ARTICLES

VEIN TO VEIN: EXPLORING BLOOD SUPPLY CHAINS IN CANADA

ABSTRACT

There is not yet any substitute for human blood which remains a scarce resource in many countries. Effective and efficient management of blood supply chains (BSCs) is utmost important in the healthcare industry. This paper gives an overview of the BSC and how blood products are used at hospitals to provide life-saving services to patients. Factoring in the blood types and their receipt compatibility, a simple inventory model is proposed. Using secondary data, the model is illustrated by way of a small case study in Nova Scotia, Canada. We highlight that due to both demand and supply uncertainties, and due to its perishable nature, inventorying blood products is not straightforward and brings with it many logistical and management challenges in the BSC.

KEYWORDS | Healthcare operations, blood products, supply chain management, inventory control, donor behaviour .

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INTRODUCTION

Supply chain management plays an important role in the healthcare industry. In particular, hospitals facilitate and provide life-saving services for patients. The supply chain is applied to both urban and remote locations, as well as sites of natural disaster. Thus there is an importance on the overall optimization of the blood supply chain.

One of the critical components of hospital operations is the supply of blood. Currently, there is no substitute for human blood and in many countries blood is considered a scarce resource. In Canada, blood donation is voluntary and the system is managed by Canadian Blood Services (CBS). There are specific standards and policies around blood testing, storage, and treatment mandated by the World Health Organization to ensure the quality of the blood, but some countries have different standards and regulations around blood testing and treatment.

CBS is a non-profit organization responsible for managing the blood supply across all the provinces and territories in Canada (excluding Quebec). It has 36 permanent sites across Canada and conducts approximately 14,000 mobile clinics annually. It collects and tests blood from the donors to ensure its safety before it is transfused into patients. Furthermore, CBS conducts research on blood and stem cells to improve quality and knowledge (CBS, 2017a).

A human body contains five litres of blood. During the blood collection procedure, one unit of blood (approximately 450 millilitres) is collected from the donor (CBS, 2017b). The human body takes up to 40 days to replenish the red blood cells, which limits the number of times an individual can donate to six times annually. Each donation can save up to three lives, and thus if an individual donated to the full potential, one individual could "improve the quality of life of as many as 18 people" in one year (CBS, 2017a).

Blood has many applications in hospitals. For example, a major surgical procedure may require a transfusion to compensate for blood loss. Transfusions are often needed for victims of severe accidents or natural disasters; it can take up to 50 units of blood to save a single car crash victim (CBS, 2017c). Furthermore, blood transfusions are needed for those with blood illnesses and disorders, including liver disease, where the liver cannot properly produce components of blood, illnesses that causes anemia (deficiencies in red blood cells) such as kidney disease or cancer, and from the use of medicine or radiation treatments (Balentine, 2016).

A perishable (time-sensitive) product is defined as a one with a limited lifetime or shelf life. Blood is perishable because its components are short-lived, which will be discussed later in the paper. Common challenges of a time-sensitive supply chain include maintaining the quality of the product by minimizing delivery time and controlling the environment, e.g., temperature and humidity (cf. Thron et al., 2007; Blackburn & Scudder, 2009; Schiavo et al., 2015).

This paper explores the details of a Blood Supply Chain (BSC), from donor to recipient or until the blood is stocked in hospitals. It identifies the level of safety stocks needed for inventory management. It is important to analyze the components of the blood and identify perishability thresholds. This will be applied in the model that addresses the demand for each blood type. In supply chain management, there are always trade-offs. The trade-offs present in the BSC are identical to those in the perishable supply chain: cost and time. However, as blood is a life-related product, there is less emphasis on cost savings. There are also trade-offs in the blood unit inventory management, namely, having excess or insufficient stock, resulting in wastage and stock-outs, respectively.

The paper proceeds as follows. In the next section, we provide a closer examination of blood. Then, the inner workings of BSCs are given along with a related literature review. As a small case, in the following section, we provide a blood inventory management model and apply it to Nova Scotia. Finally, provided are conclusions and future research avenues.

BACKGROUND ON BLOOD AND BLOOD PRODUCTS

There are four types of blood: A, B, AB, and O. Each is further categorized by the rhesus (Rh) factor, either positive (Rh+) or negative (Rh-), to denote the presence of a surface antigen. A surface antigen is a protein found on the surface of cells that elicits an immune response to foreign substances in the body. For example, Rh- blood will have an immune response to Rh+ blood because Rh+ blood cells have the Rh antigen, which will be identified as a foreign substance in the body. However, Rh+ blood will not have an immune response to Rh- because the Rh- blood cells are lacking the antigens.

