Health	O-	0.023	0.018	0.000	0.007	0.028	*Accept*
Bluewater Health	O+	0.135	0.134	0.000	0.090	0.179	*Accept*
St. Thomas Elgin General Hospital	A+	0.053	0.055	0.000	0.018	0.093	*Accept*
St. Thomas Elgin General Hospital	B+	0.003	0.002	0.000	-0.002	0.007	*Accept*
St. Thomas Elgin General Hospital	O-	0.008	0.010	0.000	0.000	0.019	*Accept*

St. Thomas Elgin General Hospital	O+	0.079	0.081	0.000	0.051	0.112	*Accept*
Stratford General Hospital	A-	0.005	0.004	0.000	-0.005	0.013	*Accept*
Stratford General Hospital	A+	0.049	0.054	0.000	0.019	0.089	*Accept*
Stratford General Hospital	AB+	0.008	0.009	0.000	-0.001	0.018	*Accept*
Stratford General Hospital	B+	0.015	0.018	0.000	0.006	0.030	*Accept*
Stratford General Hospital	O-	0.026	0.027	0.000	0.008	0.046	*Accept*
Stratford General Hospital	O+	0.090	0.103	0.000	0.065	0.141	*Accept*
Strathroy Middlesex General Hospital	A+	0.030	0.026	0.000	0.008	0.044	*Accept*
Strathroy Middlesex General Hospital	O-	0.003	0.003	0.000	-0.005	0.011	*Accept*
Strathroy Middlesex General Hospital	O+	0.038	0.040	0.000	0.008	0.072	*Accept*
LHSC University Hospital	A-	0.010	0.010	0.000	-0.001	0.021	*Accept*
LHSC University Hospital	A+	1.082	1.071	0.005	0.903	1.239	*Accept*
LHSC University Hospital	AB+	0.027	0.024	0.000	0.012	0.036	*Accept*

LHSC University Hospital	B-	0.007	0.010	0.000	-0.001	0.021	*Accept*
LHSC University Hospital	B+	0.032	0.035	0.000	0.005	0.064	*Accept*
LHSC University Hospital	O-	0.035	0.037	0.000	0.008	0.065	*Accept*
LHSC University Hospital	O+	1.030	1.058	0.005	0.891	1.224	*Accept*
LHSC Victoria Hospital	A-	0.079	0.079	0.000	0.052	0.105	*Accept*
LHSC Victoria Hospital	A+	3.083	3.050	0.012	2.787	3.313	*Accept*
LHSC Victoria Hospital	AB+	0.130	0.128	0.000	0.090	0.166	*Accept*
LHSC Victoria Hospital	B-	0.009	0.007	0.000	-0.001	0.016	*Accept*
LHSC Victoria Hospital	B+	0.607	0.614	0.002	0.505	0.723	*Accept*
LHSC Victoria Hospital	O-	0.025	0.024	0.000	0.004	0.044	*Accept*
LHSC Victoria Hospital	O+	3.253	3.269	0.007	3.074	3.464	*Accept*
Tillsonburg District Memorial Hospital	A+	0.008	0.007	0.000	-0.008	0.022	*Accept*
Tillsonburg District Memorial Hospital	B+	0.005	0.002	0.000	-0.003	0.008	*Accept*
Tillsonburg District Memorial Hospital	O+	0.016	0.014	0.000	-0.012	0.040	*Accept*
Windsor Regional Hospital Metropolitan Campus	A-	0.051	0.048	0.000	0.031	0.066	*Accept*

Windsor Regional Hospital Metropolitan Campus	A+	0.961	0.971	0.003	0.836	1.105	*Accept*
Windsor Regional Hospital Metropolitan Campus	AB-	0.003	0.001	0.000	-0.003	0.006	*Accept*
Windsor Regional Hospital Metropolitan Campus	AB+	0.056	0.057	0.000	0.016	0.098	*Accept*
Windsor Regional Hospital Metropolitan Campus	B-	0.013	0.012	0.000	-0.005	0.030	*Accept*
Windsor Regional Hospital Metropolitan Campus	B+	0.544	0.541	0.003	0.411	0.671	*Accept*
Windsor Regional Hospital Metropolitan Campus	O-	0.018	0.020	0.000	0.002	0.037	*Accept*
Windsor Regional Hospital Metropolitan Campus	O+	0.651	0.635	0.005	0.475	0.795	*Accept*
Woodstock Hospital	A-	0.019	0.021	0.000	0.008	0.034	*Accept*
Woodstock Hospital	A+	0.008	0.009	0.000	-0.005	0.023	*Accept*
Woodstock Hospital	B-	0.003	0.002	0.000	-0.002	0.007	*Accept*
Woodstock Hospital	B+	0.008	0.008	0.000	-0.001	0.016	*Accept*

Woodstock Hospital	O-	0.008	0.011	0.000	-0.002	0.024	*Accept*
Woodstock Hospital	O+	0.135	0.140	0.001	0.066	0.215	*Accept*
Norfolk General Hospital	A+	0.023	0.023	0.000	-0.006	0.053	*Accept*
Norfolk General Hospital	AB+	0.003	0.002	0.000	-0.006	0.011	*Accept*
Norfolk General Hospital	B+	0.003	0.001	0.000	-0.002	0.005	*Accept*
Norfolk General Hospital	O+	0.034	0.028	0.000	-0.002	0.059	*Accept*
Consolidated Sites	A-	8.800	8.809	0.011	8.555	9.062	*Accept*
Consolidated Sites	A+	32.232	32.224	0.047	31.709	32.739	*Accept*
Consolidated Sites	AB-	0.721	0.744	0.003	0.610	0.878	*Accept*
Consolidated Sites	AB+	4.156	4.140	0.008	3.929	4.351	*Accept*
Consolidated Sites	B-	2.348	2.381	0.005	2.206	2.556	*Accept*
Consolidated Sites	B+	9.825	9.896	0.022	9.544	10.248	*Accept*
Consolidated Sites	O-	11.368	11.503	0.038	11.040	11.966	*Accept*
Consolidated Sites	O+	25.187	25.198	0.018	24.877	25.520	*Accept*
Alexandra Hospital - Ingersoll	A-	0.005	0.005	0.000	-0.005	0.014	*Accept*
Alexandra Hospital - Ingersoll	A+	0.005	0.007	0.000	-0.009	0.023	*Accept*
Alexandra Hospital - Ingersoll	B+	0.003	0.002	0.000	-0.003	0.007	*Accept*
Alexandra Hospital - Ingersoll	O+	0.008	0.009	0.000	-0.006	0.024	*Accept*
Chatham Kent Health Alliance	A-	0.047	0.044	0.000	0.032	0.056	*Accept*

Chatham Kent Health Alliance	A+	0.252	0.255	0.001	0.175	0.335	*Accept*
Chatham Kent Health Alliance	AB+	0.003	0.003	0.000	-0.003	0.010	*Accept*

Appendix B: Tables with Statistical Significance Results

Statistical Significance compared to s,S model		
Alpha	0.05	
	p-value	**Significant**
sS with Hub & Spoke Age 6		
Wastage	1.44612E-05	Yes
Total Transport Cost	4.52471E-08	Yes
sS with Hub & Spoke Age 5		
Wastage	0.000962972	Yes
Total Transport Cost	0.007399023	Yes
sS with Hub & Spoke Age 7		
Wastage	0.048330083	Yes
Total Transport Cost	0.000310934	Yes
sS with Hub & Spoke Age 5 + Adjustments		
Wastage	2.44706E-06	Yes
Total Transport Cost	0.299198633	No
sS with Hub & Spoke Age 6 + Adjustments		
Wastage	4.24644E-08	Yes
Total Transport Cost	0.634253375	No
sS with Optimal Min 1 Day		
Wastage	3.03568E-13	Yes
Total Transport Cost	0.620416428	No
sS with Optimal Min 2 Day		
Wastage	2.8655E-13	Yes
Total Transport Cost	0.75361347	No

s,S with Hub & Spoke compared r,Q Optimal		
Alpha	0.05	
	p-value	**Significant**
Wastage	0.556208354	No
Total Transport Cost	0.400045549	No

s,S compared r,Q Hub and Spoke		
Alpha	0.05	
	p-value	**Significant**
Wastage	0.262517484	No
Total Transport Cost	0.715631181	No

Statistical Significance compared to base RQ model		
Alpha	0.05	
	p-value	**Significant**
RQ with Hub & Spoke Age 6		
Wastage	0.028910186	Yes
Total Transport Cost	3.17918E-05	Yes
RQ with Hub & Spoke Age 5		
Wastage	0.000772423	Yes
Total Transport Cost	0.000345571	Yes
RQ with Hub & Spoke Age 7		
Wastage	0.67980682	No
Total Transport Cost	1.58465E-05	Yes
RQ with Hub & Spoke Age 6 + Adjustments		
Wastage	1.0258E-06	Yes
Total Transport Cost	0.016914935	Yes
RQ with Hub & Spoke Age 7 + Adjustments		
Wastage	8.29778E-07	Yes
Total Transport Cost	0.105803374	No
RQ with Optimal Min 1 Day		
Wastage	2.40114E-09	Yes
Total Transport Cost	0.081284661	No
RQ with Optimal Min 2 Day		
Wastage	2.65562E-09	Yes
Total Transport Cost	0.001569434	Yes
sS		
Wastage	1.14995E-05	Yes
Total Transport Cost	0.007902034	Yes
sS with Hub & Spoke Age 6		
Wastage	0.064298062	No
Total Transport Cost	3.16285E-05	Yes
sS with Hub & Spoke Age 5		
Wastage	1.41834E-05	Yes
Total Transport Cost	0.788978769	No
sS with Hub & Spoke Age 5 + Adjustments		
Wastage	9.76323E-09	Yes
Total Transport Cost	0.023659569	Yes
sS with Hub & Spoke Age 6 + Adjustments		
Wastage	3.50808E-09	Yes
Total Transport Cost	0.089723836	No
sS with Hub & Spoke Age 7		
Wastage	1.32674E-05	Yes
Total Transport Cost	0.235615756	No
sS with Optimal Min 1 Day		
Wastage	2.62832E-15	Yes
Total Transport Cost	0.284731909	No
sS with Optimal Min 2 Day		
Wastage	3.04233E-15	Yes
Total Transport Cost	0.072384107	No

