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Platelet ordering policies at hospitals using stochastic integer programming model and heuristic approaches to reduce wastage

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ABSTRACT

Demand uncertainty coupled with a short shelf life of blood platelets has led to a significant wastage at hospitals. An important objective is to minimize wastage of platelets while maintaining a specified service level. To achieve this objective, a mixed integer stochastic programming model under demand uncertainty is developed. Due to the computational complexity of the problem, three heuristic rules are proposed for determining the platelet ordering policy at the hospital. The performance of these three ordering policies is compared against that of the periodic review order-up-to policy proposed in the literature using real-life data obtained from a medical center. The shelf life of arriving platelets, coefficient of variation of demand and cost parameters are varied, and their impact is analyzed on the performance measures and the best rule with respect to each setting is determined. Based on the shelf life setting and cost prioritization, the decision maker can choose the most suitable rule for the hospital.

1. Introduction

Supply chains that deliver perishable products are unique with specific challenges in comparison to those of non-perishable items due to their finite product shelf life (Nagurney, Masoumi, & Yu, 2012). van Donselaar, van Woensel, Broekmeulen, and Fransoo (2006) suggested that items which have a shelf life of 30 days or less can be categorized as perishable items. Hence, items such as blood, food, medicines, drugs and flowers are perishable, thereby leading to a significant wastage, if not utilized within that duration (Parfitt, Barthel, & Macnaughton, 2010).

Blood supply chain deals with the delivery of different components of blood (Red Blood Cells (RBC), White Blood Cells (WBC) and platelets suspended in a liquid substance called plasma) from the donor to the hospitals and surgery centers for patient treatment. The whole blood is collected at several collection sites from various donors and is then sent to blood centers. At the blood centers, blood is separated into three major blood components: RBC, plasma and platelets and is then sent to the component labs for testing for any infection such as Zika, HIV, Hepatitis A, Hepatitis B, Hepatitis C, and West Nile Virus (American Red Cross, 2017). From the sample testing, if the blood is observed to be contaminated, then the corresponding blood unit is discarded at the storage facility. Several hospitals and surgical centers place orders to the blood center for the various blood components, depending upon their needs to serve their patients. It is important to note that platelets have a shelf life of only five days, compared to other blood products, such as plasma which can be stored for more than a year. The testing procedure at the blood center takes two days and hence, the maximum life of platelets arriving at hospitals will be only three days.

Platelets, in particular, can be collected from the donor through a process called *platelet apheresis* by which blood is drawn and only platelets are extracted from the donor's blood and the remaining blood components are injected back into the donor's body. Though this method is expensive, the frequency of platelet donation can be increased to once every 2 weeks (24 times a year) instead of once every 56 days (6 times a year). From the donor site, apheresis platelets are sent to the blood center for testing and then shipped to the blood banks and hospitals as in the regular blood supply chain (American Red Cross, 2017).

It is necessary to minimize the blood wastage at hospitals for the following reasons.

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- Over the past 10 years, demand for blood has increased, but the supply of blood is not increasing enough to meet the demand. Moreover, increased FDA regulations reduce the number of eligible donors. In a 2007 survey, it has been reported that nearly 500 surgeries are canceled at hospitals during one or more days due to the shortage of blood (Nagurney et al., 2012).
- Blood products are perishable and the donated blood can only be stored for limited future use.
- Wastage of blood called "outdating" is not acceptable because less than 38% of the population is eligible for donating blood and only 5% of the eligible blood donors actually donate blood (American Red Cross, 2017; LifeStream, 2009). Also, depending upon the type of blood donation, the time between donations is a constraint and frequent donations by the same person are not possible.
- The cost of blood procurement and testing is quite high. In 2011, the average cost of purchasing one unit of RBC by hospitals from its suppliers was $210.74 (Schrijvers, 2011) and one unit of platelet by hospitals from its suppliers was $533.90 (Toner et al., 2011).

Specifically, the five-day shelf life of platelets coupled with demand uncertainty lead to about 20% wastage of the total units collected (Haijema, van Dijk, van der Wal, & Sibinga, 2009). This paper aims at developing ordering policies to reduce outdating and shortage of platelets, and to achieve this goal, a mixed integer stochastic programming model and heuristic approaches under demand uncertainty are developed.

The paper is organized as follows. A review of the literature on both perishable item and blood inventory management is presented in Section 2. The stochastic mixed integer programming model for hospital inventory management is discussed in Section 3. In Section 4, the proposed heuristic ordering policies are detailed. Computational evaluations of the stochastic programming model and the heuristics using real data from a medical center are presented in Section 5. Conclusions and potential future work are given in Section 6.

