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Pooling lead-time risk by order splitting: A critical review

Douglas J. Thomas, John E. Tyworth *

The Smeal College of Business, The Pennsylvania State University, 509 Business Administration Building,
University Park, PA 16802, USA

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Abstract

After more than 20 years of extensive study, the policy of pooling lead-time risk by simultaneously splitting replenishment orders among several suppliers continues to attract the attention of researchers. A critical review of the extant literature is conducted. Important and persistent limitations of current research are revealed that may make the policy uneconomical, in general, and more promising research directions are suggested.

Keywords: Risk pooling; Lead time; Sourcing; Supply; Inventory; Purchasing; Transportation

1. Introduction

Pooling lead-time risk by splitting replenishment orders simultaneously among multiple suppliers is a sourcing policy that has attracted the attention of academic researchers for more than 20 years. The policy is theoretically appealing for several reasons. First, pooling lead-time uncertainty among several suppliers is a way to reduce the safety stock needed to meet service targets or alternatively, the expected number of backorders for a prescribed level of safety stock. Second, successive deliveries of smaller "split" orders will reduce cycle stock. Third, the incremental ordering cost of the second and subsequent orders may be relatively small in a variety of settings.

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* Corresponding author. Tel.: +1 814 865 1866.
E-mail address: jet@psu.edu (J.E. Tyworth).

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When using long-term contracts and blanket orders, for example, source-selection activities, such as quotations and bid evaluations, are sunk costs, while order processing activities, such as formal order releases, invoices, and acknowledgements, can be either simplified or eliminated.

Thus, the value proposition is that the savings in both cycle and safety stock holding cost, as well as in shortage cost, may exceed the incremental ordering costs. The longevity of, as well as the continued interest in, this stream of research is testimony to the appeal of that proposition. Yet, despite the impressive amount of past and present work on pooling lead-time risk by order splitting, it is difficult to find any substantive evidence of successful applications in academic or practitioner literature. This oddity provides the motivation to re-examine the research stream in the context of the real problem domain. A critical review and synthesis of the extant literature will reveal important gaps in the treatment of system inventories and transportation. In light of these gaps, a broader "system" view of the supply chain is considered. Using this wider lens, the reduction in cycle stock that is found in current theory vanishes, while potentially large increases in the incremental shipping costs appear. Both outcomes have the potential to make this approach to pooling lead-time risk uneconomical, in general.

The paper proceeds as follows: The second section of the paper presents an overview of the salient research on order splitting to explain the scope and focus of the research reviewed. The third section examines the framework used by researchers for the economic analysis of order splitting. A discussion of important gaps in that framework follows in section four. Finally, the paper closes with suggestions for some future research directions that are likely to have a visible impact on management practices.

2. Overview of the literature

The stream of research on order splitting follows two major tracks. The first focuses on statistical theory and methods for estimating the effect of splitting on the distribution of effective lead times and, in turn, on safety stock holding costs and shortage costs. The second track concentrates on economic analysis—or more specifically, on developing long run average cost models to assess the performance of split models in relation to non-split models under common conditions. As the discussion in the next section of the paper will demonstrate, the theory that order splitting reduces cycle stock has played an important role in the economic analysis. For the convenience of the reader, and to facilitate concise discussion, we have organized the relevant studies by track in Table 1, listed them in chronological order, and included a third list that shows the studies that embrace elements of the cycle-stock reduction theory.

The potential area of application that is most often described in the studies listed in Table 1 is a "multiple-sourcing environment." Other proposed characteristics include a JIT philosophy and long-term contracts (see, for example, Pan and Liao, 1989; Ramasesh, 1990; Hong and Hayya, 1992; Kelle and Miller, 2001; Ryu and Lee, 2003). Upstream in the supply chain, the flow of products from suppliers to manufacturing plants might include (1) maintenance, repair, and operating (MRO) supplies (Pan, 1990), (2) raw materials or component parts (Sedarage et al., 1999; Ghodsypour and O'Brien, 2001), which may be strategic items procured worldwide (Kelle and Miller, 2001), or (3) high value components such as jet engines (Hayya et al., 1987). Meanwhile, suggestions for the products flowing downstream from manufacturers or distribution centers to