Appendix C: Results – Base r,Q Model

Run of Base RQ Model							
Hosp Inv Trigger	Hosp Inv UpTo	Supp Inv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost
1	1	1	5.792582	3.86978	$ 1,010,754.00	$ 642,921.60	$ 1,653,675.60
1	1	2	13.980496	2.099451	$ 1,244,320.00	$ 361,338.30	$ 1,605,658.30
1	1	3	26.305764	1.918407	$ 1,396,405.00	$ 329,062.40	$ 1,725,467.40
1	1	4	26.259066	1.912363	$ 1,402,363.00	$ 326,668.50	$ 1,729,031.50
1	2	1	7.632692	2.462088	$ 1,136,430.00	$ 454,452.00	$ 1,590,882.00
1	2	2	18.808517	1.557967	$ 1,426,631.00	$ 278,741.30	$ 1,705,372.30
1	2	3	26.245053	1.443407	$ 1,541,139.00	$ 257,445.50	$ 1,798,584.50
1	2	4	26.390934	1.484341	$ 1,523,221.00	$ 266,485.70	$ 1,789,706.70
1	3	1	9.216758	1.441209	$ 1,385,772.00	$ 285,011.00	$ 1,670,783.00
1	3	2	21.23159	0.9892858	$ 1,760,329.00	$ 187,520.00	$ 1,947,849.00
1	3	3	26.2511	0.9406594	$ 1,829,599.00	$ 180,767.30	$ 2,010,366.30
1	3	4	26.264563	0.932143	$ 1,821,980.00	$ 178,664.10	$ 2,000,644.10
1	4	1	9.609615	1.044231	$ 1,607,862.00	$ 210,726.70	$ 1,818,588.70
1	4	2	22.200004	0.6928571	$ 1,969,547.00	$ 131,434.00	$ 2,100,981.00
1	4	3	26.24836	0.6497253	$ 2,044,830.00	$ 123,143.30	$ 2,167,973.30
1	4	4	26.33764	0.6697803	$ 2,036,231.00	$ 126,048.60	$ 2,162,279.60
2	2	1	8.256045	1.869231	$ 1,237,158.00	$ 341,631.90	$ 1,578,789.90
2	2	2	19.688457	1.257967	$ 1,511,935.00	$ 214,860.90	$ 1,726,795.90
2	2	3	26.269228	1.214011	$ 1,626,668.00	$ 209,762.00	$ 1,836,430.00
2	2	4	26.305219	1.212637	$ 1,624,505.00	$ 208,886.00	$ 1,833,391.00
2	3	1	10.441484	1.064835	$ 1,485,106.00	$ 207,432.20	$ 1,692,538.20
2	3	2	23.03984	0.7821429	$ 1,856,047.00	$ 144,247.40	$ 2,000,294.40
2	3	3	26.27061	0.7653847	$ 1,904,253.00	$ 141,503.90	$ 2,045,756.90
2	3	4	26.26044	0.7631868	$ 1,901,842.00	$ 141,481.60	$ 2,043,323.60
2	4	1	11.689011	0.8258243	$ 1,669,147.00	$ 160,148.70	$ 1,829,295.70
2	4	2	24.50605	0.6008242	$ 1,984,809.00	$ 108,782.30	$ 2,093,591.30
2	4	3	26.33901	0.6019231	$ 2,035,661.00	$ 109,062.80	$ 2,144,723.80
2	4	4	26.32143	0.5991759	$ 2,039,067.00	$ 109,134.00	$ 2,148,201.00
3	3	1	13.826101	0.8208792	$ 1,600,358.00	$ 150,732.80	$ 1,751,090.80
3	3	2	26.089556	0.7505495	$ 1,941,310.00	$ 135,356.30	$ 2,076,666.30
3	3	3	26.270607	0.7123626	$ 1,949,693.00	$ 128,974.00	$ 2,078,667.00
3	3	4	26.226646	0.7318682	$ 1,966,631.00	$ 131,939.10	$ 2,098,570.10
3	4	1	16.405496	0.6950549	$ 1,725,648.00	$ 125,765.60	$ 1,851,413.60
3	4	2	26.330222	0.645055	$ 1,922,951.00	$ 115,910.70	$ 2,038,861.70
3	4	3	26.276918	0.623077	$ 1,924,311.00	$ 112,441.70	$ 2,036,752.70
3	4	4	26.27335	0.6189561	$ 1,927,277.00	$ 111,873.00	$ 2,039,150.00
4	4	1	24.7695042	0.6387363	$ 1,826,818.00	$ 113,237.20	$ 1,940,055.20
4	4	2	26.2384591	0.6239012	$ 1,869,101.00	$ 111,686.30	$ 1,980,787.30
4	4	3	26.2065915	0.6288463	$ 1,871,163.00	$ 111,324.00	$ 1,982,487.00
4	4	4	26.2752767	0.6214287	$ 1,861,656.00	$ 111,009.90	$ 1,972,665.90
		Average	21.6337571	1.09438882	$ 1,710,013.20	$ 197,440.37	$ 1,907,453.57
		Min	5.792582	0.5991759	$ 1,010,754.00	$ 108,782.30	$ 1,578,789.90
		Max	26.390934	3.86978	$ 2,044,830.00	$ 642,921.60	$ 2,167,973.30
		st dev	6.83677459	0.661545058		112092.2939	177633.7827
		CI	2.1187384	0.205014938		$ 34,737.76	55049.27958

Appendix D: Results from Optimal Transport Policy with r,Q Ordering

Run of Optimization Model Min 1 day demand									
HospInv Trigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	0.04972527	14.85275	$ 608,764.90	$ 1,387,108.00	$ 1,995,872.90	-99%	21%
1	1	2	4.393682	7.962087	$ 762,890.90	$ 1,142,699.00	$ 1,905,589.90	-69%	19%
1	1	3	12.196154	5.214835	$ 958,847.20	$ 891,329.60	$ 1,850,176.80	-54%	7%
1	1	4	16.003296	4.417857	$ 1,090,106.00	$ 733,480.80	$ 1,823,586.80	-39%	5%
1	2	1	0.16236269	6.76621	$ 626,753.20	$ 1,330,767.00	$ 1,957,520.20	-98%	23%
1	2	2	5.8969775	4.47033	$ 899,037.70	$ 898,464.20	$ 1,797,501.90	-69%	5%
1	2	3	13.6989002	2.602473	$ 1,215,690.00	$ 509,547.40	$ 1,725,237.40	-48%	-4%
1	2	4	21.043681	2.379945	$ 1,338,365.00	$ 462,382.50	$ 1,800,747.50	-20%	1%
1	3	1	0.37994513	5.363737	$ 811,519.80	$ 1,053,051.00	$ 1,864,570.80	-96%	12%
1	3	2	8.6274718	2.484615	$ 1,278,288.00	$ 488,372.70	$ 1,766,660.70	-59%	-9%
1	3	3	16.6208732	1.56511	$ 1,542,626.00	$ 302,170.20	$ 1,844,796.20	-37%	-8%
1	3	4	25.6332394	1.481868	$ 1,634,025.00	$ 283,203.50	$ 1,917,228.50	-2%	-4%
1	4	1	0.70357141	4.958791	$ 903,311.00	$ 976,660.30	$ 1,879,971.30	-93%	3%
1	4	2	11.8620824	1.65989	$ 1,518,649.00	$ 323,844.70	$ 1,842,493.70	-47%	-12%
1	4	3	21.4934088	1.252198	$ 1,696,089.00	$ 240,697.90	$ 1,936,786.90	-18%	-11%
1	4	4	26.2615412	1.254945	$ 1,735,133.00	$ 241,289.20	$ 1,976,422.20	0%	-9%
2	2	1	0.62060443	5.738187	$ 669,629.20	$ 1,200,467.00	$ 1,870,096.20	-92%	18%
2	2	2	10.21071758	2.809341	$ 1,136,536.00	$ 566,859.00	$ 1,703,395.00	-48%	-1%
2	2	3	19.54011132	2.021978	$ 1,302,210.00	$ 391,631.60	$ 1,693,841.60	-26%	-8%
2	2	4	26.2225266	2.021978	$ 1,333,880.00	$ 397,886.50	$ 1,731,766.50	0%	-6%
2	3	1	1.3406598	4.438461	$ 902,641.80	$ 913,804.00	$ 1,816,445.80	-87%	7%
2	3	2	13.41373374	1.742583	$ 1,455,709.00	$ 336,148.40	$ 1,791,857.40	-42%	-10%
2	3	3	24.16264	1.468132	$ 1,569,944.00	$ 281,647.40	$ 1,851,591.40	-8%	-9%
2	3	4	26.32115506	1.393681	$ 1,581,444.00	$ 268,097.20	$ 1,849,541.20	0%	-9%
2	4	1	2.34395637	3.973901	$ 1,004,650.00	$ 822,768.40	$ 1,827,418.40	-80%	0%
2	4	2	16.94313099	1.328022	$ 1,664,950.00	$ 253,107.10	$ 1,918,057.10	-31%	-8%
2	4	3	26.06181143	1.241758	$ 1,762,058.00	$ 234,485.00	$ 1,996,543.00	-1%	-7%
2	4	4	26.25055308	1.223626	$ 1,757,992.00	$ 235,342.60	$ 1,993,334.60	0%	-7%
3	3	1	4.69065904	3.310439	$ 1,067,410.00	$ 685,144.40	$ 1,752,554.40	-66%	0%
3	3	2	21.3725289	1.377198	$ 1,522,311.00	$ 261,324.50	$ 1,783,635.50	-18%	-14%
3	3	3	26.26016539	1.312637	$ 1,542,618.00	$ 250,567.70	$ 1,793,185.70	0%	-14%
3	3	4	26.28928484	1.302473	$ 1,542,821.00	$ 248,487.20	$ 1,791,308.20	0%	-15%
3	4	1	5.5093404	2.66511	$ 1,253,199.00	$ 552,012.90	$ 1,805,211.90	-66%	-2%
3	4	2	24.53900791	1.20989	$ 1,729,550.00	$ 226,510.40	$ 1,956,060.40	-7%	-4%
3	4	3	26.26291396	1.18022	$ 1,735,155.00	$ 221,814.00	$ 1,956,969.00	0%	-4%
3	4	4	26.26263978	1.178846	$ 1,737,207.00	$ 222,562.80	$ 1,959,769.80	0%	-4%
4	4	1	11.84066099	2.670604	$ 1,243,247.00	$ 570,011.00	$ 1,813,258.00	-52%	-7%
4	4	2	26.31208681	1.380495	$ 1,662,357.00	$ 269,233.60	$ 1,931,590.60	0%	-2%
4	4	3	26.25989154	1.365659	$ 1,662,605.00	$ 266,563.70	$ 1,929,168.70	0%	-3%
4	4	4	26.28159154	1.368956	$ 1,660,334.00	$ 267,209.40	$ 1,927,543.40	0%	-2%
		Average	15.75848209	2.9602954	$ 1,328,013.84	$ 530,218.85	$ 1,858,232.69	-37%	-2%
		Min	0.04972527	1.178846	$ 608,764.90	$ 221,814.00	$ 1,693,841.60	-99%	-15%
		Max	26.32115506	14.85275	$ 1,762,058.00	$ 1,387,108.00	$ 1,996,543.00	0%	23%

Transport Min 2 days demand									
HospInv Trigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	0.09285715	12.82061	$ 603,172.50	$ 1,358,758.00	$ 1,961,930.50	-98%	19%
1	1	2	4.0813188	7.666209	$ 756,242.00	$ 1,146,089.00	$ 1,902,331.00	-71%	18%
1	1	3	12.126648	5.146154	$ 949,915.90	$ 872,266.50	$ 1,822,182.40	-54%	6%
1	1	4	16.487637	4.252472	$ 1,105,876.00	$ 692,020.70	$ 1,797,896.70	-37%	4%
1	2	1	0.18214289	6.387362	$ 629,311.30	$ 1,270,134.00	$ 1,899,445.30	-98%	19%
1	2	2	5.9623614	4.239835	$ 889,877.30	$ 858,114.30	$ 1,747,991.60	-68%	2%
1	2	3	14.1057696	2.156319	$ 1,228,628.00	$ 414,835.90	$ 1,643,463.90	-46%	-9%
1	2	4	21.370059	1.917858	$ 1,351,712.00	$ 365,940.80	$ 1,717,652.80	-19%	-4%
1	3	1	0.39038464	5.020879	$ 830,270.00	$ 1,007,069.00	$ 1,837,339.00	-96%	10%
1	3	2	8.7016496	2.285989	$ 1,265,215.00	$ 453,665.70	$ 1,718,880.70	-59%	-12%
1	3	3	16.8340701	1.297802	$ 1,530,770.00	$ 242,052.30	$ 1,772,822.30	-36%	-12%
1	3	4	25.3423062	1.301374	$ 1,633,129.00	$ 241,123.30	$ 1,874,252.30	-4%	-6%
1	4	1	0.71428576	4.281044	$ 938,431.70	$ 868,256.50	$ 1,806,688.20	-93%	-1%
1	4	2	11.6662113	1.432967	$ 1,478,694.00	$ 278,112.50	$ 1,756,806.50	-47%	-16%
1	4	3	21.505216	1.099176	$ 1,650,738.00	$ 203,734.40	$ 1,854,472.40	-18%	-14%
1	4	4	26.2648382	1.021154	$ 1,692,184.00	$ 188,588.00	$ 1,880,772.00	0%	-13%
2	2	1	0.59560442	5.537637	$ 686,353.20	$ 1,158,648.00	$ 1,845,001.20	-93%	17%
2	2	2	10.41895231	2.482692	$ 1,140,500.00	$ 496,345.30	$ 1,636,845.30	-47%	-5%
2	2	3	19.80274989	1.692033	$ 1,333,679.00	$ 310,916.40	$ 1,644,595.40	-25%	-10%
2	2	4	26.32582133	1.611813	$ 1,369,724.00	$ 302,059.80	$ 1,671,783.80	0%	-9%
2	3	1	1.31785767	3.969231	$ 914,202.90	$ 844,340.70	$ 1,758,543.60	-87%	4%
2	3	2	13.64505132	1.379396	$ 1,431,919.00	$ 260,447.80	$ 1,692,366.80	-41%	-15%
2	3	3	24.35988726	1.093956	$ 1,539,986.00	$ 201,447.10	$ 1,741,433.10	-7%	-15%
2	3	4	26.31264011	1.129121	$ 1,557,809.00	$ 206,480.80	$ 1,764,289.80	0%	-14%
2	4	1	2.2664833	3.526648	$ 1,032,721.00	$ 748,553.10	$ 1,781,274.10	-81%	-3%
2	4	2	17.14450627	1.038736	$ 1,636,915.00	$ 188,250.70	$ 1,825,165.70	-30%	-13%
2	4	3	26.10989143	1.031593	$ 1,724,331.00	$ 188,029.80	$ 1,912,360.80	-1%	-11%
2	4	4	26.23544363	0.9887363	$ 1,726,571.00	$ 180,243.50	$ 1,906,814.50	0%	-11%
3	3	1	4.59478012	3.031044	$ 1,094,024.00	$ 637,192.00	$ 1,731,216.00	-67%	-1%
3	3	2	21.55137176	1.156044	$ 1,553,586.00	$ 209,528.40	$ 1,763,114.40	-17%	-15%
3	3	3	26.26456429	1.05522	$ 1,578,445.00	$ 190,529.00	$ 1,768,974.00	0%	-15%
3	3	4	26.24176011	1.05522	$ 1,574,439.00	$ 191,142.70	$ 1,765,581.70	0%	-16%
3	4	1	5.63653914	2.417857	$ 1,265,689.00	$ 505,416.10	$ 1,771,105.10	-66%	-4%
3	4	2	24.76016561	1.017033	$ 1,743,686.00	$ 180,789.70	$ 1,924,475.70	-6%	-6%
3	4	3	26.26785923	0.9681319	$ 1,750,257.00	$ 173,480.70	$ 1,923,737.70	0%	-6%
3	4	4	26.26675868	0.9755495	$ 1,744,518.00	$ 175,229.50	$ 1,919,747.50	0%	-6%
4	4	1	12.00246736	2.540934	$ 1,265,027.00	$ 540,777.90	$ 1,805,804.90	-52%	-7%
4	4	2	26.30192626	1.142857	$ 1,702,346.00	$ 213,992.80	$ 1,916,338.80	0%	-3%
4	4	3	26.28076626	1.136539	$ 1,699,732.00	$ 214,943.70	$ 1,914,675.70	0%	-3%
4	4	4	26.27746626	1.138187	$ 1,699,708.00	$ 215,440.80	$ 1,915,148.80	0%	-3%
		Average	15.82022674	2.636085318	$ 1,332,508.37	$ 474,874.68	$ 1,807,383.05	-37%	-4%
		Min	0.09285715	0.9681319	$ 603,172.50	$ 173,480.70	$ 1,636,845.30	-98%	-16%
		Max	26.32582133	12.82061	$ 1,750,257.00	$ 1,358,758.00	$ 1,961,930.50	0%	19%

