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A Markov decision process-based policy characterization approach for a stochastic inventory control problem with unreliable sourcing

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ABSTRACT

We consider a single-product periodic-review inventory system for a retailer who has adopted a dual sourcing strategy to cope with potential supply process interruptions. Orders are placed to a perfectly reliable supplier and/or to a less reliable supplier that offers a better price. The success of an order placed to the unreliable supplier depends on his supply status that has a Markovian nature. The inventory control problem for this unreliable supply chain is modeled as a discrete-time Markov decision process (MDP) in order to find the optimal ordering decisions. Through numerical experimentation, the structure of the optimal ordering policy under several cost scenarios and different supplier reliability levels is determined. Four basic policy structures are found and are referred as case 1: order only from the unreliable supplier; case 2: order simultaneously from both suppliers or only from the unreliable supplier depending on the inventory level; case 3: order from one or the other but not both suppliers simultaneously; and case 4: order only from the reliable supplier. For all cases, (s, S)-like policies characterize perfectly the optimal ordering decisions due to the existence of the fixed ordering cost. Further experimentation is done to study the effects of changes in several system parameters (cost parameters such as fixed ordering cost, unit purchasing cost, backorder cost as well as the supplier reliability level) on the ordering policy and cost of the system.

1. Introduction

Uncertainties in the supply process should be taken into consideration when making ordering decisions in order to manage inventories in an effective way and assure a desired customer service level. Uncertainty might be present in the quantity, quality or timing of orders delivered due to several factors. Possible internal causes include random machine/equipment breakdowns, process adjustments, a heavier-than-normal workload, shortages in the capacity of the supplier or material availability, labor strikes, etc. External causes include transportation disruptions due to accidents or bad weather conditions, natural disasters, or market-related causes such as price fluctuations, price subject to inflationary increases, scarcity of goods, etc. For instance, exposure to heat might affect the quality of perishable food, a traffic accident can delay the delivery of an order, and fire could destroy product partially or entirely. It is possible that the market price is so high that some companies find it prohibitively expensive to purchase the product (Parlar and Berkin, 1991). Or in case of a scarcity of goods, a supplier may prefer to satisfy the demand of major players at the expense of minor players (Arreola-Risa and Decroix, 1998). Such factors can result in changing the status of a source of supply from 'available' to 'unavailable' (or in other terms, from 'on' to 'off', or 'up' to 'down'), hence interrupt the supply process (Mohebbi, 2004). Proactive firms adopt several supply-side tactics to cope with potential supply chain disruptions such as sourcing from multiple suppliers or holding more inventory (Tomlin, 2006). Due to the risks arising from the dependency on a single supplier such as uncertainty in the quality and quantity of the supply, supplier diversification (i.e. using multiple suppliers for the same product) is increasingly used by the buyers (Swaminathan and Shanthikumar, 1999). In addition to reducing the risk of no or partial delivery of the order, using multiple suppliers has other advantages such as creating competition that can yield better quality and/or better price (Anupindi and Akella, 1993). Even when there is no risk for supply disruptions, many firms prefer to use dual sourcing where one supplier offers faster product delivery (i.e. better responsiveness) at higher sourcing cost compared to the other supplier. In this case, the firms usually

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get the greater part of their products from the cheaper supplier with longer lead time, but turn to the more expensive supplier with expedited service when needed (see e.g. Veeraraghavan and Scheller-Wolf, 2008; Allon and Van Mieghem, 2010; Sheopuri et al., 2010; Arts et al., 2011).

We consider an infinite-horizon, single-product, periodic-review inventory system for a retailer who has adopted a dual sourcing strategy to cope with potential supply interruptions. Amongst the two suppliers, one is perfectly reliable while the other is not but offers a lower price. The unreliable supplier can be in "up" or "down" states modeled as a two-state Markov process. Supplier availability at the beginning of period does not guarantee the successful delivery of the product by the end of period because the lead time is not zero and so there is a risk that the supplier becomes unavailable when the order is still in progress. An order in progress is canceled if the supplier ends up being unavailable by the end of period. When the unreliable supplier is down, the retailer's only option is to source from the reliable supplier. Fixed costs of ordering are considered along with the unit purchasing, holding and backordering costs.

We formulate the problem as a Markov decision process (MDP) in order to determine the optimal policy which is a list of the optimal action to follow (i.e. the optimal order quantities from both suppliers) in each possible state of the system. While optimal, the MDP policy does not provide managerial insight into the structure of the policy. Therefore in order to develop this insight, we use the process of policy characterization to define a generalizable ordering policy in a structured way using a few control parameters. This process consists of the following steps. First, we find the optimal policy using the MDP for a set of problem instances in an extensive numerical experimentation over a range of cost configurations of the system and different supply unreliability levels. Then, through careful observation of MDP solutions, we identify candidate policy structures that mimic the optimal decisions in each state. The accuracy of the characterization can be found by comparing the cost found using the characterization with that of the MDP optimal policy.