Table 1
Literature review

Study effects of splitting on effective lead time	Conduct total cost analysis	Consider cycle stock reduction
Kelle and Miller (2001)	Ryu and Lee (2003)	Ryu and Lee (2003)
Geetha and Achary (2000)	Ghodsypour and O'Brien (2001)	Ghodsypour and O'Brien (2001)
Fong et al. (2000)	Chiang (2001)	Chiang (2001)
Fong and Gempeshaw (1996)	Tyworth and Ruiz-Torres (2000)	Hill (1996)
Guo and Ganeshan (1995)	Sedarage et al. (1999)	Ganeshan et al. (1999)
Fong and Ord (1993)	Ganeshan et al. (1999)	Chiang and Chiang (1996)
Fong (1992)	Mohebbi and Posner (1998)	Gupta and Kini (1995)
Ramasesh (1991)	Chiang and Chiang (1996)	Lau and Zhao (1994)
Pan et al. (1991)	Gupta and Kini (1995)	Chiang and Benton (1994)
Sculli and Shum (1990)	Lau and Zhao (1994)	Ramasesh et al. (1993)
Kelle and Silver (1990)	Lau and Lau (1994)	Lau and Zhao (1993)
Kelle and Silver (1990b)	Chiang and Benton (1994)	Zhou and Lau (1992)
Hayya et al. (1987)	Ramasesh et al. (1993)	Hong and Hayya (1992)
Sculli and Wu (1981)	Lau and Zhao (1993)	Ramasesh et al. (1991)
	Hong and Hayya (1992)	Pan et al. (1991)
	Ramasesh et al. (1991)	Sculli and Shum (1990)
	Ramasesh (1990)	Ramasesh (1990)
		Pan and Liao (1989)
		Moinzadeh and Nahmias (1988)

retailers include clothing and textiles sourced globally (Chiang and Benton, 1994), retail consumables (Mohebbi and Posner, 1998), and auto parts (Chiang, 2001).

The focus of the studies in Table 1 is predominately on a single-item, single echelon setting that encompasses uncertain lead times and continuous review inventory systems. Additionally, these studies cover a wide range of assumptions and conditions, including all the usual suspects such as (1) different probability distributions for demand and lead time (2) dual or multiple sources, (3) equal or unequal splits, (4) service or shortage inventory control criteria, and (5) different supplier prices. By contrast, several studies considered the deterministic lead-time setting and developed adaptations of the EOQ model (Pan and Liao, 1989; Ramasesh, 1990; Gupta and Kini, 1995).

3. Policy analysis framework

The studies that developed long run average total cost models are listed in the second column of Table 1. Following basic inventory theory, the models include inventory holding cost, ordering cost, and shortage cost. The key issue is whether the savings in holding and shortage costs will outweigh the incremental costs of ordering. Although the issue is simple, the quantification of savings and incremental costs is not.

3.1. Savings in safety stock holding cost and shortage costs

The concept of effective lead time represents the heart of the work on pooling lead-time risk by splitting orders. In theory, this risk-pooling approach will reduce the mean and variance of effective lead time and thus the safety stock required for a pre-specified service target or, alternatively, the expected total shortage cost for a fixed level of safety stock. Sculli and Wu (1981) appear to be the first to present the concept of "effective lead time," which they defined as the minimum lead time among the set of independent, random lead times of suppliers. Their study, as well as the others listed in the first column of Table 1, indicated that a firm can achieve higher service levels for any amount of safety stock when facing the effective lead-time distribution for several suppliers, rather than the lead-time distribution for an individual supplier.