Appendix E: Results from Hub and Spoke Model with r,Q Ordering

Run of Tranship Model with 1 Day (age 6)									
HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	5.331869	3.435439	$ 1,498,894.00	$ 576,270.00	$ 2,075,164.00	-8%	25%
1	1	2	13.790105	1.725824	$ 1,556,199.00	$ 294,741.30	$ 1,850,940.30	-1%	15%
1	1	3	26.08599	1.555495	$ 1,595,231.00	$ 261,909.60	$ 1,857,140.60	-1%	8%
1	1	4	26.265105	1.551099	$ 1,599,583.00	$ 263,367.10	$ 1,862,950.10	0%	8%
1	2	1	7.795055	2.326648	$ 1,599,185.00	$ 434,550.20	$ 2,033,735.20	2%	28%
1	2	2	18.42775	1.48489	$ 1,683,478.00	$ 263,734.40	$ 1,947,212.40	-2%	14%
1	2	3	26.362633	1.412088	$ 1,739,180.00	$ 250,679.00	$ 1,989,859.00	0%	11%
1	2	4	26.367311	1.40467	$ 1,730,479.00	$ 249,786.80	$ 1,980,265.80	0%	11%
1	3	1	9.013737	1.382692	$ 1,679,921.00	$ 277,482.30	$ 1,957,403.30	-2%	17%
1	3	2	22.1761	0.9642857	$ 1,837,307.00	$ 182,382.50	$ 2,019,689.50	4%	4%
1	3	3	26.238182	0.8670331	$ 1,863,671.00	$ 165,411.00	$ 2,029,082.00	0%	1%
1	3	4	26.259614	0.8686813	$ 1,865,606.00	$ 165,251.30	$ 2,030,857.30	0%	2%
1	4	1	10.08489	1	$ 1,760,711.00	$ 203,976.00	$ 1,964,687.00	5%	8%
1	4	2	22.71538	0.6854396	$ 1,883,725.00	$ 129,731.10	$ 2,013,456.10	2%	-4%
1	4	3	26.26182	0.6549451	$ 1,893,847.00	$ 122,772.80	$ 2,016,619.80	0%	-7%
1	4	4	26.35687	0.662088	$ 1,914,311.00	$ 125,579.50	$ 2,039,890.50	0%	-6%
2	2	1	8.589835	1.802198	$ 1,646,548.00	$ 330,498.10	$ 1,977,046.10	4%	25%
2	2	2	19.828294	1.334066	$ 1,751,806.00	$ 231,047.50	$ 1,982,853.50	1%	15%
2	2	3	26.287365	1.241484	$ 1,806,099.00	$ 215,264.10	$ 2,021,363.10	0%	10%
2	2	4	26.298631	1.228572	$ 1,810,058.00	$ 213,224.10	$ 2,023,282.10	0%	10%
2	3	1	10.48434	1.047253	$ 1,731,368.00	$ 202,527.50	$ 1,933,895.50	0%	14%
2	3	2	23.64506	0.7832417	$ 1,923,209.00	$ 142,443.50	$ 2,065,652.50	3%	3%
2	3	3	26.24561	0.745055	$ 1,939,970.00	$ 136,885.00	$ 2,076,855.00	0%	2%
2	3	4	26.26758	0.7434067	$ 1,935,176.00	$ 136,732.60	$ 2,071,908.60	0%	1%
2	4	1	12.432146	0.8098902	$ 1,803,392.00	$ 154,367.40	$ 1,957,759.40	6%	7%
2	4	2	24.896154	0.5945055	$ 1,933,610.00	$ 106,479.90	$ 2,040,089.90	2%	-3%
2	4	3	26.30522	0.589011	$ 1,943,668.00	$ 107,440.90	$ 2,051,108.90	0%	-4%
2	4	4	26.2827	0.5909341	$ 1,950,620.00	$ 107,652.00	$ 2,058,272.00	0%	-4%
3	3	1	14.061817	0.8417584	$ 1,810,244.00	$ 156,230.20	$ 1,966,474.20	2%	12%
3	3	2	26.162907	0.6678572	$ 2,011,644.00	$ 119,511.00	$ 2,131,155.00	0%	3%
3	3	3	26.28571	0.6917582	$ 2,016,250.00	$ 124,538.70	$ 2,140,788.70	0%	3%
3	3	4	26.198904	0.7192308	$ 2,011,969.00	$ 128,844.10	$ 2,140,813.10	0%	2%
3	4	1	17.710167	0.6615385	$ 1,857,811.00	$ 123,395.60	$ 1,981,206.60	8%	7%
3	4	2	26.316755	0.5939561	$ 1,949,218.00	$ 106,519.20	$ 2,055,737.20	0%	1%
3	4	3	26.332692	0.5917583	$ 1,950,092.00	$ 106,282.00	$ 2,056,374.00	0%	1%
3	4	4	26.267861	0.5857144	$ 1,949,822.00	$ 105,322.00	$ 2,055,144.00	0%	1%
4	4	1	24.9508193	0.6156594	$ 1,890,920.00	$ 110,004.30	$ 2,000,924.30	1%	3%
4	4	2	26.2604433	0.6013737	$ 1,911,968.00	$ 109,050.20	$ 2,021,018.20	0%	2%
4	4	3	26.2074157	0.6258243	$ 1,913,581.00	$ 112,770.30	$ 2,026,351.30	0%	2%
4	4	4	26.2873576	0.6005495	$ 1,909,554.00	$ 108,673.80	$ 2,018,227.80	0%	2%
		Average	21.75345487	1.032197845	$ 1,826,498.13	$ 186,583.22	$ 2,013,081.35	1%	6%
		Min	5.331869	0.5857144	$ 1,498,894.00	$ 105,322.00	$ 1,850,940.30	-8%	-7%
		Max	26.367311	3.435439	$ 2,016,250.00	$ 576,270.00	$ 2,140,813.10	8%	28%

Tranship with 2 Days (age 5)								Improvement from Base	
HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	5.828847	3.241759	$ 1,498,695.00	$ 547,059.60	$ 2,045,754.60	1%	24%
1	1	2	15.079665	1.553571	$ 1,545,422.00	$ 267,666.70	$ 1,813,088.70	8%	13%
1	1	3	26.021431	1.475	$ 1,597,399.00	$ 250,067.70	$ 1,847,466.70	-1%	7%
1	1	4	26.268959	1.420879	$ 1,603,599.00	$ 240,027.90	$ 1,843,626.90	0%	7%
1	2	1	7.676373	2.300275	$ 1,594,244.00	$ 428,814.80	$ 2,023,058.80	1%	27%
1	2	2	18.675551	1.421703	$ 1,670,335.00	$ 255,013.00	$ 1,925,348.00	-1%	13%
1	2	3	26.318954	1.33956	$ 1,723,645.00	$ 235,544.60	$ 1,959,189.60	0%	9%
1	2	4	26.281595	1.322253	$ 1,722,384.00	$ 232,026.80	$ 1,954,410.80	0%	9%
1	3	1	9.383516	1.413736	$ 1,670,996.00	$ 287,339.60	$ 1,958,335.60	2%	17%
1	3	2	22.438193	0.9024726	$ 1,822,708.00	$ 173,681.30	$ 1,996,389.30	6%	2%
1	3	3	26.26208	0.871154	$ 1,858,863.00	$ 167,670.00	$ 2,026,533.00	0%	1%
1	3	4	26.30495	0.8895605	$ 1,845,917.00	$ 171,834.70	$ 2,017,751.70	0%	1%
1	4	1	10.643956	1.012912	$ 1,742,239.00	$ 206,149.30	$ 1,948,388.30	11%	7%
1	4	2	23.0239	0.7324177	$ 1,854,088.00	$ 144,085.80	$ 1,998,173.80	4%	-5%
1	4	3	26.32363	0.6799451	$ 1,855,596.00	$ 131,317.40	$ 1,986,913.40	0%	-8%
1	4	4	26.22912	0.6774725	$ 1,852,830.00	$ 130,361.50	$ 1,983,191.50	0%	-8%
2	2	1	8.462913	1.834616	$ 1,647,255.00	$ 336,257.70	$ 1,983,512.70	3%	26%
2	2	2	20.262636	1.373077	$ 1,741,421.00	$ 237,499.10	$ 1,978,920.10	3%	15%
2	2	3	26.311262	1.223626	$ 1,802,549.00	$ 211,738.70	$ 2,014,287.70	0%	10%
2	2	4	26.284072	1.225	$ 1,796,936.00	$ 212,031.70	$ 2,008,967.70	0%	10%
2	3	1	10.822527	1.062363	$ 1,740,093.00	$ 205,205.50	$ 1,945,298.50	4%	15%
2	3	2	24.1849	0.7914835	$ 1,919,822.00	$ 148,351.50	$ 2,068,173.50	5%	3%
2	3	3	26.26923	0.7956044	$ 1,935,124.00	$ 149,902.70	$ 2,085,026.70	0%	2%
2	3	4	26.25412	0.7870879	$ 1,935,280.00	$ 147,798.70	$ 2,083,078.70	0%	2%
2	4	1	13.103849	0.8329671	$ 1,787,733.00	$ 161,790.80	$ 1,949,523.80	12%	7%
2	4	2	25.406868	0.632143	$ 1,898,064.00	$ 116,530.70	$ 2,014,594.70	4%	-4%
2	4	3	26.270328	0.6307693	$ 1,910,771.00	$ 116,874.80	$ 2,027,645.80	0%	-5%
2	4	4	26.238189	0.6255495	$ 1,911,000.00	$ 115,812.60	$ 2,026,812.60	0%	-6%
3	3	1	14.815114	0.8890111	$ 1,808,395.00	$ 168,463.40	$ 1,976,858.40	7%	13%
3	3	2	26.127474	0.7398352	$ 1,981,135.00	$ 136,537.10	$ 2,117,672.10	0%	2%
3	3	3	26.266758	0.7425824	$ 1,995,494.00	$ 135,946.00	$ 2,131,440.00	0%	3%
3	3	4	26.300273	0.7409341	$ 1,995,077.00	$ 135,823.00	$ 2,130,900.00	0%	2%
3	4	1	18.519234	0.7228023	$ 1,830,146.00	$ 135,520.00	$ 1,965,666.00	13%	6%
3	4	2	26.307146	0.6510989	$ 1,925,012.00	$ 118,825.70	$ 2,043,837.70	0%	0%
3	4	3	26.321429	0.65	$ 1,925,559.00	$ 118,717.70	$ 2,044,276.70	0%	0%
3	4	4	26.267308	0.6431319	$ 1,925,925.00	$ 117,787.80	$ 2,043,712.80	0%	0%
4	4	1	25.5467014	0.6714286	$ 1,863,862.00	$ 123,049.70	$ 1,986,911.70	3%	2%
4	4	2	26.2802231	0.6873627	$ 1,872,768.00	$ 127,068.40	$ 1,999,836.40	0%	1%
4	4	3	26.2230818	0.6815934	$ 1,869,704.00	$ 123,970.00	$ 1,993,674.00	0%	1%
4	4	4	26.2211535	0.6826923	$ 1,870,292.00	$ 124,296.90	$ 1,994,588.90	0%	1%
		Average	21.94568775	1.03928575	$ 1,808,709.43	$ 189,861.52	$ 1,998,570.95	2%	5%
		Min	5.828847	0.6255495	$ 1,498,695.00	$ 115,812.60	$ 1,813,088.70	-1%	-8%
		Max	26.32363	3.241759	$ 1,995,494.00	$ 547,059.60	$ 2,131,440.00	13%	27%