Therefore, there are a total of eight blood types, taking Rh factors into consideration. As a result, blood compatibility is based on the blood type and the Rh factor because each blood type produces unique surface antigens and antibodies against blood antigens. The presence of antigens and antibodies is shown in Exhibit 1. Blood also produces certain types of antigens, A and B. For example, blood type A contains A antigens, which produce antibodies against the B antigen (Anti-B). Blood type AB produces both A and B antigens, and thus does not produce any antibodies as both A and B antigens are accepted. On the other hand, blood type O lacks any antigen, and therefore produces antibodies against both A and B antigens.

**Exhibit 1. Blood types, and their antigen and antibodies**

Blood Type	Antigens Produced	Antibodies Produced
A	A antigen	Anti – B
B	B antigen	Anti – A
AB	A & B antigens	N/A
O	N/A	Anti – A & B

The most common blood type in Canada is O+ found in 39% of the population while AB- is the least common blood type, found in only 0.5% of the population. Moreover, blood type O- is a universal donor (7% of the Canadian population), where AB+ is a universal recipient, the 2.5% of the population (CBS, 2017d).

Blood Components

In humans, blood is produced in the bone marrow and has four components: red blood cells (RBCs), white blood cells (WBCs), platelets, and plasma (see Figure 1). Each component has different uses. RBCs are mainly used during surgery and for those undergoing cancer treatment. Platelets are used for cancer patients and those with bleeding disorders. Plasma is used during extensive surgery, for trauma patients, and for those with liver disease. Lastly, WBCs are not used for transfusion as they are part of the body's immune system and would not be accepted by a different immune system.

Figure 1. Components of blood (CBS, 2017d)
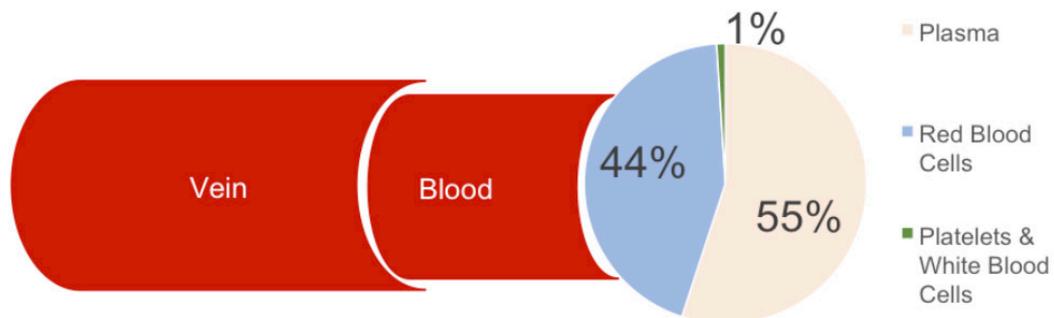
The function and capabilities of individual blood components (red blood cells, white blood cells, platelets, and plasma) is shown in Exhibit 2.

Exhibit 2. Components of Whole Blood and Their Functionality (CBS, 2017d)

Red blood cells (RBC)	RBCs, also known as erythrocytes are responsible for carrying oxygen to tissues and accounts for 40 - 45% of the blood volume. A gas exchange occurs in the capillaries in the alveoli (air sacs) in the lung. Carbon dioxide diffuses out of the bloodstream and oxygen is attached to the RBC to yield oxygenated RBC. Carbon dioxide is eliminated from the lungs with exhalation and oxygen is obtained by inhalation. WBCs, also known as leukocytes are part of the body's immune system and provide protection against infectious disease and foreign invaders.

White blood cells (WBC)	WBCs account for 1% of the total volume. In order to prevent the donor's white blood cells from suppressing the recipient's immune system, WBCs are isolated and removed from whole blood samples.
Platelets	Platelets or thrombocytes are responsible for blood clotting to help stop bleeding. It is a small component of the blood volume, accounting for less than 1% of the blood volume.
Plasma	A majority of the blood is made of plasma, which is a fluid accounting for 55% of the blood volume. The plasma is composed of 92% water and 7% vital proteins. Cryoprecipitate is a component of plasma, which is rich in clotting factors (The American National Red Cross, 2017).