Characterization of the policy is important, because it makes it easier to interpret the structure of the policy. The effects of changes in system parameters on the optimal ordering decisions can be easily seen through the characterized policies by observing how their structure and/or the values of the control parameters change. To the best of our knowledge, none of the published work provides all the different optimal policy structures derived in this paper for similar inventory systems under supply disruptions.

The contents of the paper are organized as follows: Section 2 provides a review of work published on inventory models under supply interruptions. Section 3 describes the unreliable supply problem considered for a retailer with two suppliers, and provides the MDP formulations of the inventory control and sourcing problem for the retailer. Section 4 introduces the MDP-based characterization procedure that is employed to convert the optimal ordering decisions into a policy that can be defined using a few control parameters. In Section 5, first, through an empirical analysis, various types of optimal ordering policy structures that exist for such an unreliable supply chain are derived. Then, further computational study is done to show the impacts of changes in several system parameters on the optimal ordering policy structure and/or optimal cost. Section 6 summarizes our findings and suggests directions for further research.

2. Related literature

With the trend towards having multiple suppliers, there is a wealth of literature dealing with dual sourcing however we focus here on the more limited works that deal with some form of unreliable supply. Most of this assumes a single-period problem. For example, Serel (2008) identifies the optimal policy for the case with two suppliers, one having the risk of being unavailable while the other guarantees supply of any desired amount. Chopra et al. (2007) and Giri (2011) consider a single-period model where the primary supplier provides cheaper yet uncertain supply while the secondary supplier is perfectly reliable but the retailer cannot order more than the quantity reserved in advance. Chopra et al. (2007) develop a model for a risk-neutral retailer while Giri (2011) derives the optimal dual sourcing strategy for a risk averse retailer. Tomlin (2006) considers an infinite-horizon periodic-review model, where the unreliable supplier is modeled as an infinite-state discrete-time Markov process, where the states indicate whether the supplier is up or if down, for how many periods it has been down since the last up state. They find that the supplier reliability and the nature of the disruptions (e.g., frequent but short versus rare but long) are key determinants of the optimal strategy.

The existence of many sources of supply disruption has motivated the derivation of models of supply disruptions. Existing models differ with respect to several characteristics such as the sourcing strategy (a single supplier vs. two or more suppliers), the timing of the inventory control (periodic-review vs. continuous-review inventory systems), the nature of product demand (deterministic stationary or non-stationary vs. stochastic), the nature of supply lead time (zero lead time or positive deterministic vs. stochastic lead time), the existence of fixed set up/ordering cost, the nature of the planning horizon (single vs. multiple periods, finite vs. infinite horizon) as well as the form of the supply uncertainty (i.e. how the unreliable suppliers' availability process is modeled). Supply uncertainty may take several different forms, as explained below.

Random durations of on/off periods refer to stochastic durations of the supplier's on and off periods (Gupta, 1996; Parlar, 1997; Arreola-Risa and DeCroix, 1998; Mohebbi, 2003, 2004; Mohebbi and Hao, 2008). Some work assumes that an order placed when the supplier is on is not affected if the supplier goes to off mode during the processing of the order (Mohebbi, 2003, 2004) while in other work, an outstanding order is interrupted when this occurs and is restarted as soon as it becomes available (Mohebbi and Hao, 2008). In Arreola-Risa and DeCroix (1998), an order can be placed only if the supplier is available and the order delivery is instantaneous.

Random yield means that when an order is placed, the amount received may not be exactly equal to the one ordered. The fraction of order delivered is represented by a random variable. In some models with random yield, a random fraction of the order is delivered immediately (i.e. 0 lead time) and the rest is canceled (e.g. Henig and Gerchak, 1990; Gerchak and Parlar, 1990; Parlar and Wang, 1993) while in other models, the rest is delivered next period (e.g. Moinzadeh and Lee, 1989; Bassok and Akella, 1991). Anupindi and Akella (1993) analyze both random yield situations.

Supply with Bernoulli-nature is a special case of random yield where the yield variable (the fraction delivered) takes the value of either 0 or 1, i.e. full delivery or none at all. For example, if the order is made to an external supplier, it is possible that the ordered quantity may not reach its destination due to some unforeseen circumstance. Another example is that of a perishable product such as blood or some types of food which may no longer be usable when it reaches its destination due to transportation delays or bad weather conditions (Ozekici and Parlar, 1999).

Unreliable delivery time refers to stochastic lead times, a common problem in industry. Anupindi and Akella (1993) and Swaminathan and Shanthikumar (1999) consider unreliable suppliers who either deliver the entire order immediately or the next period. Kelle and