The thought of improved service with less safety stock and reduced shortage costs led Hayya et al. (1987) to theorize that multiple sourcing could be grounded in total cost reduction, besides the mainstream reasons such as enhanced competition and relationship building. The theory gained momentum from two studies by Kelle and Silver (1990a,b), who concluded that order splitting could be beneficial when the lead-time uncertainty is moderate-to-high and the order quantity is large relative to mean of effective lead-time demand. Shortly thereafter, Pan et al. (1991, p. 4) observed that "a large cost savings may be achieved by switching to a multiple-sourcing policy if lead time is volatile." Since then, many other studies considering total cost analysis (listed in the second column of Table 1) have appeared and provide evidence that splitting orders can reduce total costs.

3.2. Savings in cycle stock holding cost

The notion that order splitting can reduce cycle stock was initially illustrated in the deterministic lead-time setting by Pan and Liao (1989) and Ramasesh (1990) and later by Gupta and Kini (1995). These studies expanded the basic EOQ model to calculate the replenishment quantity (Q) and the number of deliveries from n suppliers of size Q/n to minimize total cost in a JIT environment. Splitting orders equally among n suppliers reduced cycle stock from one half of the replenishment quantity (Q) to one half of the split quantity (Q/n).

Zhou and Lau (1992) presented evidence of cycle stock savings in the stochastic lead time setting, when they concluded that (1) "another major benefit is in the reduction of average inventory" and (2) "this benefit can only be realized when one selects a second supplier with a larger average lead time than the first supplier." Similar conclusions appeared again in two of their subsequent studies (Lau and Zhao, 1993, 1994), where they indicated that the benefit to cycle stock from order splitting would be much greater than the benefit to safety stock or shortage costs. This theme also appears in Lau and Lau (1994), Chiang and Chiang (1996), and Chiang (2001).

3.3. Incremental ordering costs

During the early stages of research on order splitting, several researchers posited that the number of deliveries should have little or no effect on aggregate order cost because the individual elements—such as specifications, bid evaluations, and contract documentation—are largely fixed (Pan and Liao, 1989; Sculli and Shum, 1990). Thus a single parameter (A) was used for aggregate ordering cost in both non-splitting and splitting models. Larson (1989), however, noted that this approach effectively sets delivery cost to zero, so that "inventory carrying cost can be minimized without impacting ordering cost by setting the number of deliveries equal to the blanket order quantity...” Ramasesh (1990, p. 73) subsequently defended the single parameter approach as follows:

> While the freight and inspection costs increase with the number of shipments per order, opportunity costs and the costs associated with receiving, handling, and storage decrease. The exact mathematical form of these changes is too complex to model. As a first-order approximation, assume that the changes in either direction balance out and treat the aggregate cost per shipment as constant. This assumption is defensible and useful for implementation because it is much simpler for practitioners to come up with a reliable estimate of the aggregate cost per shipment rather than speculate on the mathematical form of the cost relationships.

Nevertheless, several studies appearing after 1990, including two co-authored by Ramasesh (1991, 1993), abandoned the “no effect” premise and began to use either multiplicative or additive models to determine how order costs respond to order splitting.

3.3.1. Multiplicative models

The general multiplicative model of aggregate order cost per replenishment cycle (A) for the dual-source setting is as follows:

$$A = \alpha A_s \tag{1}$$

where A_s represents the aggregate order cost for a single source. Thus, $\alpha = 1$ for a single source and $1 \leqslant \alpha \leqslant 2$ for two sources, which allows the incremental cost of ordering to possibly double. Studies taking this approach include Ramasesh et al. (1991), Ramasesh et al. (1993), Chiang and Benton (1994), Mohebbi and Posner (1998).

Meanwhile, Hong and Hayya (1992) offered a multiplicative formulation for n suppliers (or deliveries) by substituting a non-decreasing function $\alpha(n)$ for α in Eq. (1) as follows:

$$A = \alpha(n)A \tag{2}$$

Three shapes were considered: convex (exponential function), linear-step, and concave (logarithmic). Ghodsypour and O’Brien (2001, p. 21) used this approach with a linear step-function.

