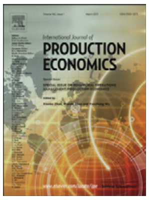
Int. J. Production Economics 143 (2013) 527–535

Contents lists available at SciVerse ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe



A model for performance evaluation and stock optimization in a kit management problem

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ARTICLE INFO

Available online 1 February 2012

Keywords:
Kit management
Performance evaluation
Correlated arrivals
Base-stock policy
Service logistics

ABSTRACT

In this paper we consider a kit planning problem where demand occurrences are not for individual items, but for kits (a group of items). Each kit contains an arbitrary number of items. Kit demands occur according to a Poisson process. Whenever a kit demand occurs, only one item from the kit is used and the rest is returned as unused. The item that will be used from the kit is not known in advance and the whole kit has to stay at the demand site for the whole duration. The used item is replenished through a stochastic supply system, with possible capacity limitation. This model has applications in health care (planning surgical implant inventories), and repair kit management systems. As a demand for a kit triggers simultaneous demands for the items within the kit, the individual demand arrival processes for the items in that kit are correlated. Therefore, finding the joint probability distribution of the number of items that are outstanding, and hence finding the probability of kit availability, is generally difficult. We can obtain these terms in a fairly explicit form under the assumption that an item which is not in stock when a kit demand occurs can be obtained through borrowing from an emergency supply channel. As soon as a unit of such an item becomes available, it is returned back to its original supply source. We also formulate an optimization problem where the expected holding cost of items is minimized, and pre-specified kit availability constraints are satisfied. Since the optimization problem is hard to solve, we provide a heuristic procedure for obtaining the stock levels, and test the quality of the heuristic.

1. Introduction and literature survey

Consider a medical center specialized in orthopedic surgeries related to the central nervous system, for example, spinal surgeries. Orthopedic operations require the preparation of sets of necessary items (surgical kits) to be used in operations. A kit consists of *tools* (hammer, plier, etc.) and *surgical implants* (for example, screws, rods, pedicle hooks). Tools in a surgical kit can be used repeatedly in many types of operations, as many operations would require same types of tools and the tool lifetimes are generally long. Surgical implants contained in the kit, on the other hand, would depend on the type of the operation carried out. A surgical kit contains several implants of the same type (say, several sizes of a hook type), but the exact size that will be used on a particular patient is often decided during the surgery. Therefore, in a particular operation only one implant is consumed and the remaining content of the kit (tools and unused implants) are sterilized and returned to medical center's storage. Since tools and implants are expensive items, the medical center would like to know how many units of each item to stock in the inventory, and the proportion of kit demands that can directly be satisfied from the shelf.

Another possible application is planning spare parts inventories to be used by repair crews. Upon arrival of a repair request, the repair crew prepares a kit of spare parts, without knowing which exact part will be used. The part to be replaced is known after the inspection of the malfunctioning unit at customer's site.

We can identify a number of inventory planning related issues with the above mentioned application: (1) customer demand (say, upon planning a surgery) occurs not for the individual tools or implants, but for a surgical kit, (2) only one implant from the kit is used in the surgery and the rest of the items are returned, (3) one item may be contained in more than one kit, as the formation of a kit depends on several factors, such as age, weight, height, etc. of the patient, and (4) from the time a kit is formed and sent for an operation, until the time that unused items are returned, none of the items in the kit can be used to satisfy other kit demands. From an inventory theoretic point of view, these characteristics lead to an interesting and challenging system environment.

In this article our aim is to provide a modeling and optimization framework for the kit planning problem described above.

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doi:10.1016/j.ijpe.2012.01.028

Our development consists of two major steps. First, given a particular inventory policy we define important performance measures for the availability of a kit, and describe an exact procedure for computing these performance measures. Then, we introduce an optimization model for the optimal stocking amounts of the individual items, and present a heuristic procedure, based on the exact computation of kit-availability measures, for finding the near-optimal stocking levels. For managing the inventory of the items, we employ an item dependent base-stock policy: a replenishment order is given as soon as the inventory position of an item drops below its base-stock level. Whenever a kit demand occurs, if any item within the kit is not available, then it is obtained exogenously through emergency channels (for instance, by borrowing it from a nearby medical inventory) with zero lead time. As soon as this item becomes on-hand available (after a possible return within a kit, or after replenishment) it is returned to the exogenous source. Essentially, this implies that items not available in the inventory are backlogged. In this study, our main objective is to minimize the long-run average cost of holding inventories satisfying a target probability of being able to form kits from available on-hand stock.

One important feature of our research is that the demands for sets of individual items are coupled. A coupled demand in our context means that when a demand occurs for a particular kit, all the items contained in the kit leave the stocking location together. The returns of items to the inventory are also coupled (with the exception of the item consumed in a demand), as the unused items return to the stocking location together. Since a kit demand triggers demand for a set of items, our paper is related to the literature where item demands exhibit a correlated behavior. In what follows we review the related literature in three categories: multi-item systems with correlated demand, Assemble-to-Order (ATO) systems, and service logistics models (specifically, repair kit planning problems and service tool inventory systems).

