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The inventory billboard effect on the lead-time decision

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ABSTRACT

This research brings together two important research streams: lead-time management and the inventory billboard effect. While traditional inventory theory, which assumes that demand is independent of the average on-hand inventory, recommends that lead-time be reduced to the lowest level possible, it is clearly not the case when inventory exhibits the billboard effect, which refers to the demand stimulating effect of inventory. We use analytical models to examine the firm's optimal lead-time decision in the presence of the inventory billboard effect in two scenarios: with and without inventory based competition. We begin with the single firm scenario, where a firm employs the base stock policy for the infinite horizon continuous-review inventory problem with a deterministic lead-time and inventory dependent demand. The firm's decisions are to choose the optimal lead-time and the corresponding base stock level to maximize its expected profit rate. We find that the inventory billboard effect favors a long lead-time, because a long lead-time results in a higher inventory level, which in turn induces more demand. We then consider the case where two firms compete on inventory for customer demand. We completely characterize the unique Nash equilibrium and provide closed-form solutions, which allow us to conclude that inventory based competition pressures both firms to increase the lead-time. Our numerical studies show that the extent to which demand depends on inventory amplify the impact of competition on the optimal decisions and the associated profit. Our findings suggest that lead-time reduction, although widely advocated by popular production philosophies such as Just-in-Time, has to be carefully evaluated when inventory exhibits billboard effect.

1. Introduction

Lead-time has long been recognized as a crucial component of inventory management. Its importance has been well explained in operations management textbooks: it affects the degree of uncertainties in the demand during lead-time, which in turn determines the safety stock level and the associated total inventory costs. An immediate implication of the above logic is that lead-time reduction, if possible, leads to lower safety stock, hence lower average on-hand inventory, lower inventory holding cost, and higher profit. As a result, many companies regard the lead-time decision as an important strategy and strive to shorten it as much as possible to improve inventory efficiency, as evidenced by the widespread use of the Just-in-Time (JIT) system, which places a lot of emphasis on lead-time reduction, e.g., locating facilities in close proximity to suppliers.

A very short lead-time, however, may not necessarily be a sound strategy in some cases. In fact, Blackburn (2012) observes that over the past decades supply chains have gotten longer instead of shorter, and the flow of goods through the chains has become slower rather than faster, which implies a longer lead-time in effect. This can be explained by several reasons. First, lead-time reduction does not come free. Instead, it usually requires substantial investments. For instance, Marks & Spencer had to invest heavily in mobile radio frequency identification technology to achieve lead-time reduction by shortening the reading time for each tagged dolly (Delgardo and Wilding, 2004). Gerchak and Parlar (1991) and Ray et al. (2004) use analytical models to show that lead-time reduction has to be carefully evaluated against its investment requirements.

Second, the characteristics of the product may favor a relatively long lead-time. In a well-known qualitative framework, Fisher (1997) categorizes products as functional or innovative depending on such factors as contribution margin, margin of forecast error, and product variety. He uses a number of real life examples to illustrate that supply chains featuring relatively long lead-times are more suitable for functional products. de Treville et al. (2014)

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use quantitative finance tools to provide a useful foundation for quantifying demand unpredictability. They demonstrate that lead-time reduction is not warranted unless the demand volatility is high and demand forecast evolves over time.

Third, in traditional inventory theories, demand is commonly assumed to be independent of the amount of inventory carried. Therefore, the advantages of lead-time reduction are discussed without recognizing the inventory billboard effect, which refers to the positive impact of inventory on customer demand (Cachon and Olivares, 2012). This effect is also known as inventory (or shelf space) dependent demand, and has been observed in a wide range of industries (Whitin, 1957; Wolfe, 1968; Koschat, 2008), especially at the retail level in the fast moving consumer goods (FMCG) industry. It is clear that when demand is stimulated by inventory, the firm has an incentive to stock more, which in turn calls for a longer lead-time. Therefore, it is no longer optimal for the lead-time to be as short as possible.

Our paper focuses on the inventory billboard effect, and investigates the following research questions: in the presence of the inventory billboard effect, how should the firm determine the cost minimizing lead-time together with the corresponding inventory decision? Further, how does the inventory based competition affect the optimal lead-time choice? To answer these questions, we set up a stylized model to conduct an economic analysis of the lead-time decision, taking into consideration the inventory billboard effect. We begin with the single firm scenario, where a firm employs the base stock policy for the infinite horizon continuous-review inventory problem with deterministic lead-time. The average demand rate depends on the firm's average on-hand inventory. Both the mean and the range (a measure of uncertainties) of the random demand during lead-time increase in lead-time and average demand rate. The firm's decision is to choose the optimal lead-time and the corresponding base stock level to maximize its expected profit rate. We then extend the single firm model to the scenario where two firms compete on inventory for customers. We study how the firms should set their equilibrium lead-times and base stock levels simultaneously.