A survey of blood supply chain and related literature

In this section, we look at how a BSC works and identify challenges related to its management, including determination of the optimal level of blood stocks. The related key literature is included.

How does a BSC work?

Much like any supply chain, the one for human blood involves many bodies, each responsible for a value-added task. There are complexities that accompany each stage of the BSC, often termed the 'vein to vein chain' (CBS, 2014).

Upon demand for human blood, blood banks engage in volunteer donor recruitment to generate adequate supply. In Canada, CBS performs this task as well as the collection phase of the chain. The scope of this study considers hospitals as the customers for blood and responsible for communicating demand to CBS (the supplier). Fig. 2 illustrates the BSC chain.

Figure 2. BSC stages from the origination of demand to patient transfusion (CBS, 2017c)
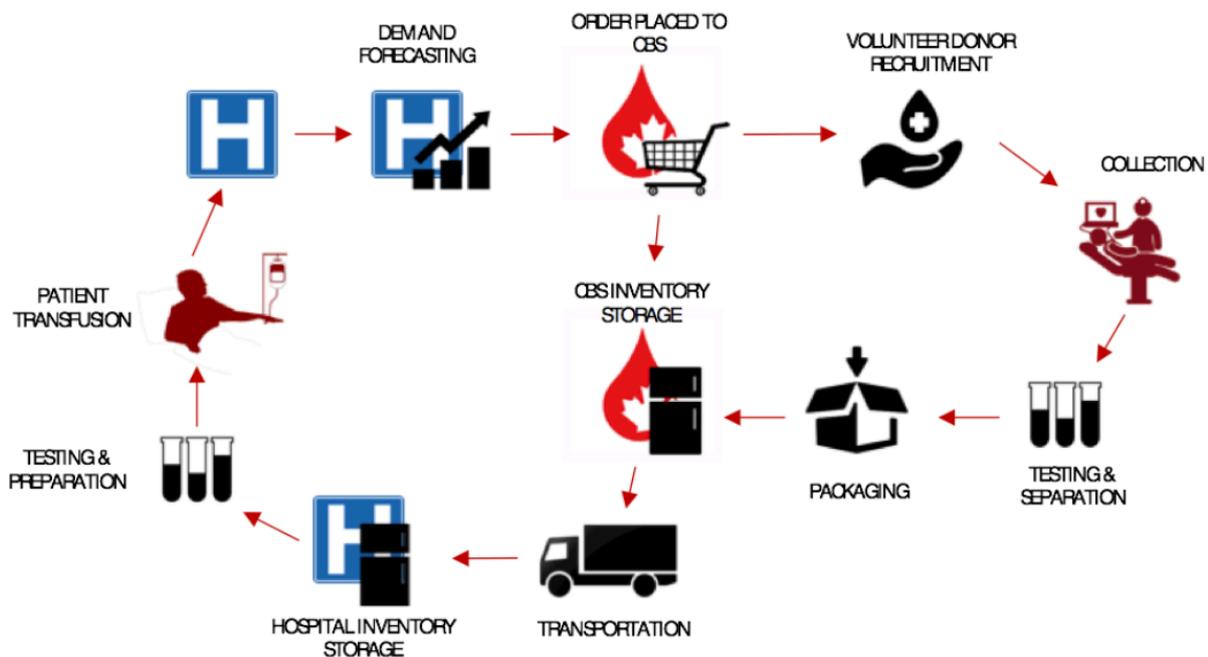
Inappropriate donors are filtered out during the collection phase, which involves iron level testing and a thorough questionnaire that identifies healthy individuals with no history of blood-threatening disease. This process maximizes the likelihood of usable samples and works to minimize the number of unusable collections. The entire collection process from start to finish takes about one hour, and includes the extraction of one unit of blood, and four test tubes of blood that are used for the testing phase. During the testing, the whole blood sample is separated into RBCs and plasma, and each is tested individually. The tests

performed include blood group typing, RBC antibody screening, RBC antigen screening (phenotyping), and infectious disease testing (including HIV, hepatitis, HTLV, syphilis, West Nile, and Chagas disease).

The packaging phase of the BSC involves labelling and packaging in plastic bags. There are many factors in the transportation phase, including the use of a tamper-evident device that makes any form of tampering immediately visible. CBS uses a variety of shipping container and ice-packing configurations, depending on the shipping temperature required. The temperature requirement differs for the different components of blood, and must be maintained throughout the entire transportation route. Before transfusion, the blood is defrosted/warmed from its chilled state, mixed, and undergoes pre-transfusion testing. This testing involves extracting a sample from the intended recipient for ABO and Rh blood typing and antibody screening. A test for compatibility between the extracted sample and inventory blood RBCs is done, as well as cross-matching between inventory and patient plasma.