3.3.2. Additive models

The additive model of order cost divides aggregate ordering cost (A) into two components as follows:

$$A = O + nI \tag{3}$$

The first (O) represents the fixed cost elements that do not change with the number of deliveries, such as the preparation of specifications and request for bids, the bid evaluations, the contract documents, the letters of credit. The second component (nI) captures the aggregate incremental costs of splitting orders, including shipping, receiving, handling, and inspection. This approach was used by Lau and Zhao (1993, 1994), Chiang and Chiang (1996), Sedarage et al. (1999), Chiang (2001). Additionally, Gupta and Kini (1995) used a variation of Eq. (3) in which O was equal to the aggregate ordering cost A previously discussed, but I represented a fixed shipping cost only.

4. Gaps in the framework

From the foregoing discussion, it can be seen that the studies reviewed have given little attention to transportation economies of scale. Essentially, transportation has been treated nominally as part of the aggregate order cost that, with few exceptions, was assumed to increase proportionately with the number of splits (n). In other words, researchers assumed that the cost per shipment was constant and unaffected by the quantity or weight shipped, the length of supply lines, or the mode of transportation. This approach persists (see, for example, Ryu and Lee, 2003), although it is well-established in the literature that weight, distance and mode heavily influence transportation costs, while the importance of transportation in JIT and other relevant settings has been discussed at length. Examples include Abdelwahab and Sargious (1990), and Evers (1996, 1997, 1999) in the logistics literature, Diaby and Martel (1993) and Sarmiento and Nagi (1999) in the industrial engineering/operations research literature, Campbell and Joshi (1991), Robinson et al. (1993), and Ghodsypour and O'Brien (2001) in the production-operations management literature, Schonberger and Gilbert (1985) in the management literature, and Zeng (1998) in the marketing literature.

Only two of the studies listed in Table 1 consider transportation economies of scale. Ganeshan et al. (1999) treated transportation cost as a non-linear function of the order quantity for a given distance and mode. Likewise, Tyworth and Ruiz-Torres (2000) used a similar specification to replicate the study by Chiang and Benton (1994) and found that transportation cost can strongly influence the single versus dual sourcing decision under a broad set of realistic conditions.

In addition, the studies appear to seriously underestimate the level of transportation costs. The parameter values assigned to the aggregate order costs for the single supplier, which include transportation costs, ranged from \$30 to \$300 dollars per order. By contrast, a well-known annual survey of logistics costs and service by Davis and Drumm (2003) indicates that transportation cost comprised 2.6% of sales for the average company in the manufacturing sector in 2003, which is more than eight times the amount (0.3% of sales) for order entry, customer service, and order administration combined.

A similar transportation cost-to-order cost ratio, as well as the potential effects of splitting orders on transportation costs, can be demonstrated with real freight rates. For example, observe the rates in Fig. 1, which increase disproportionately as the shipping weight decreases. Even with the typical mark down (50%) on the published rate that is often given important shippers, the cost of a 20,000 lb shipment over a 500-mile lane would be \$2475, or about eight times the maximum level assumed for aggregate order cost (\$300) in the studies reviewed. The cost of two 10,000 lb shipments, moreover, would increase the total shipping cost by about 33% to \$3303. This kind of rate structure, which is common in the less-than-truckload (LTL) market, would mean that aggregate order cost is likely to increase sharply after the first split. LTL shipments beyond 500 miles would shift rates upward, making transportation more influential on order-splitting decisions. Additionally, the choice of mode would affect transportation costs considerably, especially in the context of global sourcing where the choice might be between air and sea modes.

