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Infinite-horizon models for inventory control under yield uncertainty and disruptions

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ABSTRACT

We consider a firm facing supply chain risk in two forms: disruptions and yield uncertainty. We demonstrate the importance of analyzing a sufficiently long time horizon when modeling inventory systems subject to supply disruptions. Several previous papers have used single-period newsboy-style models to study supply disruptions, and we show that such models underestimate the risk of supply disruptions and generate sub-optimal solutions. We consider one case where a firm's only sourcing option is an unreliable supplier subject to disruptions and yield uncertainty, and a second case where a second, reliable (but more expensive) supplier is available. We develop models for both cases to determine the optimal order and reserve quantities. We then compare these results to those found when a single-period approximation is used. We demonstrate that a single-period approximation causes increases in cost, under-utilizes the unreliable supplier, and distorts the order quantities that should be placed with the reliable supplier in the two-supplier case. Moreover, using a single-period model can lead to selecting the wrong strategy for mitigating supply risk.

1. Introduction

The need for quantitative models addressing supply chain risk management is growing with the global expansion of supply chains. In this paper, we provide such a quantitative model by focusing on supply uncertainty, a particularly important aspect of supply chain risk and one that has received a great deal of attention in both the research and practitioner communities in recent years. Literature on inventory management contains numerous single-period models, and these models often provide excellent results. However, when supply disruptions are possible, single-period models can grossly underestimate the risk that disruptions pose to the system. In this paper we demonstrate that single-period models do not generate solutions that provide enough protection from disruptions.

We consider two types of supply uncertainty: yield uncertainty and disruptions. Yield uncertainty occurs when the quantity of supply delivered is a random variable, typically modeled as either a random additive or multiplicative quantity. Disruptions occur when supply is subject to partial or complete failure. Disruptions can be more difficult to analyze than yield uncertainty because the state variables (e.g., inventory level) are typically more strongly correlated over time under disruptions than under yield uncertainty. Truncating the time horizon to consider only a single period makes this analysis easier and may allow for closed-form results; several papers employ this approach (e.g., [11,12,39]). However, as we demonstrate, truncating also underestimates the disruption risk.

Analysis of systems with yield uncertainty provides solutions that parallel classical newsboy results; that is, the optimal order level is the sum of the mean demand (cycle stock) plus an additional amount determined by the cost and variability parameters (safety stock). However, managers have other options besides using safety stock to mitigate supply uncertainty. Other strategies include acceptance, when protecting against supply uncertainty is too costly and the best policy is to ignore it, and mitigation through the use of backup suppliers [37], product substitution [5], or other alternatives to satisfy demand.

Supply uncertainty has gained increased attention in recent years. Notable events such as the 9/11 terrorist attacks or major natural disasters have brought focus to supply chain disruption studies. One example of how a company can recover quickly from disruptions when proper disruption management techniques are used is Wal-Mart's performance after the Hurricane Katrina disaster in the Gulf coast. Wal-Mart has personnel dedicated to tracking potential disruptions and planning for or coping with them. With Katrina approaching, Wal-Mart overstocked its nearby distribution centers with items it knew would be needed (such as bottled water, Pop-Tarts, and generators), and after Katrina struck, its strong transportation network allowed it to

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respond quickly to deliver supplies and reduce the disruption to its supply chain. Without this planning, Wal-Mart's recovery time would have been much longer and much more costly for the company [18]. Home Depot, too, had learned from past hurricanes and was better prepared to handle the demand after the disruption caused by Katrina. They stocked up on supplies that would be demanded by customers, as well as supplies necessary to get their stores back up and running [7]. Both of these companies continually address disruption risk and had policies in place for coping with the impending disaster. This proactive planning for disruptions allowed them to efficiently prepare for and recover from the hurricane.

Supply disruptions can also be caused by factors other than major catastrophes. More common incidents such as snow storms, customs delays, fires, strikes, slow shipments, etc. can halt production and/or transportation capability, causing lead time delays that disrupt material flow. As supply chains grow globally, there are higher chances for such delays. Capacity shortfalls at a supplier may also cause disruptions, particularly if a firm is not the supplier's highest-priority customer. Sometimes disruptions are a planned part of a supplier–retailer relationship based on contracted material availability. If, for example, a supplier promises an 80% material availability in their contract with a retailer, then the retailer can anticipate that its supply will be unavailable up to 20% of the time. Additionally, suppliers may be internal to a firm, and improving process reliability may be more costly than mitigating disrupted supply through inventory use.