The last stage of the supply chain is blood transfusion, during which the end user receives the required blood collected from donors.

Hospitals are responsible for their own inventory management, which entails estimating demand, selecting safety stock volumes, and minimizing wastage. Hospitals utilize different inventory systems, however few use sophisticated models to dictate replenishment policies and instead rely on employee opinions and past trends (Williamson & Devine, 2013). When hospitals reach their reorder points, they place an order with a blood bank, which for this report is CBS. CBS in turn sends the hospitals the stock they do have, and then engages in donor recruitment to replenish its own inventory.

Complexities within the BSC

Several complexities that exist in the supply chain pose challenges to minimizing cost and time. As there is no alternative to meeting the demand for blood, and there is no substitute for human blood, the utmost care and thoroughness must be applied to ensure minimal waste. Efficient and effective blood banking is an essential part of health services and has a direct impact on the success of medical treatments (Pierskalla, 2005). Some of these complexities include expiry time, temperature and trans-

portation requirements, extensive testing, and the potential for testing errors.

Whole blood, which is the original collection from donors, has a shelf life of 21–35 days depending on the type of anticoagulant used prior to its components being separated (ANRC, 2017). RBCs must be stored at 1–6 degrees Celsius and have a shelf life of 42 days (CBS, 2016). Plasma must be stored at -18 degrees and has a shelf life of 12 months (CBS, 2015). Platelets have a shelf life of up to 5 days, and must be stored at 20–24 degrees (room temperature). Lastly, cryoprecipitate (a component of plasma) has a shelf life of 12 months when kept below -18 degrees (BCA, 2017). Once any of the packaging has been broken or the component has been thawed, all must be used within 24 hours (cryoprecipitate in 4–5 hours).

These various storage requirements pose extreme challenges for inventory and replenishment management, as one transfusion recipient may require more than one blood product, which requires the management of all products with different storage periods. While many recipients require known and predetermined products scheduled in advance (for surgery for example), an increased risk of supply shortage exists for emergencies and unexpected events.

Supply uncertainty in BSC

Most significant, though, is the uncertainty of demand and supply, which pose serious challenges for distribution network requirements and inventory management. The preparation of the different components of whole blood results in significant costs because component has a different storage requirement and shelf life.

Given that the supply of blood comes from volunteer donors, the quantity is unknown and can be considered a random variable. Soliciting efforts by blood banks are not guaranteed to generate stable or substantial supply. Supply levels are becoming increasingly difficult to attain because of the number of viruses and conditions that must be screened out. A study of daily donation volumes in Chicago blood banks showed that, day to day, the number of units collected ranged from zero to 1,100, exhibiting the high variability and difficulty in predicting supply (Pierskalla, 2005). Donor recruitment strategies used in Canada and the UK include online marketing efforts, telephoning previous donors, allowing donors to fill out the health checklists at home prior

to their appointment to reduce the time of the visit, and mobile collection clinics. Although recruitment has increased in recent years, still only 4% of eligible Canadians donate while on average 7% of Canadians require blood products each year (McGinn, 2017). Furthermore, while an individual can donate up to six times per year, most Canadians who donate only do so twice per year (CBS, 2017a). Another struggle with retaining donors is donor well-being following donation, which has become more complex due to iron deficiencies, increased fainting, and dehydration (Osorio et al., 2017). While Canada has now implemented screening systems to reduce these occurrences, this also limits the supply because donors who are deemed ineligible to donate once are less likely to return. These supply deficiencies pose serious health risks, including surgery cancellations.

Uncertainty of demand for blood types

There exists uncertainty inherently in demand for blood. Although hospitals can track historical demand rates, in the case of demand for blood, historical trends are not always accurate at predicting future demand, which is subject to the influence of uncontrollable factors such as natural disasters or weather that results in more accidents. Common demand-forecasting techniques used by hospitals include an analysis of historical and seasonal trends, environmental scans, clinical volume trends, patient-specific future plans (e.g., surgeries), and discard and wastage data (CBS, 2014). Demand forecasting for blood banks is also complex, and challenges often result from asymmetric information. Changes to hospital policies or transfusion protocols

and the introduction of new treatments, for example, can greatly increase the demand for blood and a lack of communication with blood banks can lead to supply deficiencies (Pierskalla, 2005). Increased pressure to solve the issue of matching supply with demand is stemming from the growing aging population in Canada. It is estimated that overall demand for blood will increase by 10% between 2013 and 2023 due to cancer treatments in elderly patients, the growing population of elderly patients, and violent trauma in younger people (Williamson & Devine, 2013).

