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Blood platelet inventory management with protection levels

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ABSTRACT

We consider a discrete-time inventory system for a perishable product where demand exists for product of different ages; an example of such a product is blood platelets. In addition to the classical costs for inventory holding, outdating, and shortage, our model includes substitution (mismatch) costs incurred when a demand for a certain-aged item is satisfied by a different-aged item. We propose a simple inventory replenishment and allocation heuristic to minimize the expected total cost over an infinite time horizon. In our heuristic, inventory of the newest items is replenished in fixed quantities and the newest items are protected for future use by limiting some substitutions when making allocation decisions according to a critical-level policy. We model our problem as a Markov Decision Process (MDP), derive the costs of our heuristic policy, and computationally compare this policy to extant "near optimal" policies in the literature. Our extensive computational study shows that our policy leads to superior performance compared to existing heuristics in the literature, particularly when supplies are limited.

1. Introduction

According to the American Red Cross, "every two seconds an American needs blood." Cognizant of this, every day tens of thousands of Americans donate blood. But this is only half of the story: Witnessing an influx of donors one week after the 9/11 terrorist attacks, Altman (2001) stated "Few people realize that blood is perishable and cannot be stored indefinitely. Blood centers function more as pipelines than banks, and there is a steady need for donors." Altman's words highlight the perishability of blood, and also point to the importance of maximizing the utilization of blood resources. Although more than 1.5 million components of blood platelets are transfused each year in the US (Sullivan & Wallace, 2005), 17 percent of platelet units collected in the US were outdated in 2004 (AABB, 2005). Exacerbating these problems, Landro (2009) reported a decrease in overall blood collection in 27 percent of the US blood centers because of the swine-flu pandemic, and she emphasized blood centers' plans to allocate blood to the sickest patients. Similarly, during Hurricane Sandy the demand for platelets increased significantly due to critical surgeries and cancelation of over 300 blood drives in 14 states (Aleccia, 2012). Although blood centers and hospitals had sufficient red blood inventories, there was a critical shortage of platelets due to their very short shelf life (3 days) and the unavailability of donors (Aleccia, 2012). Williamson and Devine (2013) also discuss the need for efficient management of platelet inventories due to their high perishability and increasing demand due to an aging population and more aggressive cancer treatments, which involve regular platelet transfusions.

Although meeting demand is of paramount importance, the cost of handling blood products cannot be ignored: Statistics from the Canadian Institute for Health Information reveal that the total expenditures of the Canadian Blood Services increased 51 percent in 2001–2002 compared to an increase in health care costs of 25 percent on average (Wilson & Hebert, 2003). An increase in testing and safety measures, new donor recruitment programs, a surge in demand for blood products, and inefficient usage of resources were all cited as the possible reasons for this cost increase (Wilson & Hebert, 2003). Thus it is crucial that society find ways to reduce costs *and* improve utilization within blood supply chains, so as to make the best use of limited blood resources.

Blood inventory management has been extensively studied in the operations research and management science literature. We refer the readers to the survey papers by Nahmias (1982, 2011), Prastacos (1982), Pierskalla (2004), Karaesmen, Scheller-Wolf, and Deniz (2011), Beliën and Forcé (2012), and Bakker, Riezebos, and Teunter (2012). Blood products are prototypical examples of age-based perishable products for which consumers (patients) or hospitals (major consumption points) have specific preferences, differentiated by product age: Even though patients do not necessarily know the age

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of platelets they are receiving, there are medical and/or logistical reasons, which we discuss below, that cause demand for blood products to be age-differentiated. However, research that considers this particular issue is rather limited.

In this paper, we study a problem in which demand is differentiated by the age of product, as in the case of blood platelets. The central question is how age-differentiated inventory should be replenished and managed to satisfy this age-differentiated demand. Note that, for perishable items, the age composition of stock on hand is determined both by how goods are replenished and how goods are issued (i.e., inventory is allocated): When fresher products are substitutes for aged ones, an inventory manager has the option of satisfying demand for older items from the on-hand inventory of fresher items. But using inventory on hand to satisfy the demand for the current period may not be cost-optimal when there are costs associated with substitutes – as in Deniz, Karaesmen, and Scheller-Wolf (2010) – and/or when excess demand can be satisfied using alternate sources (for example via expediting). One may be better off rationing (protecting) the inventory of fresh items in the current period and incurring relevant costs (lost sales, backorder, or expediting); this may lead to savings in future periods when inventory can be used to satisfy the demand for more important (fresher) products. For example, this may be an attractive option for a blood center that has contracts with hospitals which specify service levels based on the age of the product – as in Fontaine et al. (2009).

This paper is organized as follows: We define the decision problem in Section 2, discuss the challenges associated with it, and provide an overview of our approach and others in the literature. Our heuristic policy is introduced in Section 3. Results of computational experiments are presented in Section 4. Further computations are done in Sections 5 and 6 to test the sensitivity of our heuristic policy and system performance to cost parameters and availability of supply, respectively. The paper ends with a discussion of future research directions in Section 7.

