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The lead-time reliability paradox and inconsistent value-of-reliability estimates

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ABSTRACT

The value-of-reliability (VOR) reflects the savings in inventory-system costs from more reliable (less variable) lead times. Previous studies have revealed that more reliable, but positively skewed, lead times could actually increase optimal safety inventory when the probability of satisfying all demand during a replenishment cycle drops below 70%. Researchers claim that this paradox affects most firms and that it explains the inconsistent VOR estimates found in the transportation economics literature. Our investigation reveals that firms interested in high product availability may safely ignore the paradox and that less lead-time variability consistently increases VOR, the paradox notwithstanding.

1. Introduction

The inconsistent value-of-reliability (VOR) estimates found in the transportation economics literature over the past 25 years indicate the difficulty that shippers face when trying to determine the economic value of reliable lead times. The recent initiative by Massachusetts Institute of Technology's Global Ocean Reliability Initiative (Fransoo and Lee, 2013; Johnson and Dupin, 2012), along with current industry commentary (e.g., Drewry Supply Chain Advisors, 2013), reaffirm the significance of the problem. This state of affairs inspired Dullaert and Zamparini (2013) to consider an anomalous lead-time phenomenon, which was first reported by Song (1994), as a novel explanation for the wide variety of VOR figures obtained in empirical transportation research. Song (1994) revealed that more lead-time reliability or, equivalently, less lead-time variability, could unexpectedly increase the optimal safety inventory. Chopra et al. (2004) investigate this paradox of lead-time reliability, hereafter the "paradox". They found that the paradox appears when the cycle service level (CSL), defined as the probability of satisfying all demand during a replenishment cycle, is below some threshold near 70% and when an asymmetrical (positively-skewed) distribution characterizes demand during lead time (DDLT).

In light of such conditions, the potential of the paradox to explain VOR inconsistency appears promising for two reasons. First, empirical evidence has shown that lead-time distributions often exhibit positive skewness (Das et al., 2013; Johnson and Dupin, 2012; Piercy and Ballou, 1978; Tyworth and O'Neill, 1997), which means that lead-time demand distributions are likely to have the same attribute. Second, Chopra et al. (2004, pp. 3–4) claim that most firms operate with CSLs below the 70% threshold. They based this claim on the product fill rate, which measures the fraction of annual unit demand that is met from inventory. They argued that most firms seek high levels of product availability—with product fill rates in the 97–99% range, and that these fill rates imply CSLs in the 50–70% range.

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Dullaert and Zamparini (2013, pp. 191, 199) continued this line of research. They studied the paradox's relationship with VOR assessment in a real-life setting and concluded that the paradox explains the wide-variety of VOR estimates, which includes negative values. We re-examine this claim, as well as the Chopra et al. (2004) claim about the underlying practical significance of the paradox, by expanding the analysis to consider two important product availability dimensions: fill rates and shortage costs. Our investigation makes the following contributions to the transportation and logistics literature. We show that more lead-time reliability always increases VOR. We do so by using the Dullaert and Zamparini's (2013) field experiments to consider product availability and to reveal the necessary conditions for high product availability (product fill-rate) targets to result in low CSLs and the consequent implications for VOR estimation. Finally, we show why the firms that seek high levels of product availability can safely ignore the paradox.

The rest of the paper progresses as follows: Section 2 reviews the extant literature; Section 3 investigates the effect of the paradox on VOR assessment; Section 4 examines the argument that most companies are exposed to the paradox; and Section 5 presents the conclusions.

2. Literature review

Song (1994) investigated how optimal base-stock levels respond to lead-time uncertainty in a simple inventory system with no fixed costs, no pipeline stock, and complete backorders. The system setting included a compound Poisson demand process coupled with a sequential lead-time process. In this scenario, orders never crossed and lead times were dependent. The study compared two systems and showed that the system with a stochastically larger lead time may not necessarily have a higher optimal average cost, because variability effects sometimes dominate (Song, 1994, p. 612). By contrast, the system with more variable lead time always has a higher long-run average total cost for any fixed base-stock policy.

Chopra et al. (2004) investigated the effect of lead-time uncertainty on reorder points and safety stock when demand and lead time are represented by independent and identically distributed random variables. They showed that the paradox appears when CSLs are below 70%. They argue that the paradox is significant, as "...most firms in practice operate at cycle service levels in the 50–70% range, rather than the 95–99% range that is often assumed" (p. 3). They conceded that "...managers often focus on the fill rate as a service quality measure" (p. 4). Using computational evidence, they showed that most firms aim for product fill rates between 97% and 99% and that these service targets imply CSLs between 50% and 70%. Their claim also supported the conclusion that "...for cycle service levels where most firms operate, the normal approximation erroneously encourages managers to focus on reducing the variability of lead times when they would be better off reducing lead-time itself" (p. 4). Many researchers have cited this conclusion as evidence of the flaws of the normal distribution and thus the importance of considering other distributions, such as the gamma, to characterize lead times (e.g., Bischak et al., 2013; Fang et al., 2013; Käki et al., 2013; Warsing et al., 2013).

Wang and Hill (2006) extended the Chopra et al. (2004) study by adding granularity to the CSL range in which the paradox has an effect. They identified a "counter" zone in the 50–60% range, where safety stock increases in response to better lead-time reliability, and a "recursive" zone in the 60–70% range, where safety stock increases and then either recursively decreases or remains constant.

Song et al. (2010) investigated the behavior of optimal long-run average costs in response to stochastically less variable lead times. Their setting encompassed a continuous review system, a single item, a pure Poisson demand process, and a sequential, dependent lead-time process. They noted that Song (1994) had previously studied a special case of the continuous-review system considered in the Song et al. (2010) paper and that Chopra et al. (2004) supported Song's (1994) findings. Additionally, Song et al. (2010) found that "...less variable lead-time or lead-time demand *always reduces the system cost*" (p. 68).

Blackburn (2012) developed a way to calculate the marginal value of lead time for a given lot size, CSL, and lead time. He defined the marginal value of lead time as the change in unit inventory costs per unit change in lead time. The expected total annual cost expression includes costs for holding pipeline, safety, and cycle inventories, ordering, backorders, and production. Blackburn also constructed a marginal value of time measure by dividing the marginal value of lead time by the annual cost of goods sold. He considered the lead-time mean as linear in the variance of lead time, and the standard deviation of lead time. His quantitative examples demonstrated that for functional products, the marginal value of time "...tends to fall within a range of 0.4–0.8% of unit product cost per week of lead-time change," which led him to conclude that "inventory related costs, when measured as a percentage of unit cost are relatively insensitive to changes in lead-time" (p. 403).

Fang et al. (2013) also developed expressions for the marginal values of the lead-time mean, the lead-time variance, and the demand variance to assist practitioners in determining the relative effectiveness of modifying these supply and demand attributes. They did not assume that order quantity (Q) and CSL policies were necessarily optimal, but excluded pipeline stock holding cost and production cost in their expected total annual cost function. Additionally, they considered correlations between the lead-time mean and variance and found that the relative effectiveness of reductions in the lead-time mean versus the variance depends strongly on these correlations.

Bischak et al. (2013) developed an analytic model of expected costs that uses a novel approximation of the effective lead-time distribution when replenishment orders arrive out of sequence. This total annual-cost model included costs for holding safety and cycle inventory, ordering, and backorders. The setting encompassed positively skewed (gamma) distributions of demand and lead time. They found that the optimal expected total annual cost for a periodic review system was sensitive to