Current research on BSC management

Most of the research performed on the mismatch of supply and demand concludes that it is quite challenging to optimize the gap between the two because both are uncertain. Most research on optimal management of the BSC therefore focuses on two components of the supply chain that are less uncertain but equally difficult to optimize: network optimization and inventory management. While the model presented in this report concerns inventory management, it is important to review the impact that network has on lead time and therefore inventory replenishment policies.

The BSC consists of many players in the four echelons or stages of the chain – collection, production, inventory, and distribution – that together make up the BSC network. Network optimization assesses the policies and decisions connecting all four stages, the effectiveness of which is most easily assessed by the number of stock-outs experienced (Fig. 3 provides a flow chart of these stages).

Figure 3. Flow chart of the four BSC echelons/stages (based on Osorio et al., 2017)
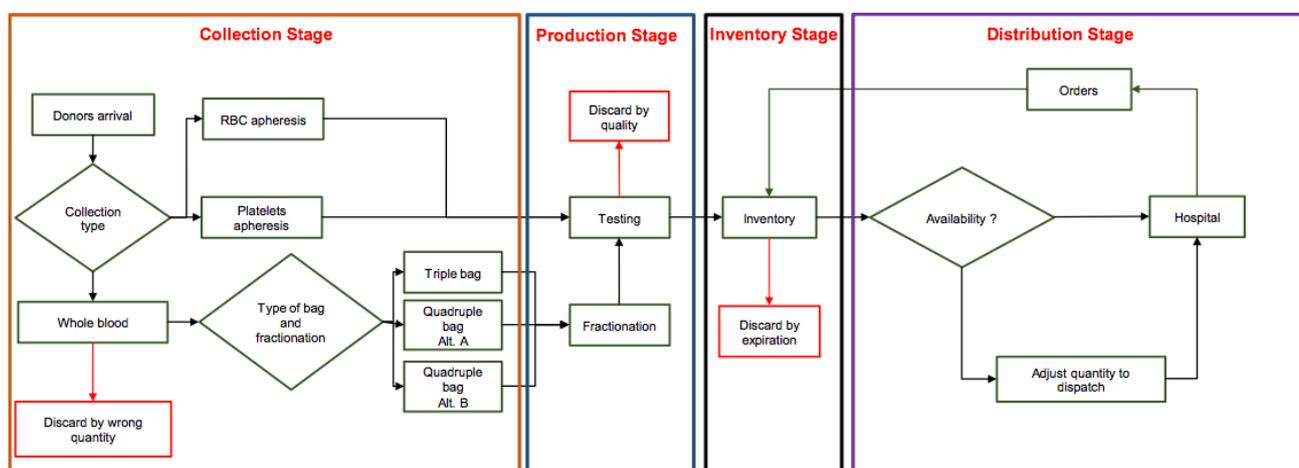
Research on network optimization uses cost minimization as the main driver. Costs often include wastage, spoilage, and stock-out costs, rather than traditional supply chain optimization costs such as transportation, storage, and routing methods. The various models used in recent research assess the most effective network policies and decisions that minimize the damage and disposal of blood units.

One study in particular focuses on regionalized blood banking systems. Nagurney et al. (2012) develop am algorithmic model that measures the perishability of blood using arc multipliers, discarding costs resulting from wastage, demand uncertainty, and shortages and quantifies the risk of supply issues. The model provides an equation for total operating costs that can be minimized, factors in the cost of perishability at each node of the chain, and presents an optimal path flow. In theory this model can be applied to any blood bank network by substituting the corresponding inputs, but does not offer an optimal network design applicable to most scenarios.

Simulation models are also popular because they allow for random variables and ranges of variables that mimic the uncertainty of demand and supply at each stage of the chain. A simulation model represents the daily behaviours of the BSC system, the optimization of which supports decisions around the number of required donors, and collection and production methods that minimize overall costs. Such simulation models can be utilized by hospitals to manage short-term demand forecasting; however, challenges with uptake involve complexity in estimating the value ranges of the various variables involved.