It is appropriate now, perhaps, to revisit the proposition (Ramasesh, 1990) that aggregate ordering cost will be unaffected by splitting, because the increases in transportation and inspection costs will be offset by decreases in receiving, handling, and storage costs. This argument seems unrealistic for two reasons. First, the relative magnitude of transportation cost appears to be seriously understated, as the forgoing discussion clearly illustrates. Second, and more important, the

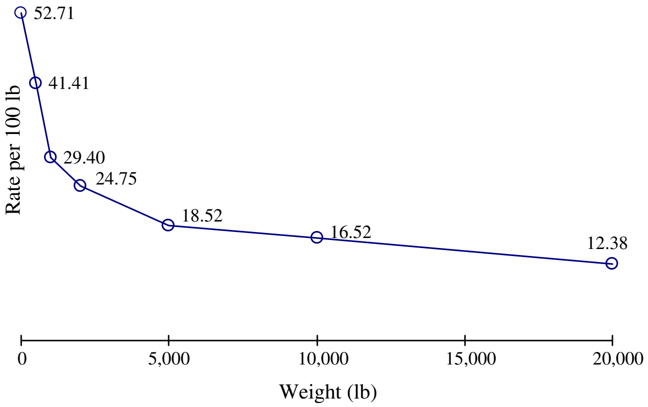

Fig. 1. Illustration of Class 100 Rates for 500-mile Lane. *Source*: Roadway Express Tariff 507, February 2002 with 50% discount.

proposition that two or more small shipments are more efficient to receive, handle, and store than one large shipment is untenable. Indeed, the cost per unit for either receiving or handling costs should remain constant at best and, perhaps, might even increase.

One way to capture the influence of weight, distance, and mode on transportation cost is to model freight rates as a function of the weight, or equivalently, order quantity for a given lane, class of freight, and mode (Langley, 1981; Swanseth and Godfrey, 1996; Tyworth and Zeng, 1998). Another way is to calculate the fixed shipment charge per order as a function of the order quantity in pounds (lb) and then calibrate the parameters of the non-decreasing function $\alpha(n)$ for the aggregate order cost shown in Eq. (2). As mentioned above, Hong and Hayya (1992) proposed this approach and tried several functional forms including logarithmic, linear step and exponential, although it appears that transportation economies of scale would suggest a concave shape as illustrated in Fig. 2.

4.1. Cycle stock reduction and system inventory

As previously discussed, many studies have indicated that order splitting can reduce cycle stock. Recall that the assumption in the deterministic setting was that splitting an order of Q units equally among n suppliers would reduce cycle stock from $Q/2$ to $(Q/n)/2$. The underlying theory in the stochastic setting is, perhaps, most easily understood by examining Fig. 3. In this illustration, orders are split equally between two suppliers having random lead times. The early arriving split (Q_1) increases average cycle inventory, while the late arriving split (Q_2) decreases average cycle inventory. If the expected lead times are the same, the expected area of these trapezoids would also be the same, and no cycle stock reduction would result. If one supplier's lead time was longer than the other's, however, the area of the "reduction" parallelogram would exceed the area of the "increase" trapezoid, and average cycle inventory would be reduced. It is worth repeating that this theory led Lau and Zhao (1993, 1994) to declare that the benefit to cycle stock from order splitting would be much greater than the benefit to safety stock and Chiang and Chiang (1996) and Chiang (2001) to make similar observations. Additionally, Hill (1996) and Ganeshan et al. (1999) used a comparable framework for cycle stock in their analyses of order splitting.

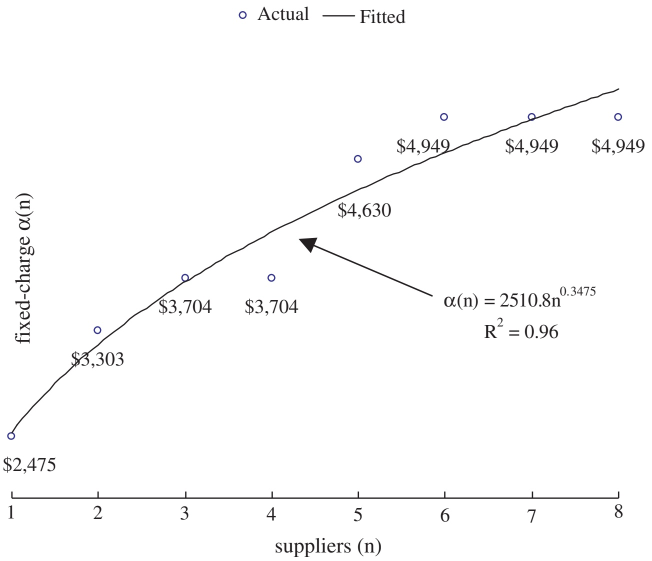

Fig. 2. Fixed charge per shipment and number of suppliers. *Source*: Roadway Express Class Tariff 507, February 2002, Class 100 rates with 50% discount and 500 mile lane.