Tranship with 0 Days (Age 7) with reduction at hub and age change

HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	4.0486264	6.500549	$ 1,303,582.00	$ 976,395.60	$ 2,279,977.60	-30%	38%
1	1	2	12.1046661	4.681044	$ 1,362,341.00	$ 747,200.90	$ 2,109,541.90	-13%	31%
1	1	3	19.536816	3.782692	$ 1,388,134.00	$ 587,721.40	$ 1,975,855.40	-26%	15%
1	1	4	26.271425	3.677472	$ 1,387,730.00	$ 577,097.40	$ 1,964,827.40	0%	14%
1	2	1	4.823901	4.60989	$ 1,397,667.00	$ 775,214.80	$ 2,172,881.80	-37%	37%
1	2	2	12.6228006	2.609616	$ 1,479,634.00	$ 442,320.80	$ 1,921,954.80	-33%	13%
1	2	3	20.276371	1.956044	$ 1,514,969.00	$ 325,315.60	$ 1,840,284.60	-23%	2%
1	2	4	26.307694	1.870055	$ 1,517,288.00	$ 312,115.40	$ 1,829,403.40	0%	2%
1	3	1	4.371978	2.284616	$ 1,504,587.00	$ 423,788.10	$ 1,928,375.10	-53%	15%
1	3	2	11.847527	1.121154	$ 1,551,343.00	$ 203,960.00	$ 1,755,303.00	-44%	-10%
1	3	3	20.923073	0.945055	$ 1,564,710.00	$ 167,942.50	$ 1,732,652.50	-20%	-14%
1	3	4	26.259888	0.890934	$ 1,562,321.00	$ 159,082.40	$ 1,721,403.40	0%	-14%
1	4	1	5.1406591	1.835714	$ 1,517,562.00	$ 341,993.00	$ 1,859,555.00	-47%	2%
1	4	2	13.802749	0.848901	$ 1,581,714.00	$ 154,688.00	$ 1,736,402.00	-38%	-17%
1	4	3	22.702748	0.796703	$ 1,587,957.00	$ 148,396.40	$ 1,736,353.40	-14%	-20%
1	4	4	26.243134	0.747802	$ 1,577,591.00	$ 139,399.00	$ 1,716,990.00	0%	-21%
2	2	1	5.529121	3.583517	$ 1,436,168.00	$ 593,562.20	$ 2,029,730.20	-33%	29%
2	2	2	13.986264	1.537637	$ 1,547,746.00	$ 261,184.40	$ 1,808,930.40	-29%	5%
2	2	3	23.877748	1.30522	$ 1,567,008.00	$ 220,526.90	$ 1,787,534.90	-9%	-3%
2	2	4	26.265114	1.208242	$ 1,566,713.00	$ 203,344.70	$ 1,770,057.70	0%	-3%
2	3	1	7.0953293	1.310165	$ 1,553,296.00	$ 248,591.70	$ 1,801,887.70	-32%	6%
2	3	2	16.002743	0.767857	$ 1,604,137.00	$ 139,576.10	$ 1,743,713.10	-31%	-13%
2	3	3	25.812633	0.733517	$ 1,610,128.00	$ 132,107.20	$ 1,742,235.20	-2%	-15%
2	3	4	26.237636	0.703846	$ 1,608,499.00	$ 126,874.50	$ 1,735,373.50	0%	-15%
2	4	1	8.8293953	1.008242	$ 1,576,281.00	$ 187,165.50	$ 1,763,446.50	-24%	-4%
2	4	2	19.4645611	0.58956	$ 1,647,325.00	$ 104,640.80	$ 1,751,965.80	-21%	-16%
2	4	3	26.249442	0.599451	$ 1,643,570.00	$ 108,212.90	$ 1,751,782.90	0%	-18%
2	4	4	26.292577	0.595604	$ 1,643,129.00	$ 107,764.00	$ 1,750,893.00	0%	-18%
3	3	1	10.8475293	0.872802	$ 1,613,052.00	$ 161,583.70	$ 1,774,635.70	-22%	1%
3	3	2	23.812362	0.721154	$ 1,656,553.00	$ 129,752.80	$ 1,786,305.80	-9%	-14%
3	3	3	26.252199	0.68489	$ 1,660,188.00	$ 122,882.60	$ 1,783,070.60	0%	-14%
3	3	4	26.25412	0.687088	$ 1,660,058.00	$ 123,262.20	$ 1,783,320.20	0%	-15%
3	4	1	14.8280201	0.601099	$ 1,657,656.00	$ 113,180.00	$ 1,770,836.00	-10%	-4%
3	4	2	26.1021981	0.547253	$ 1,707,619.00	$ 100,881.70	$ 1,808,500.70	-1%	-11%
3	4	3	26.2521998	0.562363	$ 1,701,659.00	$ 102,192.40	$ 1,803,851.40	0%	-11%
3	4	4	26.2634589	0.559341	$ 1,702,473.00	$ 101,509.10	$ 1,803,982.10	0%	-12%
4	4	1	22.4090646	0.614561	$ 1,705,977.00	$ 111,129.60	$ 1,817,106.60	-10%	-6%
4	4	2	26.338466	0.593681	$ 1,719,128.00	$ 104,785.30	$ 1,823,913.30	0%	-8%
4	4	3	26.3038513	0.586264	$ 1,719,034.00	$ 103,607.90	$ 1,822,641.90	0%	-8%
4	4	4	26.3030219	0.585714	$ 1,719,768.00	$ 103,751.40	$ 1,823,519.40	0%	-8%
		Average	19.1223278	1.517933	$ 1,575,657.38	$ 257,367.52	$ 1,833,024.90	-15%	-3%
		Min	4.0486264	0.547253	$ 1,303,582.00	$ 100,881.70	$ 1,716,990.00	-53%	-21%
		Max	26.338466	6.500549	$ 1,719,768.00	$ 976,395.60	$ 2,279,977.60	0%	38%

Run of Tranship Model with 1 Day (age 6) adjusted ordering									
HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	3.9939563	6.189836	$ 1,319,813.00	$ 916,949.00	$ 2,236,762.00	-31%	35%
1	1	2	11.6118148	4.032967	$ 1,380,080.00	$ 648,284.40	$ 2,028,364.40	-17%	26%
1	1	3	19.870603	2.901923	$ 1,413,733.00	$ 462,407.30	$ 1,876,140.30	-24%	9%
1	1	4	26.261814	2.932418	$ 1,413,112.00	$ 464,811.80	$ 1,877,923.80	0%	9%
1	2	1	4.4881872	4.212363	$ 1,405,038.00	$ 718,753.20	$ 2,123,791.20	-41%	33%
1	2	2	12.6409299	2.443407	$ 1,477,394.00	$ 415,292.40	$ 1,892,686.40	-33%	11%
1	2	3	20.633515	1.626374	$ 1,517,643.00	$ 275,520.40	$ 1,793,163.40	-21%	0%
1	2	4	26.326927	1.570879	$ 1,525,401.00	$ 264,404.60	$ 1,789,805.60	0%	0%
1	3	1	4.40522	2.068681	$ 1,489,825.00	$ 395,536.70	$ 1,885,361.70	-52%	13%
1	3	2	11.980494	1.070879	$ 1,528,129.00	$ 198,317.80	$ 1,726,446.80	-44%	-11%
1	3	3	21.39341	0.928297	$ 1,550,693.00	$ 172,510.50	$ 1,723,203.50	-19%	-14%
1	3	4	26.278302	0.874176	$ 1,549,306.00	$ 160,542.60	$ 1,709,848.60	0%	-15%
1	4	1	5.5035711	1.616209	$ 1,502,678.00	$ 306,953.80	$ 1,809,631.80	-43%	0%
1	4	2	14.047805	0.737637	$ 1,552,146.00	$ 138,497.50	$ 1,690,643.50	-37%	-20%
1	4	3	23.283238	0.758242	$ 1,588,255.00	$ 145,749.90	$ 1,734,004.90	-11%	-20%
1	4	4	26.228301	0.717308	$ 1,582,459.00	$ 138,304.60	$ 1,720,763.60	0%	-20%
2	2	1	5.425275	3.145055	$ 1,449,294.00	$ 530,960.90	$ 1,980,254.90	-34%	25%
2	2	2	14.35577	1.497527	$ 1,533,680.00	$ 254,857.20	$ 1,788,537.20	-27%	4%
2	2	3	23.985714	1.205769	$ 1,553,191.00	$ 202,499.30	$ 1,755,690.30	-9%	-4%
2	2	4	26.240937	1.197802	$ 1,563,687.00	$ 202,838.60	$ 1,766,525.60	0%	-4%
2	3	1	6.8016484	1.284341	$ 1,529,908.00	$ 244,081.70	$ 1,773,989.70	-35%	5%
2	3	2	16.484888	0.819506	$ 1,592,384.00	$ 150,038.00	$ 1,742,422.00	-28%	-13%
2	3	3	26.117307	0.763736	$ 1,599,892.00	$ 141,451.20	$ 1,741,343.20	-1%	-15%
2	3	4	26.252749	0.729396	$ 1,596,175.00	$ 133,508.00	$ 1,729,683.00	0%	-15%
2	4	1	9.1961539	0.989286	$ 1,548,282.00	$ 187,307.40	$ 1,735,589.40	-21%	-5%
2	4	2	19.7626407	0.656044	$ 1,604,835.00	$ 119,746.20	$ 1,724,581.20	-19%	-18%
2	4	3	26.263459	0.662363	$ 1,626,518.00	$ 122,922.00	$ 1,749,440.00	0%	-18%
2	4	4	26.248625	0.654945	$ 1,627,668.00	$ 121,787.00	$ 1,749,455.00	0%	-19%
3	3	1	11.2684088	0.867582	$ 1,593,757.00	$ 160,619.00	$ 1,754,376.00	-18%	0%
3	3	2	23.909612	0.663462	$ 1,642,407.00	$ 114,727.20	$ 1,757,134.20	-8%	-15%
3	3	3	26.259065	0.675	$ 1,638,186.00	$ 119,640.70	$ 1,757,826.70	0%	-15%
3	3	4	26.266761	0.674176	$ 1,638,647.00	$ 119,407.90	$ 1,758,054.90	0%	-16%
3	4	1	15.1005463	0.670055	$ 1,621,691.00	$ 122,617.60	$ 1,744,308.60	-8%	-6%
3	4	2	26.1214322	0.603571	$ 1,647,121.00	$ 107,368.00	$ 1,754,489.00	-1%	-14%
3	4	3	26.2370864	0.585989	$ 1,645,991.00	$ 102,931.90	$ 1,748,922.90	0%	-14%
3	4	4	26.250271	0.588736	$ 1,645,347.00	$ 103,615.40	$ 1,748,962.40	0%	-14%
4	4	1	23.1596141	0.606593	$ 1,670,345.00	$ 107,675.90	$ 1,778,020.90	-6%	-8%
4	4	2	26.3304866	0.611813	$ 1,680,873.00	$ 109,389.60	$ 1,790,262.60	0%	-10%
4	4	3	26.2939571	0.606319	$ 1,681,110.00	$ 108,774.10	$ 1,789,884.10	0%	-10%
4	4	4	26.2969771	0.606319	$ 1,681,048.00	$ 108,820.00	$ 1,789,868.00	0%	-9%
		Average	19.2394368	1.401175	$ 1,560,193.55	$ 240,510.53	$ 1,800,704.08	-15%	-4%
		Min	3.9939563	0.585989	$ 1,319,813.00	$ 102,931.90	$ 1,690,643.50	-52%	-20%
		Max	26.3304866	6.189836	$ 1,681,110.00	$ 916,949.00	$ 2,236,762.00	0%	35%

