



Emergency orders in the periodic-review inventory system with fixed ordering costs and compound Poisson demand



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ABSTRACT

Emergency orders have shorter lead times but incur extra costs compared to normal orders. We present a discrete-time Markov decision model where normal orders are issued according to a reorder point policy with a fixed order quantity, whereas emergency orders are controlled by a state-dependent reorder point policy with a target stock level. A rapid policy iteration algorithm is used to find and evaluate the policy that minimizes the long-run average cost per review period. In addition to fixed and variable costs for normal and emergency orders our model includes linear holding and backorder costs. The review period is of any given length. Neither the normal order nor the emergency order lead time are required to be integer multiples of the review period.

The numerical study shows that the mixed policy found from our Markov decision model generally outperforms the best pure replenishment policy using either only normal or only emergency orders. Our model provides results that are similar to or slightly better than the results obtained with earlier models in the literature. Moreover, because our model accommodates compound Poisson demand, we are able to demonstrate that considerable cost reductions can then be obtained with the mixed policy when compared to the best pure replenishment policy. Finally, using sensitivity analysis we observe that a result on when a mixed policy is most beneficial, which has been found to hold for the simpler model without fixed ordering costs, seems to hold also for the more complex model that we investigate.

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1. Introduction

Today's competitive business environment highlights the importance of agile and flexible supply chains. To support the fulfilment of these requirements, inventory management often involves emergency-order procedures in addition to the normal ordering procedures. Emergency orders are supposedly more expensive than normal orders but may nevertheless be warranted by their ability to hedge against demand uncertainty. In case of unusually high demand during a normal-order lead time and facing the risk of shortages, an emergency order with a shorter lead time can then be issued to replenish the inventory. The shorter lead time may be achieved by using delivery shipments by air instead of by surface transportation, by buying from a retailer instead of from the manufacturer, or by buying from outside instead of producing internally. Moreover, in some industries there are suppliers who differ in terms of the prices and lead times that they offer.

This paper presents a new model for determining a good policy for issuing emergency and normal orders in a single-item inventory system in which both order types incur fixed costs and shortages are backordered. The specification of the new model assumes periodic review where the review period can be of any given length. Hence, a sufficiently short review period can be used to approximate continuous review. Neither the normal order nor the emergency order lead time need to be an integer multiple of the review period. In [Section 2](#) we specify how the lead times and the review period need to be related.

Our model differs from previously studied periodic review models. [Sethi et al. \(2003\)](#) assume that the lead times of emergency and normal orders are one and two review periods, respectively. [Lee et al. \(2006\)](#), [Huggins and Olsen \(2010\)](#) and [Chen et al. \(2012\)](#) assume zero lead time for emergency orders. [Veeraraghavan and Scheller-Wolf \(2008\)](#) and [Sheopuri et al. \(2010\)](#) assume only that the former lead time is shorter than the latter, but they ignore fixed ordering costs. Fixed ordering costs are also ignored by [Song and Zipkin \(2009\)](#) who allow stochastic lead times.

[Moynadeh and Nahmias \(1988\)](#) and [Minner \(2003\)](#) review the literature on multi-supplier inventory models with fixed ordering costs. The first reference shows how the standard single-item

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continuous review policy specified by a reorder point and a fixed order quantity can be extended to incorporate both normal and emergency orders by specifying the two policy variables for each order type. The model proposed is approximate. Johansen and Thorstenson (1998) present Markov models for determining optimal values for these variables when demand is Poisson and at most one order of each type may be outstanding at any time. They assume that emergency orders have a much shorter lead time than normal orders and they allow issuing an emergency order only when one normal order is already outstanding. Their simple model assumes that the reorder point for emergency orders is independent of the remaining lead time of the normal order outstanding, but they also present a Markov decision model allowing the reorder point to depend on when the normal order will be delivered.

A similar setting with fixed ordering costs for both types of orders is considered by Gaukler et al. (2008). They assume staged and stochastic normal order lead times. Staged lead times imply that progress information can be updated at several stages during the total lead time. Their focus on stochastic lead times seems to be driven by the misconception that information about lead-time progress has no value when lead times are deterministic. An approximate analytical model is used to show that a near-optimal emergency order policy is of the reorder point type for each stage of the normal order lead time. Simulation is then used to evaluate the effect of issuing fixed-size emergency orders based on normal order progress information.