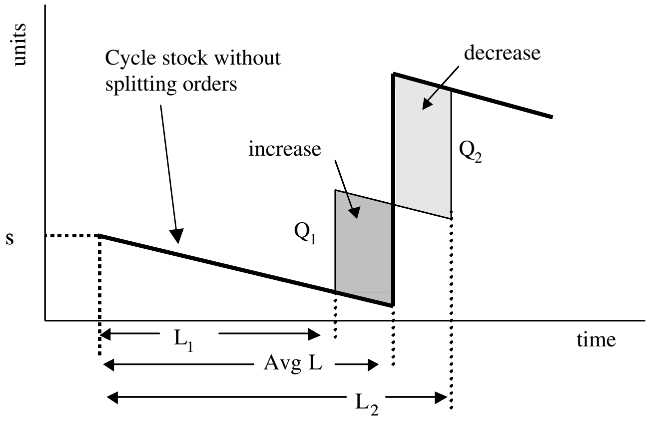

Fig. 3. Effects of order splitting on cycle stock.

The gap in the theory is that it does not consider inventory in the pipeline despite the "end-to-end" system perspective underlying supply chain management thought and the treatment of in-transit inventories in the mainstream literature (see, for example, Leenders and Fearon, 2002; Coyle et al., 2003; Bowersox et al., 2002). This is physical inventory in the system, regardless of the terms of sale.

Excluding in-transit inventory is an important omission, because simultaneously splitting an order among suppliers does not reduce the combined amount of in-transit stock and cycle stock in the system. As Fig. 4 illustrates, the increase in in-transit stock precisely offsets the reduction in

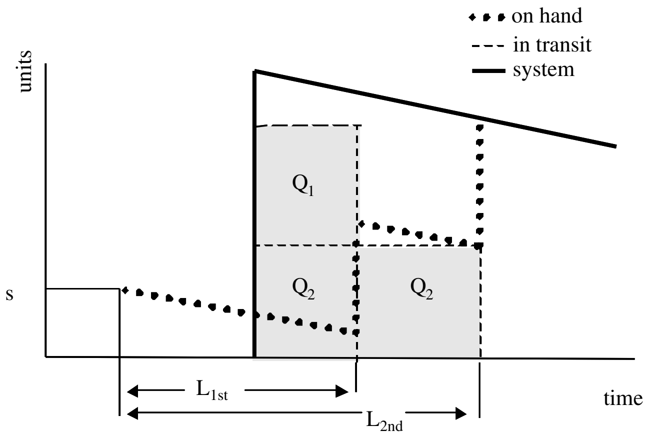

Fig. 4. In-transit and cycle inventories combined.

cycle stock. Of course, the shift of inventory from on-site to in-transit will provide a small system-cost benefit when the holding cost per unit is less for goods in transit than for goods at a downstream outlet, but this nuance might not survive Occam's Razor. In addition, it is important to observe that the system-inventory perspective does not clash with JIT theory, for a reduction in the order quantity Q will still reduce cycle, and total system, inventory. By contrast, splitting Q simultaneously among suppliers does not reduce the amount of system inventory. Thus, for fixed values of s and Q, the only important benefit of such a risk pooling policy is a reduction in shortage (backorders or lost sales) cost. Nevertheless, this benefit can still make the order-splitting proposition worthwhile. As the ensuing discussion indicates, however, very high lead-time variation may be the requisite condition for successful applications.