Tranship with 0 Days (Age 7)									
HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	5.352747	3.538737	$ 1,506,037.00	$ 596,250.60	$ 2,102,287.60	-8%	27%
1	1	2	14.139009	1.870605	$ 1,579,080.00	$ 324,236.20	$ 1,903,316.20	1%	19%
1	1	3	26.286812	1.707967	$ 1,603,093.00	$ 291,230.10	$ 1,894,323.10	0%	10%
1	1	4	26.254392	1.713462	$ 1,604,038.00	$ 292,920.50	$ 1,896,958.50	0%	10%
1	2	1	7.795054	2.386264	$ 1,599,031.00	$ 444,473.70	$ 2,043,504.70	2%	28%
1	2	2	18.033245	1.518407	$ 1,698,379.00	$ 267,471.30	$ 1,965,850.30	-4%	15%
1	2	3	26.247254	1.418132	$ 1,742,698.00	$ 253,086.70	$ 1,995,784.70	0%	11%
1	2	4	26.377746	1.456868	$ 1,745,287.00	$ 258,837.90	$ 2,004,124.90	0%	12%
1	3	1	8.841758	1.441758	$ 1,678,371.00	$ 285,738.10	$ 1,964,109.10	-4%	18%
1	3	2	21.540106	0.9354396	$ 1,840,317.00	$ 176,512.60	$ 2,016,829.60	1%	4%
1	3	3	26.257146	0.8766484	$ 1,866,542.00	$ 167,398.30	$ 2,033,940.30	0%	1%
1	3	4	26.226922	0.8604396	$ 1,850,231.00	$ 163,538.80	$ 2,013,769.80	0%	1%
1	4	1	9.579396	0.9736264	$ 1,760,922.00	$ 198,098.00	$ 1,959,020.00	0%	8%
1	4	2	22.62775	0.6255495	$ 1,868,615.00	$ 117,791.30	$ 1,986,406.30	2%	-5%
1	4	3	26.29148	0.603022	$ 1,898,002.00	$ 112,157.40	$ 2,010,159.40	0%	-7%
1	4	4	26.34396	0.6145605	$ 1,896,867.00	$ 113,789.10	$ 2,010,656.10	0%	-7%
2	2	1	8.599175	1.725824	$ 1,657,755.00	$ 313,120.90	$ 1,970,875.90	4%	25%
2	2	2	19.668132	1.267583	$ 1,767,472.00	$ 218,761.60	$ 1,986,233.60	0%	15%
2	2	3	26.283242	1.228572	$ 1,806,417.00	$ 212,354.80	$ 2,018,771.80	0%	10%
2	2	4	26.301372	1.228297	$ 1,816,063.00	$ 211,954.20	$ 2,028,017.20	0%	11%
2	3	1	10.332142	1.048626	$ 1,744,057.00	$ 203,416.70	$ 1,947,473.70	-1%	15%
2	3	2	23.40522	0.7865385	$ 1,913,522.00	$ 144,330.50	$ 2,057,852.50	2%	3%
2	3	3	26.23682	0.7335166	$ 1,947,070.00	$ 135,129.00	$ 2,082,199.00	0%	2%
2	3	4	26.24643	0.7329671	$ 1,947,950.00	$ 134,963.90	$ 2,082,913.90	0%	2%
2	4	1	11.886263	0.7524725	$ 1,803,462.00	$ 145,380.10	$ 1,948,842.10	2%	7%
2	4	2	24.72033	0.5887364	$ 1,921,741.00	$ 106,065.60	$ 2,027,806.60	1%	-3%
2	4	3	26.33928	0.5695055	$ 1,936,902.00	$ 102,892.70	$ 2,039,794.70	0%	-5%
2	4	4	26.38159	0.5752748	$ 1,938,413.00	$ 104,105.30	$ 2,042,518.30	0%	-5%
3	3	1	13.900275	0.8299451	$ 1,822,544.00	$ 153,111.80	$ 1,975,655.80	1%	13%
3	3	2	25.958246	0.7140111	$ 2,024,194.00	$ 129,904.30	$ 2,154,098.30	-1%	4%
3	3	3	26.270883	0.7038462	$ 2,028,416.00	$ 128,005.80	$ 2,156,421.80	0%	4%
3	3	4	26.21044	0.7409341	$ 2,029,642.00	$ 134,952.50	$ 2,164,594.50	0%	3%
3	4	1	16.828846	0.6686814	$ 1,874,746.00	$ 124,310.60	$ 1,999,056.60	3%	8%
3	4	2	26.251653	0.5989012	$ 1,961,602.00	$ 106,981.60	$ 2,068,583.60	0%	1%
3	4	3	26.278295	0.5975275	$ 1,959,767.00	$ 107,187.40	$ 2,066,954.40	0%	1%
3	4	4	26.282142	0.5967034	$ 1,959,017.00	$ 106,802.70	$ 2,065,819.70	0%	1%
4	4	1	24.5002736	0.6478022	$ 1,933,991.00	$ 117,399.80	$ 2,051,390.80	-1%	6%
4	4	2	26.2618113	0.6244506	$ 1,959,377.00	$ 111,284.20	$ 2,070,661.20	0%	5%
4	4	3	26.2999967	0.6153847	$ 1,959,567.00	$ 109,966.10	$ 2,069,533.10	0%	4%
4	4	4	26.2939621	0.6244506	$ 1,959,197.00	$ 111,460.10	$ 2,070,657.10	0%	5%
		Average	21.64828992	1.043550938	$ 1,835,259.85	$ 188,434.32	$ 2,023,694.17	0%	7%
		Min	5.352747	0.5695055	$ 1,506,037.00	$ 102,892.70	$ 1,894,323.10	-8%	-7%
		Max	26.38159	3.538737	$ 2,029,642.00	$ 596,250.60	$ 2,164,594.50	4%	28%

Appendix F: Results from Base s,S Policy

Run of Base ss Model								Improvement from base RQ	
Hosp Inv Trigger	Hosp Inv UpTo	Supp Inv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	5.200824	7.213187	1025414	650769.5	$ 1,676,183.50	-10%	1%
1	1	2	11.723351	4.915385	1270707	373433.3	$ 1,644,140.30	-16%	2%
1	1	3	26.151924	4.642033	1460868	359937.1	$ 1,820,805.10	-1%	6%
1	1	4	26.264288	4.575274	1451813	352246.9	$ 1,804,059.90	0%	4%
1	2	1	5.11566	7.070329	1030252	627525.9	$ 1,657,777.90	-33%	4%
1	2	2	11.726374	4.897527	1280801	381588.3	$ 1,662,389.30	-38%	-3%
1	2	3	26.062909	4.623901	1463084	360348.1	$ 1,823,432.10	-1%	1%
1	2	4	26.254392	4.571154	1453235	351553.7	$ 1,804,788.70	-1%	1%
1	3	1	4.852473	6.516484	1165770	552721.6	$ 1,718,491.60	-47%	3%
1	3	2	11.641758	4.454395	1433541	315007.2	$ 1,748,548.20	-45%	-10%
1	3	3	26.223631	4.183517	1629682	301544.6	$ 1,931,226.60	0%	-4%
1	3	4	26.245055	4.206593	1625935	303328.2	$ 1,929,263.20	0%	-4%
1	4	1	5.307967	6.21511	1253936	492473.8	$ 1,746,409.80	-45%	-4%
1	4	2	12.377749	4.342857	1537162	271569.2	$ 1,808,731.20	-44%	-14%
1	4	3	26.209895	3.904945	1712827	250824.7	$ 1,963,651.70	0%	-9%
1	4	4	26.252194	3.93489	1707582	253790.3	$ 1,961,372.30	0%	-9%
2	2	1	6.065385	1.97555	1192309	362633.9	$ 1,554,942.90	-27%	-2%
2	2	2	14.747798	1.328022	1406963	225997.5	$ 1,632,960.50	-25%	-5%
2	2	3	26.281869	1.263461	1592437	216657	$ 1,809,094.00	0%	-1%
2	2	4	26.339562	1.287363	1592678	221592.8	$ 1,814,270.80	0%	-1%
2	3	1	6.309616	1.540385	1326402	298671.2	$ 1,625,073.20	-40%	-4%
2	3	2	14.503297	0.9063188	1570442	170526.7	$ 1,740,968.70	-37%	-13%
2	3	3	26.274448	0.8887362	1753670	166970.3	$ 1,920,640.30	0%	-6%
2	3	4	26.229126	0.8939561	1751766	167898.9	$ 1,919,664.90	0%	-6%
2	4	1	6.682418	1.311538	1376014	257324.3	$ 1,633,338.30	-43%	-11%
2	4	2	14.959342	0.8173078	1634853	156572.1	$ 1,791,425.10	-39%	-14%
2	4	3	26.077747	0.8175824	1830403	157177.2	$ 1,987,580.20	-1%	-7%
2	4	4	26.23626	0.8035715	1838689	153426.7	$ 1,992,115.70	0%	-7%
3	3	1	7.644505	0.9629123	1452347	189320.5	$ 1,641,667.50	-45%	-6%
3	3	2	16.771978	0.5945056	1729086	110048.4	$ 1,839,134.40	-36%	-11%
3	3	3	26.33682	0.6568681	1950874	121337.4	$ 2,072,211.40	0%	0%
3	3	4	26.33076	0.6571429	1951071	121373.9	$ 2,072,444.90	0%	-1%
3	4	1	7.742308	0.8760989	1518524	176087.9	$ 1,694,611.90	-53%	-8%
3	4	2	16.639012	0.5549451	1791363	103092.6	$ 1,894,455.60	-37%	-7%
3	4	3	26.24066	0.5554945	2025148	104522.3	$ 2,129,670.30	0%	5%
3	4	4	26.21731	0.5502747	2031579	103605.2	$ 2,135,184.20	0%	5%
4	4	1	11.5554923	0.6755496	1613893	125812	$ 1,739,705.00	-53%	-10%
4	4	2	23.743957	0.4728023	2070433	84289.64	$ 2,154,722.64	-10%	9%
4	4	3	26.25275	0.495055	2121171	86975.33	$ 2,208,146.33	0%	11%
4	4	4	26.253024	0.4942308	2119655	86895.14	$ 2,206,550.14	0%	12%
		Average	18.5011472	2.541181315	$ 1,593,609.48	$ 254,186.78	$ 1,847,796.26	-18%	-3%
		Min	4.852473	0.4728023	$ 1,025,414.00	$ 84,289.64	$ 1,554,942.90	-53%	-14%
		Max	26.339562	7.213187	$ 2,121,171.00	$ 650,769.50	$ 2,208,146.33	0%	12%