Axsäter (2007) presents a heuristic decision rule for issuing emergency orders in a continuous review setting. His rule is based on actual information about the remaining lead times of outstanding orders and it has no restriction on the number of orders outstanding. Like in this paper, he allows demand to be compound Poisson. However, he only provides numerical examples having pure Poisson demand. Hence, for pure Poisson demand we use his reported results, which include those of Johansen and Thorstenson (ibid.), as the basis for comparisons with our new results. In order to simplify the exposition and the presentation of our numerical examples with compound Poisson demand we assume that customer demands follow a geometric distribution. This compounding distribution has also been observed in practice (Johnston et al., 2003). Mohebbi and Posner (1999) also treat an inventory system with emergency orders under compound Poisson demand but with lost sales.

Recently, Axsäter (2014) notices that the above heuristic decision rule will work less well in situations where a suggested emergency order provides a small expected net profit. In order to avoid such situations he introduces the option to postpone deciding whether or not to issue an emergency order. He suggests to incorporate this option by letting emergency orders be evaluated and initiated in a periodic review system with review period denoted by T . Upon a review point of this system his improved decision rule prescribes to issue an emergency order of the size maximizing the expected net profit if this emergency order provides a positive expected net profit which is larger than the maximum expected net profit obtainable for an emergency order with lead time prolonged by kT . He assumes in his numerical examples that $k=1$, that emergency orders incur no fixed cost and that demand is pure Poisson.

Other related recent references include Zhou et al. (2011) who treat a periodic review inventory system for a fixed life-time product. With dual sourcing they employ a pre-determined order amount for its normal order and a target-stock level for its emergency order. Alvarez et al. (2013) consider emergency orders as a service differentiator between customer classes when a spare part is out of stock. They do not consider fixed ordering costs and assume base-stock policies, pure Poisson demand and exponentially distributed normal order lead times.

The main contribution of our paper is a model and computational procedure for obtaining good ordering policies that combine normal and emergency orders while allowing for both fixed ordering costs and compound Poisson demand. Our model is an extension of the model in Johansen and Thorstenson (1998). However, the current model has the following important characteristics that distinguishes it from the earlier one: Periodic review is used (which for practical applications is more realistic), order arrivals are not approximated by a Bernoulli process but are Poisson, compound Poisson demand is accommodated, the emergency order lead time is not required to be small compared to the normal order lead time, the review period is not required to be equal to the lead time for emergency orders, an inventory position is used as the basis for making emergency order decisions, and there is no enforcement of emergency orders when backorders exceed a given level. Given the assumptions stated, the current model is exact and includes accounting for the correct costs incurred by the demand process. These characteristics represent considerable relaxations and developments compared to the assumptions used in the earlier model.

Thus, our current model can be used to evaluate the cost savings that are obtainable from combining normal and emergency orders in a periodic review setting with fixed ordering costs. The numerical study shows that such savings might be considerable, especially when customer demand is volatile and/or the average costs of the pure emergency and normal replenishment policies are of similar magnitudes. Compared to the method suggested in Axsäter (2007) our method is computationally more efficient. With only a few exceptions the performance of our method is either at the same level as or, particularly when demand is volatile, significantly better than the results obtained with his method.

This paper is organized as follows. Our modeling is divided into four parts in Section 2. First, assumptions about lead times, costs, and demands are introduced. Next, in Section 2.1 we describe three pure replenishment policies used for initialization and benchmarking purposes. The pure policies consist of an emergency order policy characterized by a reorder point and a target stock level (a.k.a. an order-up-to level), and two reorder point policies for normal orders with either a fixed order quantity or a target stock level. The last two parts of Section 2 present a Markov decision model for the combination of normal and emergency orders followed by a specification of its solution by a policy-iteration algorithm (PIA). Some computational details are further specified in Appendices A and B. Our numerical study is presented in Section 3 and includes Tables 1–4. First, we introduce a base case and present its computational results in detail. Next, we use test beds from the literature referred to above and compare with our new results. In addition, we compute completely new results for a range of compound Poisson demand cases. Finally, we carry out a sensitivity analysis with respect to fixed and variable costs. In this analysis we also investigate a result stated in Veeraraghavan and Scheller-Wolf (2008) regarding when the largest relative cost improvement can be obtained with the combined order policy. Section 4 provides concluding remarks.

2. Modeling

The inventory system is controlled by issuing normal replenishment orders and emergency orders. They have constant lead times L and l , respectively, and $L-l$ is a multiple $\bar{n} \geq 1$ of the review period τ . It is not required that l/τ is an integer, and $l=0$ is not excluded. The fixed costs incurred by issuing a normal order and an emergency order are K and k , respectively. The difference between the variable costs per emergency-ordered unit and per

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