Our main results are summarized as follows. In the single firm case, we obtain closed-form solutions for the optimal lead-time and base stock strategies, which allow us to understand how various parameters affect the optimal decisions. We find that the inventory billboard effect favors a long lead-time, because a long lead-time results in a higher inventory level, which in turn induces more demand. The optimal decisions are driven by tradeoffs between the gain from the extra demand stimulated and the increased inventory holding cost. In the competition case, we completely characterize the equilibrium lead-time and base stock decisions and provide closed-form solutions for the unique Nash equilibrium. We find that the effect of the inventory based competition is to further prolong the lead time. Finally, we observe from numerical experiments that the extent to which demand depends on inventory amplifies the impact of competition on the optimal decisions and profit.

Our paper makes contributions to the literature from both theoretical and managerial standpoints. From a theoretical perspective, we endogenize the lead-time decision while demands exhibit inventory billboard effects and provide closed-form solutions to this complex problem. To the best of our knowledge, we are among the first to bring together two important research streams: lead-time management and the inventory billboard effect. Moreover, we add to the knowledge base by using a rigorous analytical model to uncover the effect of inventory based competition in this context. From a managerial perspective, we offer new insights into lead-time related decisions to industry practitioners. We caution that although lead-time reduction strategy suggested by prior research is viable when demand is independent of inventory, it deserves further investigation in the presence of the inventory billboard effect. Specifically, when demand is stimulated by inventory, firms cannot take for granted that they can always benefit from lead-time reduction. It is only rational to do so when the current lead-time is above a certain threshold. Furthermore, inventory based competition tends to be against lead-time reduction.

The remainder of the paper is organized as follows. Section 2 outlines related literature. We study the inventory billboard effect on the lead-time reduction decision of a single firm in Section 3, and extend the model in Section 4 to consider the case where two firms compete for customers on inventory. Numerical examples are presented in Section 5. The paper concludes in Section 6 with a discussion of future research directions. All proofs are collected in the appendix.

2. Literature review

Our work brings together the research stream that studies supply lead-time in inventory systems and the literature on the inventory billboard effect.

2.1. Lead-time in inventory systems

Lead-time plays a critical role in supply chain management, especially in inventory management, as lead-time is a fundamental factor that affects key decisions and performance metrics such as system base stock level and total cost. Considerable research has been done to understand the importance of lead-time. Some papers consider deterministic lead-time for technical tractability. For instance, Kouki et al. (2015) study a perishable inventory system that operates under stochastic demand and a constant lead-time. They characterize the properties of the cost function and present an approximation procedure to find the policy parameters. Through simulations, they demonstrate their simple and efficient algorithm outperforms another approximation procedure in the literature.

Das (1975) is among the first to discuss the effect of stochastic lead time on inventory management. So and Zheng (2003) use a two-echelon supply chain model to show how the supplier's variable lead-times can amplify the variability in the order quantities of the downstream member in the supply chain. Song (1994) investigates how the behavior of the optimal base stock level and long-run average costs are influenced by the lead-time. She shows that (1) a stochastically larger lead-time requires a higher optimal base stock level, and (2) while a more variable lead-time always leads to a higher optimal average cost, the effect of lead-time variability on optimal policies depends on the inventory cost structure. Arikan et al. (2014) use a serial inventory system consisting of a manufacturer who works with overseas suppliers to investigate the inter-relation between lead-time uncertainty and the economic and environmental performance of supply chains. They quantify the effects of lead-time variability on emissions and total cost for a retailer or manufacturer with high service level requirements, and find that a change in the optimal policy from cost to emission minimization has a low impact on cost, but can have a considerably high impact on emissions. Hoque (2013) also considers uncertain lead-times. He recognizes the limitations of exponential lead-times assumed in previous vendor–buyer integrated production–inventory models, and develops a model with normal distribution of lead-time. Extensive comparative studies are carried out to highlight the significance of his different modeling approach. Heydari et al. (2008) study a four-echelon supply chain using a structural model. They find that lead-time variance affects the inventory system through changing the order variances