Appendix G: Results from Optimal Transport Model with s,S Ordering

Run of Transport Model Min 1 day demand										
HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost	
1	1	1	0.027197807	21.02555	$ 585,571.40	$ 1,447,228.00	$ 2,032,799.40	-100%	23%	
1	1	2	3.693407	12.63214	$ 772,711.00	$ 1,165,872.00	$ 1,938,583.00	-74%	21%	
1	1	3	9.149726	8.996153	$ 1,010,001.00	$ 834,213.10	$ 1,844,214.10	-65%	7%	
1	1	4	12.917034	8.690935	$ 1,113,494.00	$ 803,169.90	$ 1,916,663.90	-51%	11%	
1	2	1	0.031868133	20.78654	$ 582,473.30	$ 1,439,973.00	$ 2,022,446.30	-100%	27%	
1	2	2	3.761813	12.79258	$ 771,820.60	$ 1,173,588.00	$ 1,945,408.60	-80%	14%	
1	2	3	8.983517	8.987363	$ 1,022,554.00	$ 829,042.00	$ 1,851,596.00	-66%	3%	
1	2	4	12.607143	8.824724	$ 1,116,177.00	$ 827,148.70	$ 1,943,325.70	-52%	9%	
1	3	1	0.060439565	20.6195	$ 618,907.00	$ 1,427,578.00	$ 2,046,485.00	-99%	22%	
1	3	2	3.944506	12.95495	$ 879,829.60	$ 1,187,779.00	$ 2,067,608.60	-81%	6%	
1	3	3	9.023901	8.771978	$ 1,161,714.00	$ 795,844.10	$ 1,957,558.10	-66%	-3%	
1	3	4	13.008516	8.680494	$ 1,256,495.00	$ 808,541.30	$ 2,065,036.30	-50%	3%	
1	4	1	0.095329672	20.29176	$ 661,497.10	$ 1,376,725.00	$ 2,038,222.10	-99%	12%	
1	4	2	4.1041216	12.25961	$ 952,550.70	$ 1,125,457.00	$ 2,078,007.70	-82%	-1%	
1	4	3	8.954945	8.556318	$ 1,226,658.00	$ 746,579.90	$ 1,973,237.90	-66%	-9%	
1	4	4	12.981593	8.417033	$ 1,340,211.00	$ 759,655.60	$ 2,099,866.60	-51%	-3%	
2	2	1	0.14835167	6.068681	$ 650,403.40	$ 1,241,088.00	$ 1,891,491.40	-98%	20%	
2	2	2	5.95741734	4.108791	$ 903,756.30	$ 846,686.40	$ 1,750,442.70	-70%	1%	
2	2	3	13.08543594	2.282692	$ 1,210,547.00	$ 446,748.40	$ 1,657,295.40	-50%	-10%	
2	2	4	20.8769248	2.215659	$ 1,271,560.00	$ 440,095.30	$ 1,711,655.30	-21%	-7%	
2	3	1	0.2164835	6.043956	$ 707,416.60	$ 1,237,095.00	$ 1,944,511.60	-98%	15%	
2	3	2	6.31126398	4.002473	$ 1,009,140.00	$ 836,208.50	$ 1,845,348.50	-73%	-8%	
2	3	3	13.44890089	2.18956	$ 1,304,953.00	$ 450,962.30	$ 1,755,915.30	-49%	-14%	
2	3	4	20.6837916	2.074725	$ 1,381,028.00	$ 427,603.40	$ 1,808,631.40	-21%	-11%	
2	4	1	0.23296707	5.771978	$ 727,847.00	$ 1,186,760.00	$ 1,914,607.00	-98%	5%	
2	4	2	6.22912062	3.894506	$ 1,038,277.00	$ 818,674.90	$ 1,856,951.90	-75%	-11%	
2	4	3	13.31263352	2.167308	$ 1,366,286.00	$ 449,780.80	$ 1,816,066.80	-49%	-15%	
2	4	4	21.2049425	2.011539	$ 1,433,337.00	$ 417,090.90	$ 1,850,427.90	-19%	-14%	
3	3	1	0.74120887	3.948077	$ 902,214.40	$ 843,525.10	$ 1,745,739.50	-95%	0%	
3	3	2	11.32554868	1.817033	$ 1,328,006.00	$ 365,482.50	$ 1,693,488.50	-57%	-18%	
3	3	3	20.44286099	1.411813	$ 1,466,236.00	$ 268,255.60	$ 1,734,491.60	-22%	-17%	
3	3	4	26.23709022	1.389286	$ 1,510,184.00	$ 265,857.10	$ 1,776,041.10	0%	-15%	
3	4	1	0.8093407	3.917308	$ 915,705.30	$ 838,697.10	$ 1,754,402.40	-95%	-5%	
3	4	2	10.98489308	1.698077	$ 1,370,319.00	$ 336,745.30	$ 1,707,064.30	-58%	-16%	
3	4	3	20.21730539	1.422253	$ 1,499,962.00	$ 268,555.90	$ 1,768,517.90	-23%	-13%	
3	4	4	26.2101655	1.370879	$ 1,550,514.00	$ 264,877.20	$ 1,815,391.20	0%	-11%	
4	4	1	4.14587889	3.018406	$ 1,058,991.00	$ 656,770.10	$ 1,715,761.10	-83%	-12%	
4	4	2	18.73241956	1.287363	$ 1,522,888.00	$ 244,286.30	$ 1,767,174.30	-29%	-11%	
4	4	3	26.23736044	1.139286	$ 1,578,126.00	$ 210,014.80	$ 1,788,140.80	0%	-10%	
4	4	4	26.24038044	1.139835	$ 1,578,476.00	$ 210,194.50	$ 1,788,670.50	0%	-9%	
		Average	10.4344436	6.7419778	$ 1,108,970.94	$ 758,011.25	$ 1,866,982.19	-59%	-1%	
		Min	0.027197807	1.139286	$ 582,473.30	$ 210,014.80	$ 1,657,295.40	-100%	-18%	
		Max	26.24038044	21.02555	$ 1,578,476.00	$ 1,447,228.00	$ 2,099,866.60	0%	27%	

Transport Min 2 days demand

HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	0.043131872	21.96291	$ 558,997.90	$ 1,458,428.00	$ 2,017,425.90	-99%	22%
1	1	2	3.815934	12.90549	$ 765,417.20	$ 1,174,586.00	$ 1,940,003.20	-73%	21%
1	1	3	9.212911	8.776923	$ 1,018,444.00	$ 788,753.10	$ 1,807,197.10	-65%	5%
1	1	4	13.13489	8.466758	$ 1,131,249.00	$ 736,624.00	$ 1,867,873.00	-50%	8%
1	2	1	0.041483519	21.50769	$ 559,456.30	$ 1,484,124.00	$ 2,043,580.30	-99%	28%
1	2	2	3.810165	12.44231	$ 778,646.90	$ 1,143,017.00	$ 1,921,663.90	-80%	13%
1	2	3	9.351647	8.82912	$ 1,015,073.00	$ 799,043.40	$ 1,814,116.40	-64%	1%
1	2	4	13.021978	8.271429	$ 1,126,953.00	$ 721,288.10	$ 1,848,241.10	-51%	3%
1	3	1	0.076648351	20.78462	$ 615,420.10	$ 1,424,821.00	$ 2,040,241.10	-99%	22%
1	3	2	3.9983514	12.70247	$ 877,947.60	$ 1,165,811.00	$ 2,043,758.60	-81%	5%
1	3	3	9.648077	8.782144	$ 1,142,760.00	$ 792,605.40	$ 1,935,365.40	-63%	-4%
1	3	4	13.217583	8.235165	$ 1,278,703.00	$ 718,641.70	$ 1,997,344.70	-50%	0%
1	4	1	0.116208782	21.16099	$ 651,433.70	$ 1,409,465.00	$ 2,060,898.70	-99%	13%
1	4	2	4.2593405	12.92088	$ 931,753.20	$ 1,170,393.00	$ 2,102,146.20	-81%	0%
1	4	3	9.618682	8.532969	$ 1,223,699.00	$ 751,065.80	$ 1,974,764.80	-63%	-9%
1	4	4	13.274177	8.147253	$ 1,353,760.00	$ 695,258.20	$ 2,049,018.20	-50%	-5%
2	2	1	0.20192305	5.983517	$ 656,103.60	$ 1,232,957.00	$ 1,889,060.60	-98%	20%
2	2	2	6.10824202	3.943681	$ 899,000.10	$ 817,138.90	$ 1,716,139.00	-69%	-1%
2	2	3	13.66401396	1.903022	$ 1,227,159.00	$ 366,203.50	$ 1,593,362.50	-48%	-13%
2	2	4	20.9112641	1.776923	$ 1,306,456.00	$ 340,807.10	$ 1,647,263.10	-21%	-10%
2	3	1	0.18873622	5.697803	$ 715,496.90	$ 1,188,572.00	$ 1,904,068.90	-98%	12%
2	3	2	6.41016475	3.48544	$ 1,019,137.00	$ 741,364.70	$ 1,760,501.70	-72%	-12%
2	3	3	13.77967507	1.818956	$ 1,331,468.00	$ 363,360.30	$ 1,694,828.30	-48%	-17%
2	3	4	21.021701	1.775	$ 1,409,541.00	$ 353,565.90	$ 1,763,106.90	-20%	-14%
2	4	1	0.1983516	5.408241	$ 741,110.90	$ 1,124,571.00	$ 1,865,681.90	-98%	2%
2	4	2	6.55137332	3.851649	$ 1,024,332.00	$ 815,576.30	$ 1,839,908.30	-73%	-12%
2	4	3	13.67527978	1.748077	$ 1,370,180.00	$ 351,198.20	$ 1,721,378.20	-48%	-20%
2	4	4	21.22665109	1.722802	$ 1,468,984.00	$ 347,958.60	$ 1,816,942.60	-19%	-15%
3	3	1	0.81648355	3.670055	$ 925,536.80	$ 797,729.40	$ 1,723,266.20	-94%	-2%
3	3	2	11.45961176	1.566758	$ 1,329,160.00	$ 307,306.60	$ 1,636,466.60	-56%	-21%
3	3	3	20.58406649	1.155769	$ 1,489,897.00	$ 211,445.10	$ 1,701,342.10	-22%	-18%
3	3	4	26.23626022	1.117857	$ 1,550,425.00	$ 204,885.30	$ 1,755,310.30	0%	-16%
3	4	1	0.895055	3.648627	$ 937,387.10	$ 793,797.80	$ 1,731,184.90	-95%	-6%
3	4	2	11.40631506	1.443132	$ 1,388,429.00	$ 282,329.50	$ 1,670,758.50	-57%	-18%
3	4	3	20.52472011	1.111539	$ 1,530,941.00	$ 200,546.60	$ 1,731,487.60	-22%	-15%
3	4	4	26.25109659	1.087912	$ 1,590,450.00	$ 200,996.90	$ 1,791,446.90	0%	-12%
4	4	1	4.19533009	2.704945	$ 1,075,547.00	$ 597,173.80	$ 1,672,720.80	-83%	-14%
4	4	2	19.35275209	1.093956	$ 1,552,816.00	$ 199,077.90	$ 1,751,893.90	-26%	-12%
4	4	3	26.25604517	0.9346155	$ 1,622,439.00	$ 162,773.00	$ 1,785,212.00	0%	-10%
4	4	4	26.23462044	0.9293957	$ 1,622,296.00	$ 161,397.40	$ 1,783,693.40	0%	-10%
		Average	10.61977352	6.60021983	$ 1,120,350.16	$ 714,916.44	$ 1,835,266.60	-58%	-3%
		Min	0.041483519	0.9293957	$ 558,997.90	$ 161,397.40	$ 1,593,362.50	-99%	-21%
		Max	26.25604517	21.96291	$ 1,622,439.00	$ 1,484,124.00	$ 2,102,146.20	0%	28%

Appendix H: Results for Hub and Spoke Model with s,S Ordering

Run of Tranship Model with 1 Day (age 6)										
HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	4.882418	6.715109	$ 1,496,752.00	$ 576,270.60	$ 2,073,022.60	-16%	25%
1	1	2	13.790105	1.725824	$ 1,556,199.00	$ 294,741.30	$ 1,850,940.30	-1%	15%
1	1	3	26.08599	1.555495	$ 1,595,231.00	$ 261,909.60	$ 1,857,140.60	-1%	8%
1	1	4	26.265105	1.551099	$ 1,599,583.00	$ 263,367.10	$ 1,862,950.10	0%	8%
1	2	1	7.795055	2.326648	$ 1,599,185.00	$ 434,550.20	$ 2,033,735.20	2%	28%
1	2	2	18.42775	1.48489	$ 1,683,478.00	$ 263,734.40	$ 1,947,212.40	-2%	14%
1	2	3	26.362633	1.412088	$ 1,739,180.00	$ 250,679.00	$ 1,989,859.00	0%	11%
1	2	4	26.367311	1.40467	$ 1,730,479.00	$ 249,786.80	$ 1,980,265.80	0%	11%
1	3	1	9.013737	1.382692	$ 1,679,921.00	$ 277,482.30	$ 1,957,403.30	-2%	17%
1	3	2	22.1761	0.9642857	$ 1,837,307.00	$ 182,382.50	$ 2,019,689.50	4%	4%
1	3	3	26.238182	0.8670331	$ 1,863,671.00	$ 165,411.00	$ 2,029,082.00	0%	1%
1	3	4	26.259614	0.8686813	$ 1,865,606.00	$ 165,251.30	$ 2,030,857.30	0%	2%
1	4	1	10.08489	1	$ 1,760,711.00	$ 203,976.00	$ 1,964,687.00	5%	8%
1	4	2	22.71538	0.6854396	$ 1,883,725.00	$ 129,731.10	$ 2,013,456.10	2%	-4%
1	4	3	26.26182	0.6549451	$ 1,893,847.00	$ 122,772.80	$ 2,016,619.80	0%	-7%
1	4	4	26.35687	0.662088	$ 1,914,311.00	$ 125,579.50	$ 2,039,890.50	0%	-6%
2	2	1	8.589835	1.802198	$ 1,646,548.00	$ 330,498.10	$ 1,977,046.10	4%	25%
2	2	2	19.828294	1.334066	$ 1,751,806.00	$ 231,047.50	$ 1,982,853.50	1%	15%
2	2	3	26.287365	1.241484	$ 1,806,099.00	$ 215,264.10	$ 2,021,363.10	0%	10%
2	2	4	26.298631	1.228572	$ 1,810,058.00	$ 213,224.10	$ 2,023,282.10	0%	10%
2	3	1	10.48434	1.047253	$ 1,731,368.00	$ 202,527.50	$ 1,933,895.50	0%	14%
2	3	2	23.64506	0.7832417	$ 1,923,209.00	$ 142,443.50	$ 2,065,652.50	3%	3%
2	3	3	26.24561	0.745055	$ 1,939,970.00	$ 136,885.00	$ 2,076,855.00	0%	2%
2	3	4	26.26758	0.7434067	$ 1,935,176.00	$ 136,732.60	$ 2,071,908.60	0%	1%
2	4	1	12.432146	0.8098902	$ 1,803,392.00	$ 154,367.40	$ 1,957,759.40	6%	7%
2	4	2	24.896154	0.5945055	$ 1,933,610.00	$ 106,479.90	$ 2,040,089.90	2%	-3%
2	4	3	26.30522	0.589011	$ 1,943,668.00	$ 107,440.90	$ 2,051,108.90	0%	-4%
2	4	4	26.2827	0.5909341	$ 1,950,620.00	$ 107,652.00	$ 2,058,272.00	0%	-4%
3	3	1	14.061817	0.8417584	$ 1,810,244.00	$ 156,230.20	$ 1,966,474.20	2%	12%
3	3	2	26.162907	0.6678572	$ 2,011,644.00	$ 119,511.00	$ 2,131,155.00	0%	3%
3	3	3	26.28571	0.6917582	$ 2,016,250.00	$ 124,538.70	$ 2,140,788.70	0%	3%
3	3	4	26.198904	0.7192308	$ 2,011,969.00	$ 128,844.10	$ 2,140,813.10	0%	2%
3	4	1	17.710167	0.6615385	$ 1,857,811.00	$ 123,395.60	$ 1,981,206.60	8%	7%
3	4	2	26.316755	0.5939561	$ 1,949,218.00	$ 106,519.20	$ 2,055,737.20	0%	1%
3	4	3	26.332692	0.5917583	$ 1,950,092.00	$ 106,282.00	$ 2,056,374.00	0%	1%
3	4	4	26.267861	0.5857144	$ 1,949,822.00	$ 105,322.00	$ 2,055,144.00	0%	1%
4	4	1	24.9508193	0.6156594	$ 1,890,920.00	$ 110,004.30	$ 2,000,924.30	1%	3%
4	4	2	26.2604433	0.6013737	$ 1,911,968.00	$ 109,050.20	$ 2,021,018.20	0%	2%
4	4	3	26.2074157	0.6258243	$ 1,913,581.00	$ 112,770.30	$ 2,026,351.30	0%	2%
4	4	4	26.2873576	0.6005495	$ 1,909,554.00	$ 108,673.80	$ 2,018,227.80	0%	2%
		Average	21.7422186	1.114189595	$ 1,826,444.58	$ 186,583.24	$ 2,013,027.81	0%	6%
		Min	4.882418	0.5857144	$ 1,496,752.00	$ 105,322.00	$ 1,850,940.30	-16%	-7%
		Max	26.367311	6.715109	$ 2,016,250.00	$ 576,270.60	$ 2,140,813.10	8%	28%