MANAGING INVENTORY IN BSC

Inventory management of blood supplies requires hospitals to make decisions about optimal inventory levels, reorder points, quantities, shipment and distribution policies, and waste/repurpose policies. Demand is the sum of all individual orders (planned and emergency), but as both demand and supply are unknown, hospitals are faced with balancing the trade-offs between wastage due to excess inventory and shortages due to insufficient inventory. Inventory systems are periodic, where one period is one day and a first-in/first-out system is used to keep track of and minimize wastage of blood products.

Beliën & Forcé (2012) and Osorio et al. (2015) present a review of literature for the inventory and supply chain management of blood products, the former focusing on those quantitative models in BSCs. Current research most commonly focuses on four types of inventory management analysis: simulation and regression, Markov chain analysis, dynamic programming, queueing theory. Simulation and regression model research includes scenario generation for various compositions of storage supplies (by size of unit and age of blood). Especially in health care chains where resources are scarce and the problems complex, simulation may be a powerful tool in better decision making (Rytilä & Spens, 2006; Kopach et al., 2008). This simulation also models ordering, issuing, and cross-matching policies to identify the option resulting in least wastage. Research using Markov chain analyses applies to perishable supply chains and assesses how issuing policies are affected by inventory size and age of the blood supply. Dynamic programming research from the 1980s concludes that increasing inventory stocks is more advantageous for perishable products, but limited research using dynamic programming has been done since then. Lastly, queueing theory simulations have been developed that facilitate decision-making around the use of blood products at various demand rates. Synchronizing strategic and operational decisions, Or & Pierskalla (1979) present models to optimally determine how many and where to locate blood banks, the allocation of the hospitals to the banks, and the optimal routing of the periodic supply operation, so that both the total of transportation costs (periodic and emergency supply costs) and the system costs are minimized.

Research on hospital blood inventory management dates back to the 1960s, and consistently measures performance based on shortages, outdates, waste, and the cost of information and transportation (Stanger, Yates, Wilding, & Cotton, 2012). That literature review and study concludes that proper inventory management supports significant reduction in hospital wastage of red blood cell products in particular. The study also indicates that effective human resource training to increase awareness about the proper planning based on historical stock levels and order patterns, and increased transparency of inventory policies and procedures are key elements to improving inventory management practices. Electronic cross-matching has also become a common practice for transfusion management in larger hospitals whereby expiry dates and storage times are tracked by an electronic system to increase service levels and reduce the time required to select products (JPAC, 2016).

While there has been substantial research done on how to manage and optimize inventories of blood, both at the hospital and blood bank level, all the research reviewed refers to blood all together and does not discuss differences in demand for the different blood types. The proposed model in the next section fills this gap by assessing how reorder point and safety stock inventory policies may differ for the various levels of demand for each blood type.

Model development

Before calculating demand, it is important to understand substitutability in blood types, namely, someone of a certain blood type being able to accept a different blood type. The substitutability combinations are shown in Exhibit 3.

Exhibit 3. Blood type substitutability

Following the rows horizontally, we observe that a unit of blood type A+ can be used by patients of blood types A+ and AB+. The inventory demand (units of donor blood) for one blood type, thus, is a function of the demands that can accept it. Therefore, inventory of A+ is the sum of the A+ and AB+ demands, as these are the two blood types that can accept it. The average of this sum is then taken because the donor blood is compatible with other blood types. This leads us to redefine demand for each of the eight blood types using the following equations:

$$D_k = \sum_{i \in K} d_i \quad \text{and} \quad \sigma_k = \sqrt{\sum_{i \in K} \sigma_i^2 + 2\sum_{i > j} \rho_{ij}\sigma_i\sigma_j}$$

(1)

where k is a specific blood type and K is the set of blood types with which it is compatible. Our pro-

posed model assesses the safety stock levels of each blood type that hospitals should maintain to ensure stock-outs are avoided at the allowable risks. To measure this, the classical safety stock (sk) equation is adapted from Bagchi et al. (1984). It follows as

$$s_k = z\sqrt{\bar{T} \times \sigma_{D_k}^2 + \bar{D}_k^2 \times \sigma_T^2}$$

(2)

where z is the safety factor set by management, is the expected supply lead time, is the expected demand per period during the lead time, and are the standard deviation of demand per period and the standard deviation of supply lead time, respectively. Safety stocks in BSCs are especially important as they may be vital in absorbing uncertainty in demand for blood products (cf., Perera, Hyam, Taylor, & Chapman, 2009). Our proposed safety stock calculation factors in the compatibility of the blood types; therefore it pools the inherent variations.