Ultimately, supply disruptions are not uncommon, and firms must anticipate them. Not all firms have the buying power that Wal-Mart and Home Depot do to plan for impending disruptions, and not all disruptions have advanced warning. Thus ongoing mitigation policies must be considered, and we model disruptions with a stationary probability of occurrence in this paper. This could represent a single disruption source or multiple aggregated sources, but it characterizes the ongoing risk that a firm must continually anticipate.

One paper that models supply uncertainty in a single-period setting is that of Dada et al. [12]. The authors model a retailer with multiple unreliable suppliers in a newsboy setting, where inventory (from one or multiple suppliers) is used to mitigate generally distributed supply uncertainty, and they include disruptions as a possible realization. While their model yields excellent results for continuous supply distributions, we will demonstrate that if the firm is capable of planning proactively for future periods and the disruption risk is significant (the penalty costs for shortages are high and/or disruptions have a high probability of occurrence), the optimal base-stock levels are underestimated by single-period models. Tomlin and Wang [39] also employ a single-period model to examine dual-sourcing and mix-flexibility decisions when disruptions are present, as do Babich et al. [4] for multiple competing suppliers. We will demonstrate that single-period models also underestimate the need for backup suppliers, because they do not adequately capture the long-term risk of stocking out for multiple periods.

Another single-period model for supply disruptions is presented by Chopra, Reinhardt, and Mohan [11]. The authors consider yield uncertainty as well as disruptions in a single-period setting. They compare their optimal solution to that of a "bundled" solution, in which disruptions are not separately accounted for and the aggregate variance of the delivered quantity (accounting for both yield uncertainty and disruptions) is used for the solution. They demonstrate the error and increased costs incurred by bundling the two sources of uncertainty. We stress that one should not, as some authors have, interpret Chopra et al.'s work as a justification for ignoring one source of uncertainty when both are present (i.e., for optimizing them separately). Rather, the paper highlights the necessity of accounted for the two types of uncertainty correctly, as multiple factors affecting the same system, rather than treating them as a single random process.

In this paper, we illustrate the importance of considering multiple time periods when disruptions are present, using a model similar to that of Chopra et al. [11]. Our insights also apply, at least approximately, to other single-period disruption models, such as those of Dada et al. [12] or Tomlin and Wang [39].

Disruptions have a significant impact on future periods, and planning for these disruptions can have a significant impact on order quantities. Therefore we consider a multiple-period (in particular, infinite-horizon) model. Note that single-period models may be appropriate in some cases; for example, if product is perishable and can only be used in one period, or if a period is very long (e.g., the length of an entire selling season) and only one order may be placed to cover the season. However, single-period models are also used to find approximate solutions for the case when inventory may be carried period-to-period, and disruptions may last for relatively short periods. Therefore we focus on a system where orders may be placed periodically and disruptions may occur in any period, and assume that the length of one period is the same in either the single- or multi-period model. This allows us to demonstrate the importance of considering multiple periods if inventory may be carried and proactive measures may be taken.

We consider both a system with one unreliable supplier, as well as a system with one unreliable supplier and a second, perfectly reliable (but more expensive) supplier. We compare the costs of the system if the exact cost is used to optimize the decision variables with the cost if a single-period model is used. We demonstrate that our infinite-horizon model leads to solutions that provide lower expected costs, and that single-period models can lead to incorrect overall strategies for supply risk mitigation (e.g., acceptance instead of mitigation using alternate suppliers).

The remainder of the paper is structured as follows: Section 2 reviews the related literature, Section 3 presents the analysis for a single supplier and numerical comparisons of the exact and approximate solutions, Section 4 presents the same for the case in which a second supplier is available, and Section 5 presents conclusions and insights.

2. Literature

In this section we highlight literature focused on supply chain risk management, specifically focusing on papers considering mitigating the risk of supply disruptions or yield uncertainty. The terrorist attacks in 2001 motivated literature focusing on catastrophic disruption risk. Snyder et al. [32] thoroughly review supply disruption literature and discuss the significant growth of the field over the past decade. Sheffi [28,29] and Simchi-Levi et al. [30] stress the importance of sharing risk throughout the supply chain and the dangers of disruptions to just-in-time (JIT) systems. They indicate that JIT systems can lack buffers for supply uncertainty and can be at high risk for interruption of material flow. Lean methods in supply chain management advocate the reduction of excess suppliers, but if a company reduces to too narrow of a supplier base it leaves that company at risk if something happens to disrupt the production of one or all of those few suppliers.

Tang [36] provides a review of initiatives in supply chain risk management and cites the need for more quantitative models. He suggests that global growth of supply chains has made them more susceptible to uncertainties, and that more models are needed to