		Tranship with 2 Days (age 5)						Improvement from Base	
HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	4.918407	6.622528	$ 1,481,550.00	$ 564,051.90	$ 2,045,601.90	-15%	24%
1	1	2	13.197253	4.286263	$ 1,534,330.00	$ 277,426.30	$ 1,811,756.30	-6%	13%
1	1	3	26.364288	4.012912	$ 1,609,297.00	$ 256,477.70	$ 1,865,774.70	0%	8%
1	1	4	26.296701	4.026099	$ 1,610,458.00	$ 257,496.50	$ 1,867,954.50	0%	8%
1	2	1	5.050824	6.834615	$ 1,482,036.00	$ 581,402.70	$ 2,063,438.70	-34%	30%
1	2	2	12.76978	4.268956	$ 1,525,259.00	$ 276,275.40	$ 1,801,534.40	-32%	6%
1	2	3	26.373348	4.019231	$ 1,609,551.00	$ 257,768.50	$ 1,867,319.50	0%	4%
1	2	4	26.347257	4.046154	$ 1,610,103.00	$ 259,159.70	$ 1,869,262.70	0%	4%
1	3	1	4.468407	5.281319	$ 1,567,865.00	$ 385,071.60	$ 1,952,936.60	-52%	17%
1	3	2	13.274724	3.787363	$ 1,633,785.00	$ 205,806.30	$ 1,839,591.30	-37%	-6%
1	3	3	26.190663	3.612363	$ 1,661,703.00	$ 207,716.70	$ 1,869,419.70	0%	-7%
1	3	4	26.262362	3.609616	$ 1,661,418.00	$ 204,098.80	$ 1,865,516.80	0%	-7%
1	4	1	5.0288468	5.023077	$ 1,596,172.00	$ 325,735.90	$ 1,921,907.90	-48%	6%
1	4	2	13.746427	3.754121	$ 1,666,889.00	$ 184,229.00	$ 1,851,118.00	-38%	-12%
1	4	3	26.2217	3.501374	$ 1,693,620.00	$ 183,127.80	$ 1,876,747.80	0%	-13%
1	4	4	26.23544	3.506044	$ 1,693,030.00	$ 184,163.20	$ 1,877,193.20	0%	-13%
2	2	1	6.224176	1.968132	$ 1,583,804.00	$ 355,277.80	$ 1,939,081.80	-25%	23%
2	2	2	14.964011	1.310989	$ 1,632,415.00	$ 220,905.30	$ 1,853,320.30	-24%	7%
2	2	3	26.298353	1.276374	$ 1,717,856.00	$ 217,102.30	$ 1,934,958.30	0%	5%
2	2	4	26.362086	1.287637	$ 1,717,582.00	$ 218,923.10	$ 1,936,505.10	0%	6%
2	3	1	6.436263	1.347253	$ 1,618,768.00	$ 260,596.70	$ 1,879,364.70	-38%	11%
2	3	2	15.242582	0.9167584	$ 1,703,806.00	$ 168,403.00	$ 1,872,209.00	-34%	-6%
2	3	3	26.23489	0.907967	$ 1,764,701.00	$ 168,948.80	$ 1,933,649.80	0%	-5%
2	3	4	26.25879	0.9093407	$ 1,765,521.00	$ 169,445.10	$ 1,934,966.10	0%	-5%
2	4	1	6.911263	1.229945	$ 1,634,667.00	$ 241,572.40	$ 1,876,239.40	-41%	3%
2	4	2	15.647252	0.8549451	$ 1,722,078.00	$ 159,837.60	$ 1,881,915.60	-36%	-10%
2	4	3	26.2217	0.8263738	$ 1,789,081.00	$ 156,008.50	$ 1,945,089.50	0%	-9%
2	4	4	26.24203	0.8082418	$ 1,790,130.00	$ 152,631.80	$ 1,942,761.80	0%	-10%
3	3	1	7.891759	0.9159342	$ 1,666,451.00	$ 183,411.00	$ 1,849,862.00	-43%	6%
3	3	2	19.236814	0.66511	$ 1,804,998.00	$ 122,037.30	$ 1,927,035.30	-26%	-7%
3	3	3	26.26511	0.6324176	$ 1,868,258.00	$ 118,029.60	$ 1,986,287.60	0%	-4%
3	3	4	26.23187	0.6313187	$ 1,864,978.00	$ 117,719.70	$ 1,982,697.70	0%	-6%
3	4	1	8.583242	0.8046705	$ 1,667,670.00	$ 166,618.30	$ 1,834,288.30	-48%	-1%
3	4	2	19.351919	0.564011	$ 1,814,485.00	$ 108,737.50	$ 1,923,222.50	-27%	-6%
3	4	3	26.216759	0.5313188	$ 1,892,057.00	$ 101,240.60	$ 1,993,297.60	0%	-2%
3	4	4	26.264831	0.5376374	$ 1,891,382.00	$ 102,365.40	$ 1,993,747.40	0%	-2%
4	4	1	13.1428553	0.6607144	$ 1,715,326.00	$ 126,979.30	$ 1,842,305.30	-47%	-5%
4	4	2	25.712633	0.5189561	$ 1,941,915.00	$ 91,802.67	$ 2,033,717.67	-2%	3%
4	4	3	26.293684	0.4901099	$ 1,946,913.00	$ 86,518.92	$ 2,033,431.92	0%	3%
4	4	4	26.28022	0.489011	$ 1,946,686.00	$ 86,324.22	$ 2,033,010.22	0%	3%
		Average	18.931538	2.281930035	$ 1,702,464.85	$ 212,786.12	$ 1,915,250.97	-16%	1%
		Min	4.468407	0.489011	$ 1,481,550.00	$ 86,324.22	$ 1,801,534.40	-52%	-13%
		Max	26.373348	6.834615	$ 1,946,913.00	$ 581,402.70	$ 2,063,438.70	0%	30%

Tranship with 0 Days (Age 7)									
HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	5.108241	6.948077	$ 1,497,883.00	$ 607,445.60	$ 2,105,328.60	-12%	27%
1	1	2	11.343406	4.639011	$ 1,557,187.00	$ 339,962.40	$ 1,897,149.40	-19%	18%
1	1	3	26.293684	4.348077	$ 1,598,417.00	$ 315,224.30	$ 1,913,641.30	0%	11%
1	1	4	26.286263	4.353022	$ 1,598,037.00	$ 314,236.30	$ 1,912,273.30	0%	11%
1	2	1	5.086264	6.821429	$ 1,497,790.00	$ 594,384.60	$ 2,092,174.60	-33%	32%
1	2	2	11.218407	4.585714	$ 1,554,746.00	$ 330,795.10	$ 1,885,541.10	-40%	11%
1	2	3	26.21484	4.336539	$ 1,598,236.00	$ 316,658.20	$ 1,914,894.20	0%	6%
1	2	4	26.278023	4.349176	$ 1,598,192.00	$ 314,004.60	$ 1,912,196.60	0%	7%
1	3	1	4.916759	6.070055	$ 1,524,305.00	$ 488,737.20	$ 2,013,042.20	-47%	20%
1	3	2	10.65522	4.209066	$ 1,588,536.00	$ 277,916.70	$ 1,866,452.70	-50%	-4%
1	3	3	26.218953	3.932418	$ 1,625,463.00	$ 253,982.30	$ 1,879,445.30	0%	-7%
1	3	4	26.262913	3.904945	$ 1,625,302.00	$ 253,266.40	$ 1,878,568.40	0%	-6%
1	4	1	5.148352	5.883792	$ 1,545,694.00	$ 428,995.90	$ 1,974,689.90	-46%	9%
1	4	2	11.249177	4.131044	$ 1,606,795.00	$ 247,366.20	$ 1,854,161.20	-49%	-12%
1	4	3	26.18516	3.727473	$ 1,646,574.00	$ 220,723.00	$ 1,867,297.00	0%	-14%
1	4	4	26.23077	3.717033	$ 1,649,883.00	$ 220,374.70	$ 1,870,257.70	0%	-14%
2	2	1	6.341209	1.973077	$ 1,601,820.00	$ 359,885.10	$ 1,961,705.10	-23%	24%
2	2	2	14.497804	1.28489	$ 1,673,715.00	$ 219,649.20	$ 1,893,364.20	-26%	10%
2	2	3	26.212635	1.284341	$ 1,739,253.00	$ 220,141.30	$ 1,959,394.30	0%	7%
2	2	4	26.360445	1.285989	$ 1,735,898.00	$ 219,867.80	$ 1,955,765.80	0%	7%
2	3	1	6.180495	1.50467	$ 1,617,414.00	$ 287,852.10	$ 1,905,266.10	-41%	13%
2	3	2	14.479945	0.8931319	$ 1,698,617.00	$ 168,066.10	$ 1,866,683.10	-37%	-7%
2	3	3	26.220058	0.9024726	$ 1,765,475.00	$ 169,650.50	$ 1,935,125.50	0%	-5%
2	3	4	26.248354	0.8969782	$ 1,768,100.00	$ 168,377.80	$ 1,936,477.80	0%	-5%
2	4	1	6.464834	1.326648	$ 1,627,859.00	$ 262,988.30	$ 1,890,847.30	-45%	3%
2	4	2	14.248351	0.8239012	$ 1,726,831.00	$ 157,296.60	$ 1,884,127.60	-42%	-10%
2	4	3	26.19863	0.8252746	$ 1,791,914.00	$ 156,861.20	$ 1,948,775.20	-1%	-9%
2	4	4	26.23544	0.8065935	$ 1,794,792.00	$ 153,770.00	$ 1,948,562.00	0%	-9%
3	3	1	7.451648	0.9439561	$ 1,686,325.00	$ 186,466.30	$ 1,872,791.30	-46%	7%
3	3	2	16.933512	0.6695056	$ 1,809,197.00	$ 123,748.70	$ 1,932,945.70	-35%	-7%
3	3	3	26.34615	0.6568682	$ 1,900,978.00	$ 121,774.60	$ 2,022,752.60	0%	-3%
3	3	4	26.34039	0.6565934	$ 1,900,461.00	$ 121,757.20	$ 2,022,218.20	0%	-4%
3	4	1	7.74011	0.8206045	$ 1,703,728.00	$ 166,907.20	$ 1,870,635.20	-53%	1%
3	4	2	16.530216	0.5719782	$ 1,829,481.00	$ 107,198.90	$ 1,936,679.90	-37%	-5%
3	4	3	26.24451	0.5478022	$ 1,915,480.00	$ 103,687.30	$ 2,019,167.30	0%	-1%
3	4	4	26.26621	0.5472528	$ 1,916,522.00	$ 103,523.90	$ 2,020,045.90	0%	-1%
4	4	1	11.5986301	0.6821429	$ 1,768,279.00	$ 129,815.20	$ 1,898,094.20	-53%	-2%
4	4	2	24.005769	0.5046703	$ 2,004,412.00	$ 87,981.90	$ 2,092,393.90	-9%	6%
4	4	3	26.239832	0.4846154	$ 2,016,873.00	$ 85,174.88	$ 2,102,047.88	0%	6%
4	4	4	26.233246	0.4848901	$ 2,017,715.00	$ 85,273.38	$ 2,102,988.38	0%	7%
		Average	18.40787138	2.433392943	$ 1,708,104.48	$ 237,294.72	$ 1,945,399.20	-19%	3%
		Min	4.916759	0.4846154	$ 1,497,790.00	$ 85,174.88	$ 1,854,161.20	-53%	-14%
		Max	26.360445	6.948077	$ 2,017,715.00	$ 607,445.60	$ 2,105,328.60	0%	32%