Eq (2) is applied to all eight blood types in order to inform hospitals of how many units of product per blood type should be kept on hand at all times. It is important to note that the inputs for demand and standard deviation will depend on the geographic location of a hospital and the size of its catchment area. Additionally, because the eight blood products are used for different scenarios and purposes, variation will occur depending on which blood products are being stocked. It is recommended that hospitals calculate safety stock inventories by blood type and by their by-products together in order to minimize the number of stock-outs.

A numeric illustration: application to Nova Scotia, Canada

To better understand the model, the optimal safety stock level of each blood type is assessed using a case study of the province of Nova Scotia (NS), Canada. This study shows the estimated population for each blood type using the Canadian averages. The overall demand for blood type per replenishment period of RBCs are also explored.

The population of Canada as of July 1, 2016, was 36.3 million. NS accounts for 2.6% of the total, or 942,926 persons. The percentage of individual blood types in Canada and the corresponding estimates in NS are displayed in Table 1. NS numbers are estimates based on percentage of the Canadian population.

Table 1. Blood Donor Type Estimates

		% in Canada	# estimate in NS
A	+	36.0%	339,453
	-	6.0%	56,576
B	+	7.6%	71,662
	-	1.4%	13,201
AB	+	2.5%	23,573
	-	0.5%	4,715
O	+	39.0%	367,741
	-	7.0%	66,005

NS was chosen because it has nine post-secondary institutions, over half of which are in Halifax, the largest city in NS. Thus, the Halifax Regional Municipality is a good representation of Canada because there is a sizable influx of students from all over the country and from other nations.

Blood demand and safety stock are demonstrated by applying the model in NS. According to CIHI (2016) data, between 2014 and 2015, the age-standardized rate of hospitalization per 100,000 due to trauma was 592 in NS, which equates to 55,821 individuals. There are assumptions applied to the model for estimating blood safety stock and demand. One assumption is that one-third of the individuals hospitalized due to trauma-related injuries require blood transfusions. Therefore, it is estimated that annually 18,576 people in NS require blood transfusion. Further, the model focuses on RBC transfusion only to illustrate the number of RBC units that should be kept in hospital inventory. It is also assumed that the trauma patients in question require RBC transfusion due to a lack of oxygen and loss of blood volume.

RBCs have a shelf life of 42 days, roughly 1.5 months, and therefore require eight replenishment periods per year. As a result, the total demand for RBCs per replenishment period has been calculated as 2,322. The overall demand for blood types in Nova Scotia per replenishment period of RBCs is shown in Table 2.

The cycle demand is calculated using the demand equation. The cycle inventory has been averaged because the donor blood is compatible with other blood types as mentioned earlier with blood type substitutability. The lead time used in this study is one day, as stated by CBS. This is a conservative measure as CBS has locations in major cities, is able to deliver blood to the hospitals as required, and is known to do multiple runs in a day. A standard deviation of 10 was used for blood demand (inventory). Moreover, the model assumes a 99% safety factor as stock-outs are not acceptable for blood.

Table 2. Overall demand for blood types in NS per replenishment period of RBCs

A	+	836
	-	139
B	+	176
	-	33
AB	+	58
	-	12
O	+	906
	-	163
	Total	**2,322**

The total inventory (2,374), as shown in Table 3, is greater than the overall demand for the blood types (2,322), as shown in Table 2, indicating that there will be sufficient inventory for the anticipated demand. The cycle inventory and safety stock numbers based on the overall demand for blood types in NS per replenishment period of RBCs are shown in Table 3.

Table 3. Cycle inventory and safety stock of blood types based on overall demand for blood types in Nova Scotia per replenishment period of RBCs

		Cycle Inventory	Safety Stock	Total Inventory
A	+	447	152	598
	-	261	89	350
B	+	117	40	157
	-	70	24	94
AB	+	58	20	78
	-	35	12	47
O	+	494	167	661
	-	290	98	389
			Total	**2,374**

We also conducted a sensitivity analysis for cycle inventory and safety stock of the blood types based on the overall demand for blood types in NS per replenishment period of RBCs (see Table 4). A sensitivity analysis is used to determine the circumstances of the model under different inputs. Thus, the lead time and standard deviation of the safety stock equation have been changed to illustrate how sensitive the model is to these changes.