2. Literature review

2.1. Inventory policy for perishable items

Research on developing inventory policies for perishable items has been conducted over the past five decades. The optimal policies for perishable products with fixed life were first studied by van Zyl (1964) in which products with shelf life of only two days were considered. Later, Fries (1975) and Nahmias (1975) independently developed models for products with lifetime of more than two days. Nahmias (1978) extended the model proposed in Nahmias (1975) by including order cost. However, all papers discussed so far assumed that the products have a fixed shelf-life. This assumption was relaxed in the work by Liu and Cheung (1997) in which the authors developed inventory models for products with random lifetimes.

In 2000s Goyal and Giri (2001) were one of the first to intensively review the literature on perishable inventory. They classified the research done on perishable items into the following three categories: (1) Inventory models with fixed lifetime (see Liu & Lian, 1999; Nandakumar & Morton, 1993; Perry, 1997; Schmidt & Nahmias, 1985), (2) Inventory models with random lifetime (Liu & Cheung, 1997; Liu & Shi, 1999), and (3) Inventory models in which items decay depending upon the utility function. Goyal and Giri (2001) also suggested that demand plays an extremely important role in developing the perishable inventory model and classified past research based on the type of demand, such as deterministic demand (Hariga, 1995, 1996; Xu & Wang, 1992; Yan & Cheng, 1998) and stochastic demand (Dave, 1991; Kalpakam & Sapna, 1996).

Since 2002, many papers dealt with the supply chain strategies for perishable products (Blackburn & Scudder, 2009; Kärkkäinen, 2003; Thron, Nagy, & Wassan, 2007; van Der Vorst, Tromp, & Zee, 2009). In recent years, several extensions have been proposed to the ordering policies developed in the literature. For example, Kouki, Jemaï, and Minner (2015) developed a continuous review inventory control policy under demand stochasticity, fixed shelf life and constant lead time. The authors computed the best parameters for the ordering policy. Dobson, Pinker, and Yildiz (2017) extended the models proposed by Chen, Min, Teng, and Li (2016) and Wu, Chang, Cheng, Teng, and Al-khateeb (2016), incorporating age-dependent demand rate with decreasing utility to customers over time.

2.2. Inventory management of blood products

Compared to other blood products, the analysis of platelet inventory management is extremely complex due to its short shelf life of five days (Rajendran, 2013). The most commonly considered problem in platelet management is the order policy determination. Techniques, such as simulation, mathematical programming, and dynamic programming, have been widely used to address this issue (Blake et al., 2003; Haijema, 2013; Haijema, van der Wal, & van Dijk, 2007; Haijema, van Dijk, & van der Wal, 2017; Haijema et al., 2009; McCullough, Undis, & Allen, 1978; Sirelson & Brodheim, 1991). However, the work by Haijema et al. (2007) was one of the first to determine the production and inventory rule to minimize both shortage and outdating of platelets. The authors developed a combined Markov dynamic programming (MDP) and simulation approach and applied it to a real-life regional blood bank problem. A double-level order-up-to rule called 2D rule, was proposed, with one level corresponding to relatively new or young platelets and another related to the total inventory.

van Dijk, Haijema, van Der Wal, and Sibinga (2009) extended the research conducted by Haijema et al. (2007) by proposing a five-step approach involving downsizing of the problem to reduce the complexity of dynamic programming formulation. Order-up-to rules reduced the outdating of platelet units from nearly 18% to just 1%. While the work by van Dijk et al. (2009) used a multi-step procedure (combining dynamic programming and simulation, by selecting the order-up-to rule for each day), Blake, Heddle, Hardy, and Barty (2009) noted that their work ignored the age distribution of stock, and hence the work was rather restrictive. Haijema et al. (2009) modeled a stochastic dynamic programming simulation approach, including special periods extending the work proposed by Haijema et al. (2007). Special periods included irregular production breaks during Christmas and Easter since there was no collection of blood from the donors during Christmas, New Year and Easter. This model was applied to a blood bank and observed a reduction of annual shortage to 0.04%.

Another work by Haijema (2013) dealt with a new class of stock-level dependent order policy, called (s, S, q, Q) policy, which was basically a periodic review (s, S) policy restricted by a minimum (q) and maximum (Q) order quantities. In other words, the policy followed a periodic ordering strategy with the inclusion of upper and lower level order quantities. Optimal parameter values were determined by dynamic programming and simulation with an assumption that all platelets have a remaining shelf life of 5 days when they arrive at the blood bank. The results were compared to those of an (s, S) policy, and observed a decrease in the total cost by 7.2%.

While most work proposed in the literature considered developing ordering policies at the blood center and blood banks,