Run of Tranship Model with 1 Day (age 6) with Adjusted Hub settings

HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	3.6837915	9.590935	$ 1,314,120.00	$ 926,356.60	$ 2,240,476.60	-36%	35%
1	1	2	9.5612628	6.562913	$ 1,380,210.00	$ 610,587.90	$ 1,990,797.90	-32%	24%
1	1	3	19.206042	5.295055	$ 1,411,137.00	$ 448,175.70	$ 1,859,312.70	-27%	8%
1	1	4	26.295877	5.396979	$ 1,411,502.00	$ 468,783.50	$ 1,880,285.50	0%	9%
1	2	1	3.8516487	9.540384	$ 1,313,537.00	$ 927,506.70	$ 2,241,043.70	-50%	41%
1	2	2	9.5145607	6.516758	$ 1,382,078.00	$ 619,425.80	$ 2,001,503.80	-49%	17%
1	2	3	19.044784	5.40989	$ 1,407,722.00	$ 459,180.10	$ 1,866,902.10	-27%	4%
1	2	4	26.27198	5.408517	$ 1,411,383.00	$ 470,216.40	$ 1,881,599.40	0%	5%
1	3	1	2.627747	7.232692	$ 1,403,279.00	$ 596,265.90	$ 1,999,544.90	-71%	20%
1	3	2	8.974725	5.290385	$ 1,442,667.00	$ 411,766.90	$ 1,854,433.90	-58%	-5%
1	3	3	19.331867	4.646428	$ 1,436,479.00	$ 350,676.20	$ 1,787,155.20	-26%	-11%
1	3	4	26.295329	4.754121	$ 1,423,658.00	$ 382,254.30	$ 1,805,912.30	0%	-10%
1	4	1	2.798626	6.70989	$ 1,405,486.00	$ 539,877.20	$ 1,945,363.20	-71%	7%
1	4	2	8.806044	4.701374	$ 1,455,711.00	$ 347,544.80	$ 1,803,255.80	-60%	-14%
1	4	3	19.565384	4.430495	$ 1,433,960.00	$ 320,834.70	$ 1,754,794.70	-25%	-19%
1	4	4	26.254116	4.551923	$ 1,417,378.00	$ 352,772.80	$ 1,770,150.80	0%	-18%
2	2	1	4.2829673	3.840385	$ 1,406,974.00	$ 633,554.80	$ 2,040,528.80	-48%	29%
2	2	2	12.218129	2.048077	$ 1,501,546.00	$ 340,307.30	$ 1,841,853.30	-38%	7%
2	2	3	20.542584	1.546703	$ 1,516,323.00	$ 262,550.10	$ 1,778,873.10	-22%	-3%
2	2	4	26.336537	1.489561	$ 1,524,193.00	$ 252,649.40	$ 1,776,842.40	0%	-3%
2	3	1	3.501923	2.395055	$ 1,453,092.00	$ 418,662.40	$ 1,871,754.40	-66%	11%
2	3	2	11.69011	1.276374	$ 1,542,720.00	$ 226,880.10	$ 1,769,600.10	-49%	-12%
2	3	3	20.735991	1.060989	$ 1,529,062.00	$ 194,003.80	$ 1,723,065.80	-21%	-16%
2	3	4	26.257145	1.076648	$ 1,524,962.00	$ 197,968.60	$ 1,722,930.60	0%	-16%
2	4	1	3.698352	2.000275	$ 1,444,372.00	$ 354,288.30	$ 1,798,660.30	-68%	-2%
2	4	2	12.133791	1.149176	$ 1,531,237.00	$ 208,528.00	$ 1,739,765.00	-50%	-17%
2	4	3	20.893685	0.9785715	$ 1,524,780.00	$ 184,172.00	$ 1,708,952.00	-21%	-20%
2	4	4	26.293402	0.9703298	$ 1,511,563.00	$ 181,744.60	$ 1,693,307.60	0%	-21%
3	3	1	5.4118128	1.138187	$ 1,544,004.00	$ 219,766.00	$ 1,763,770.00	-61%	1%
3	3	2	14.011813	0.7115386	$ 1,628,862.00	$ 133,146.00	$ 1,762,008.00	-46%	-15%
3	3	3	24.55851	0.6373627	$ 1,618,036.00	$ 118,355.30	$ 1,736,391.30	-7%	-16%
3	3	4	26.32967	0.6541209	$ 1,617,008.00	$ 120,958.70	$ 1,737,966.70	0%	-17%
3	4	1	5.6313191	0.9258242	$ 1,539,615.00	$ 179,979.80	$ 1,719,594.80	-66%	-7%
3	4	2	14.232419	0.5711539	$ 1,615,570.00	$ 109,867.20	$ 1,725,437.20	-46%	-15%
3	4	3	24.6662	0.5304945	$ 1,607,948.00	$ 102,671.00	$ 1,710,619.00	-6%	-16%
3	4	4	26.28297	0.5530221	$ 1,610,805.00	$ 104,457.00	$ 1,715,262.00	0%	-16%
4	4	1	10.6335207	0.6585165	$ 1,592,061.00	$ 125,198.60	$ 1,717,259.60	-57%	-11%
4	4	2	22.2239036	0.4793957	$ 1,688,841.00	$ 84,125.28	$ 1,772,966.28	-15%	-10%
4	4	3	26.28324	0.485989	$ 1,703,851.00	$ 84,844.06	$ 1,788,695.06	0%	-10%
4	4	4	26.264288	0.481044	$ 1,704,997.00	$ 84,248.66	$ 1,789,245.66	0%	-9%
		Average	16.17995168	3.09243831	$ 1,498,318.23	$ 328,878.81	$ 1,827,197.04	-31%	-3%
		Min	2.627747	0.4793957	$ 1,313,537.00	$ 84,125.28	$ 1,693,307.60	-71%	-21%
		Max	26.336537	9.590935	$ 1,704,997.00	$ 927,506.70	$ 2,241,043.70	0%	41%

Run of Tranship Model with 2 Day (age 5) with Adjusted HubSettings									
HospInvTrigger	HospInvUpTo	SuppInv	Waste	Emergency Orders	Year Transport Cost	Year Emergency Cost	Year Total Cost	Delta Waste	Delta Total Cost
1	1	1	3.7626378	9.109065	$ 1,330,374.00	$ 869,331.50	$ 2,199,705.50	-35%	33%
1	1	2	10.5914835	5.872527	$ 1,399,515.00	$ 514,393.60	$ 1,913,908.60	-24%	19%
1	1	3	20.344778	4.369506	$ 1,462,594.00	$ 310,131.40	$ 1,772,725.40	-23%	3%
1	1	4	26.307694	4.779396	$ 1,444,417.00	$ 375,760.90	$ 1,820,177.90	0%	5%
1	2	1	3.8530223	9.212912	$ 1,327,372.00	$ 883,557.60	$ 2,210,929.60	-50%	39%
1	2	2	10.8565928	5.882418	$ 1,400,541.00	$ 516,161.70	$ 1,916,702.70	-42%	12%
1	2	3	20.159066	4.405495	$ 1,457,553.00	$ 317,321.30	$ 1,774,874.30	-23%	-1%
1	2	4	26.317306	4.794231	$ 1,444,293.00	$ 377,828.90	$ 1,822,121.90	0%	2%
1	3	1	2.5543954	5.931318	$ 1,477,481.00	$ 431,484.50	$ 1,908,965.50	-72%	14%
1	3	2	10.132692	4.474175	$ 1,488,978.00	$ 305,398.30	$ 1,794,376.30	-52%	-8%
1	3	3	20.498907	3.827198	$ 1,486,997.00	$ 242,669.20	$ 1,729,666.20	-22%	-14%
1	3	4	26.315116	4.196703	$ 1,457,721.00	$ 297,890.40	$ 1,755,611.40	0%	-12%
1	4	1	2.9282966	5.18022	$ 1,486,508.00	$ 342,624.80	$ 1,829,132.80	-70%	1%
1	4	2	10.376373	4.248077	$ 1,517,514.00	$ 265,677.90	$ 1,783,191.90	-53%	-15%
1	4	3	20.475821	3.604945	$ 1,487,656.00	$ 215,872.00	$ 1,703,528.00	-22%	-21%
1	4	4	26.270336	4.009891	$ 1,448,628.00	$ 270,740.20	$ 1,719,368.20	0%	-20%
2	2	1	4.4785715	3.624177	$ 1,415,174.00	$ 599,830.50	$ 2,015,004.50	-46%	28%
2	2	2	12.720055	1.819505	$ 1,499,317.00	$ 304,734.00	$ 1,804,051.00	-35%	4%
2	2	3	21.370605	1.375275	$ 1,530,296.00	$ 234,903.60	$ 1,765,199.60	-19%	-4%
2	2	4	26.302193	1.387088	$ 1,538,314.00	$ 236,506.70	$ 1,774,820.70	0%	-3%
2	3	1	4.023626	1.904395	$ 1,501,472.00	$ 346,260.90	$ 1,847,732.90	-61%	9%
2	3	2	12.598076	1.166484	$ 1,561,142.00	$ 213,039.40	$ 1,774,181.40	-45%	-11%
2	3	3	21.875552	0.9832417	$ 1,544,301.00	$ 180,413.40	$ 1,724,714.40	-17%	-16%
2	3	4	26.293958	0.9994506	$ 1,536,484.00	$ 186,768.10	$ 1,723,252.10	0%	-16%
2	4	1	4.047802	1.448352	$ 1,506,989.00	$ 278,477.20	$ 1,785,466.20	-65%	-2%
2	4	2	12.125549	0.9733517	$ 1,570,708.00	$ 180,489.40	$ 1,751,197.40	-51%	-16%
2	4	3	21.793956	0.8554946	$ 1,537,142.00	$ 161,645.90	$ 1,698,787.90	-17%	-21%
2	4	4	26.263191	0.9093407	$ 1,521,550.00	$ 172,000.80	$ 1,693,550.80	0%	-21%
3	3	1	6.1821437	1.019231	$ 1,560,702.00	$ 201,035.80	$ 1,761,737.80	-55%	1%
3	3	2	15.652747	0.7065935	$ 1,634,702.00	$ 135,256.10	$ 1,769,958.10	-40%	-15%
3	3	3	25.8217	0.6708792	$ 1,645,597.00	$ 122,527.20	$ 1,768,124.20	-2%	-15%
3	3	4	26.33105	0.646978	$ 1,635,858.00	$ 119,922.50	$ 1,755,780.50	0%	-16%
3	4	1	6.5439559	0.8049451	$ 1,552,930.00	$ 162,291.90	$ 1,715,221.90	-60%	-7%
3	4	2	15.804948	0.5359891	$ 1,651,300.00	$ 103,101.50	$ 1,754,401.50	-40%	-14%
3	4	3	25.79011	0.5582418	$ 1,639,304.00	$ 107,672.50	$ 1,746,976.50	-2%	-14%
3	4	4	26.28407	0.5445055	$ 1,628,027.00	$ 103,171.10	$ 1,731,198.10	0%	-15%
4	4	1	12.19176177	0.6321429	$ 1,620,935.00	$ 118,806.70	$ 1,739,741.70	-51%	-10%
4	4	2	24.304947	0.4975275	$ 1,738,365.00	$ 87,161.73	$ 1,825,526.73	-7%	-8%
4	4	3	26.2458843	0.487088	$ 1,756,971.00	$ 85,653.09	$ 1,842,624.09	0%	-7%
4	4	4	26.2549397	0.4868132	$ 1,756,903.00	$ 85,637.09	$ 1,842,540.09	0%	-7%
		Average	16.82614773	2.723379178	$ 1,530,065.63	$ 276,603.78	$ 1,806,669.41	-28%	-4%
		Min	2.5543954	0.4868132	$ 1,327,372.00	$ 85,637.09	$ 1,693,550.80	-72%	-21%
		Max	26.33105	9.212912	$ 1,756,971.00	$ 883,557.60	$ 2,210,929.60	0%	39%