In an early paper Hausman et al. (1998) incorporate the correlation between item demands for the evaluation of order fill rates, and for optimizing stock levels for a single stage, discrete time system where unsatisfied demands are backlogged. In their paper, the dependency between item demands in each period is externally imposed by using multi-variate normally distributed random variables. Using a continuous time framework, Song (1998) considers a similar single stage model under coupled Poisson demand arrivals for the items. Song's (1998) formulation leads to an exact procedure for computing the order fill rates, whereas Hausman et al. (1998) present an approximate computation. Neither of these papers consider coupled returns of items.

Our research is closely related to literature on Assemble-to-Order (ATO) systems. In an ATO system, stock levels for individual items are maintained separately, but the customer demand occurs for subsets (final products) of items. Song and Zipkin (2003) provide a review of the literature on ATO systems. Song et al. (1999) consider an ATO model with possibility of backlogging of an item (delivered whenever the item becomes available) or lost sale, and derive item or order based performance measures. Song et al. (1999) define and analyze total order service (where a customer order is completely accepted or rejected) and partial order service (where a customer order may be partially accepted) models. Iravani et al. (2004) handle a model similar to Song et al. (1999) and present a matrix geometric based approach, coupled with approximations for computing fill-rate based performance measures. Song and Yao (2002) study a single product system with randomly distributed item replenishment lead times. They derive easy-to-compute bounds for several performance measures, and utilize them in finding near optimal base-stock levels. Investigation of an ATO system under lost-sales and non-exponentially distributed replenishment times is quite challenging. Hoen et al. (2011) consider an ATO system with lost-sales and deterministic lead times. Hoen et al. (2011) present easily computable and accurate approximations for the order fill rates based on the degree of coupling between demand streams.

Our paper is also related to the literature on service logistics. In a repair kit planning context, Teunter and Klein Haneveld (2002) consider inventory control for a service part by using a "remaining time order-up-to level" policy. Specifically, they determine the initial stocking level of the item, and then gradually decrease the order-up-to level as the remaining time in the planning horizon (until the end of the service contract) decreases. Teunter (2006) considers a model for finding the optimal set of parts that will be stocked in the kit before a tour of the repair sites. Teunter's (2006) formulation allows visiting multiple job sites before returning for re-stocking of the kit. Although the model and the analysis in Teunter (2006) are quite different than those in our paper, the nature of the heuristics employed in Teunter (2006) is similar to the heuristic proposed in Section 4 of our paper.

Service tool inventory systems are similar to ATO systems in the sense that a demand for a set of service tools resemble a customer demand for a final product with several sub-components. However, unlike ATO systems, in a service tool system all the tools in the tool set eventually return to inventory. Therefore, not only demands but also returns are fully coupled. Vliegen (2009) provides a comprehensive survey on service tools inventory management literature and on its related fields. Vliegen and van Houtum (2009) study a model in which the return times of tools from the demand site are deterministic and a partial order service discipline is employed. Vliegen and van Houtum (2009) first demonstrate that the order fill rate is almost insensitive to the exact distribution of the return times, and then propose two bounding models (based on Markov processes) for approximating the order fill-rate. There are two main differences between their model and the one studied in our paper. In our paper, *any unit* of an item borrowed from an exogenous source can be returned to that exogenous source once the item becomes available. In their model, the exact unit that was borrowed needs to be returned. This subtle but important difference enables us to derive exact expressions for the performance measures. The second difference is due to the fact that in their model, all the tools return to the inventory together, whereas in our model one of the items that is consumed in the operation follows a different excursion from the rest of the items in the kit. Note that Vliegen and van Houtum (2009) present an evaluative model. That is, in Vliegen and van Houtum (2009) the fill rate performance of the system is evaluated for a given set of item stock levels, but these stock levels are not optimized. Our model can be used as an approximation for the system in Vliegen and van Houtum (2009). If we set the probability that an item will be consumed at the demand site as zero, then all the items return to inventory together, and the system becomes identical to Vliegen and van Houtum (2009) except for the case that we do not keep track of the specific item borrowed from another location.

In this paper we make three contributions. First, we present a model for managing medical tools and implants inventories that incorporates several realistic characteristics of the system. Second, we obtain exact product form expressions for the kit-readiness probability (the probability that a kit can be formed from the on-hand inventory), an important performance measure. And third, we propose and test a heuristic for finding the base-stock levels. We should note that the optimization model that we consider is more challenging than the models handled in previous studies, as in our optimization model we allow the possibility of multiple kit types with overlapping items.

The rest of the paper is organized as follows. In Section 2, we present the mathematical description of our model, and introduce