For this sensitivity analysis, the lead time has been reduced by 25% from 1 day to 0.75 days. In addition, the standard deviation of the overall demand has been increased by 10% from 10 to 11. The calculation with these inputs shows that both the safety stock and inventory decrease with a reduction in lead time and increase in standard deviation of the overall demand. In this scenario, the total inventory of blood types is below the demand for RBCs per replenishment period with 1% variance. The total inventory of blood under the sensitivity analysis has been calculated to be 2,294, where the demand of red blood cells per replenishment period is 2,322.

The case of Nova Scotia has been used with the model to determine the optimal safety stock levels of each blood type. The model focuses on the population that requires blood transfusion per replenishment period for RBCs. Total inventory exceeds the overall demand for blood types in NS, where there will be enough inventory to meet anticipated demand for blood and accommodate unexpected spikes in demand.

Table 4: Sensitivity analysis for cycle inventory and safety stock of blood types based on overall demand for blood types in Nova Scotia per replenishment period of red blood cells, where lead time has been reduced by 25% and standard deviation of demand increased by 10%

		Cycle Inventory	Safety Stock	Total Inventory
A	+	447	131	578
	-	261	77	338
B	+	117	35	152
	-	70	21	90
AB	+	58	17	75
	-	35	11	46
O	+	494	145	639
	-	290	85	375
			Total	**2,294**

CONCLUDING REMARKS

Our model is generalizable as it can be used by hospitals in both urban and remote areas if population numbers, average accident rates, or historical data on transfusion numbers for the geographic area they serve are available. It is very likely that this information is available to hospitals; Statistics Canada provides detailed information on population in cities and towns, and hospitals can track historical data on the number of transfusions that occur annually. There is also the possibility that this model can be applied to research and clinical studies that are required to use blood products.

As the case study of Nova Scotia shows, the blood type that hospitals should stock most is of type O- because it can be accepted by every other blood type. In times of donor shortages of other blood types, hospitals should replenish those blood types with O-. This in turn puts direct pressure on blood banks such as Canadian Blood Services to focus their attention on O- donors.

There is the opportunity for hospitals to forecast demand for the different blood products by calculating demand for all different scenarios that require each blood type. Examples of the most common reasons for blood transfusion include liver disease, illnesses that cause anemia, bleeding disorders, surgery, and cancers in the kidney, blood, spleen, or bone marrow (Mayo Clinic, 2017).

In recent years there has been significant discussion about private organizations disrupting the blood bank industry and providing financial compensation for blood donations. Several studies have shown that financial compensation incentivizes potential donors and is effective at increasing donation rates. Most of the plasma products Saskatchewan's hospitals use come from the U.S. To counteract this, one clinic in Saskatchewan has started paying plasma donors $25 per visit (Rienzi, 2013). Many Canadians disagree with the principle of financial incentives out of ethical concerns about exploiting Canada's poorer citizens, as well as the increased costs to perform more thorough tests because paid donors might be incentivized to lie about their health history, which poses risks to transfusion patients.

Within the Operations Management and Supply Chain Management literature, there remains much room for research on BSCs and their management. On a broader sense, the uncertainties inherent in both supply and demand sides in BSCs pose challenges in developing and executing agile supply chain networks (Lee, 2002). Due to its rare, scarce, and perishable nature, human blood and its byproducts require special inventory management models to be used at the blood banks in BSCs. Besides, giving a detailed portrayal of how BSCs operate, our supply aggregation model for blood types may be incorporated in single-period (perishable) inventory management models with supply uncertainty (cf., Käki et al., 2015) and also in developing operating characteristics for continuous review systems for perishables (e.g., Tekin et al., 2001). Furthermore, our model can feed into the current literature in which generally incorporates only demand stochasticity in BSC network optimization such as in Nagurney & Masoumi (2012), and in Jabbarzadeh et al. (2014). In the setting of BSCs, how stochastic and substitutable supply, along with demand uncertainty, impact optimal design of supply chain networks? How do geographical demand characteristics impact the network design of a BSC? How does supply of blood change over time? How can it best matched with demand varying over time? From a closed-loop SC perspective, discarding of potentially hazardous blood packaging and waste, warrants further research.

Last but not least, incorporating the donor behavior (e.g., Ülkü et al., 2015) and its implication on the optimal inventory allocation policies for blood types and products, along with quality and traceability issues (Bentahar et al., 2016) pose challenges. Add to this, compensating blood donations, lends itself as a new research venue on ethical issues and their impact on supply uncertainty in BSCs.

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