2. Problem definition and related literature

We consider a periodic-review inventory management problem for a product that has a finite lifetime (more than 1 day, $N > 1$). The product ages in a deterministic fashion; for a discussion of random degradation, see Goyal and Giri (2001), and Nahmias (2011). Any product that is not sold within N days outdates and needs to be discarded. The decision maker replenishes only the youngest (freshest) items with zero lead time. These are common assumptions in the research literature; see Nahmias (1982, 2011). The demand per day is a vector of random variables with requests for product of different ages.

As in the classical models in perishable inventory management, there are several cost components: (i) variable cost of replenishment per unit, (ii) holding cost for every item carried from one period to the next, (iii) expiration cost for items that outdate, and (iv) shortage/expediting cost for any demand that is not satisfied from on-hand inventory in any period. In addition we have (positive or negative) substitution costs for satisfying the demand of a certain age using the inventory of fresher (younger) or older items. We analyze the problem in a stationary environment.

In practice, the shelf life of blood platelets is technically 4–5 days; however, the effective shelf life is only 3 days in the U.S. (Fontaine et al., 2009). This is due to a "lead time" between donation and their being ready for transfusion, due to testing and processing. In other words, the blood center has to spend 48 hours of testing in order to comply with AABB's bacterial testing guidelines. Before this bacterial test, which was not implemented in the U.S. until 2004, the shelf life of platelets was 4 days (Fontaine et al., 2009). Therefore, we focus on $N = 3$ days here due to this case's practical relevance and manageable complexity. In recent research papers on perishable inventory management, the lifetime of the product is typically restricted to two periods, e.g., Deniz et al. (2010), Chung and Erhun (2013), Li, Lim, and Rodrigues (2009), Chen and Sapra (2008). Zhou, Leung, and Pierskalla (2011) do consider a shelf life of 3 days for platelets, and show existence of an optimal inventory policy incorporating dual modes of replenishment. We use the terms Young, Mature, and Old to differentiate among products that expire in 3, 2, and 1 period(s), respectively, and use the terms younger/youngest and fresher/freshest interchangeably. The products age at the end of each period, transitioning from Young to Mature, Mature to Old, and Old to outdated unless used to satisfy demand. We discuss the general managerial problem in Section 2.1 and our specific approach in Section 2.2.

2.1. Managerial problem

A significant majority of research on perishable goods assumes that demand is satisfied in order of arrival, and inventory is issued first-in-first-out (FIFO), i.e., oldest inventory is sold first, or last-in-first-out (LIFO), i.e., youngest inventory is sold first (Karaesmen et al., 2011; Nahmias, 2011). In these classical models, since demand is not age-differentiated, there is no benefit or penalty for satisfying a demand with younger or older goods. However, in the case of blood products, satisfying demand for a particular age of product with blood of a different age may affect patients. Furthermore, in many cases unsatisfied demand for platelets is "lost;" for example it may be satisfied by expediting from a third party due to the urgent need for the product. In this environment, there are three questions for the inventory manager: (i) The *replenishment* decision: "What should the *order quantity* for the youngest goods be?" (ii) The *allocation* decision: "Which demand should be satisfied?" (iii) The *issuance* decision: "Given the answer to question (ii), which units of inventory should be used to satisfy the demand?"

Finding an optimal policy is challenging for this general problem. Even within a restricted class of policies (e.g., an order-up-to policy in which demand is satisfied in order of arrival, under FIFO issuance) the optimal policy is state dependent: The order quantity varies in each period depending on the amount and age composition of on-hand inventory. Thus it is highly likely that one will have to account for the exact inventory of each age to determine an optimal policy; this remains an open problem when demand is age-dependent and substitution is possible. The problem becomes tractable if one restricts (i) the type of replenishment policies considered, (ii) the type of inventory allocation and issuance rules to implement, and/or (iii) the lifetime of the product (Deniz et al., 2010). In this paper, we study a replenishment policy that is used in blood inventory management, specify an allocation rule and an issuance rule based on current practice that is similar to the research literature on substitutable goods, and limit the lifetime of the product. In doing so we are able to develop an effective heuristic policy and generate insights for the general problem.

2.1.1. Replenishment decisions

Replenishing perishable inventories has been an important problem in the literature (Karaesmen et al., 2011). In our problem, a hospital blood bank manager needs to decide how many blood platelets to order every day while considering the 3 day shelf life of this expensive and critical product. In the literature it is common to restrict the replenishment decision to practical, easy-to-implement policies such as order-up-to policies or fixed-order-quantity policies (Nahmias, 2011). Such policies are also used in practice (Stanger, Yates, Wilding, & Cotton, 2012).

2.1.2. Allocation decisions

In this section, we discuss *allocation* decisions in platelet inventory management: In models with differentiated demand streams – age is the differentiating factor in our model – the decision-maker often has a choice as to which demand he or she may satisfy. We assume