4.2. Lead-time conditions

Most of the studies listed in Table 1 assumed extremely unreliable lead times conditions, which enhance the benefits to safety stock from pooling lead-time risk by order splitting. For example, Pan et al. (1991), Ramasesh et al. (1991), Lau and Zhao (1993, 1994), Ramasesh et al. (1993), Chiang and Benton (1994), and Ghodsypour and O'Brien (2001) used exponential or uniform distributions in their models, while other studies, such as Lau and Zhao (1993), Ganeshan et al. (1999), Sedarage et al. (1999), Kelle and Miller (2001), used gamma, Weibull, or beta distributions with relatively high coefficients of variation. Several researchers have defended these conditions with the suggestion that splitting orders simultaneously in such purchasing environments might be useful as an "interim" or "defensive" strategy to mitigate stockout risk or reduce inventory system costs, while a company tries to fix the real problem—namely, the extremely unreliable lead times (see, for example, Ramasesh et al., 1993; Kelle and Miller, 2001).

In addition, lead times with one order cycle are assumed to be independent. In a review of multiple-supplier inventory models, Minner (2003, p. 273) concluded that this assumption is a major shortcoming, because lead times of suppliers might be positively correlated. He suggested worldwide levels of demand for a product as a potential source. We would add two other likely sources—transportation system bottlenecks and freight consolidation at terminals—and observe that positively correlated lead times would not only complicate the analysis, but dilute the implied benefits to safety stock from pooling lead-time risk.

5. Conclusions and future directions

The economics of pooling lead-time risk by splitting orders simultaneously continues to interest academic researchers after more than 20 years of intensive study. The research has followed two major tracks. The first focuses on the statistical machinery for modeling effective lead-time demand under a variety of stochastic assumptions and enabling an assessment of the impact of pooling on reorder points, stockout risk, safety stock, and shortages. The second track concentrates on modeling cost tradeoffs and, ultimately, on a comparison of the long run average total costs for single-source versus dual- or multiple-source models under identical conditions. The research settings predominately encompass a single-item, single-stage, continuous-review inventory system and four cost elements: inventory holding cost, ordering cost, shortage cost, and purchase cost.

Although studies in both tracks provide hypothetical evidence that pooling lead-time risk by splitting orders simultaneously may be worthwhile, it is difficult, if not impossible, to find substantive empirical validation of the proposition. This paper presented a critical review and synthesis of the literature in light of the real problem domain that helps explain the apparent lack of impact of the research on management practice. The review revealed two important and persistent limitations.

First, the models do not give appropriate attention to transportation economies of scale. The research interest is overwhelmingly in the challenge of estimating average stock levels and shortages in a stochastic lead-time setting. This is a complex task that requires complicated statistical machinery and produces a high degree of granularity in the safety stock component of the long-run average total cost model. By contrast, the aggregate order cost component has much less resolution than the safety stock cost component, which prevents the models from accurately capturing the important influence that transportation can have on the economics of order-splitting. Specifically, there are important gaps with respect to the true magnitude of transportation cost, as well as the impact of order quantity (weight), supply lines (distance), and mode (especially air versus ocean shipments in a global setting) on transportation and incremental ordering costs.

Second, the current theory that a reduction in average cycle stock is *the* key benefit of splitting orders simultaneously considers only the buyer's on-hand inventory in the supply chain. The absence of in-transit inventory, however, is an important limitation, because simultaneously splitting an order among suppliers does not reduce the combined amount of in-transit stock and cycle stock in the system. Consequently, the only meaningful benefit of pooling lead times is to safety stock from a total system-cost perspective.

In addition, other critics have observed that lead times within one order cycle may not be independent. If the lead times are positively correlated, the potential safety stock savings obtained from pooling lead times would be diluted. Likewise, the safety stock savings will decrease under less extreme lead-time conditions than found in most studies.

Collectively, these limitations make the value proposition rather dubious. Thus future research in this area should include case studies, simulations, and surveys to determine whether companies use such order splitting methods and the business setting where successful applications appear. In addition, future research efforts should investigate other methods of splitting orders that offer more promise. One approach suggested by Hill (1996) is for a single supplier to receive an order and then split it into smaller shipments released sequentially. One could then take advantage of actual information about future deliveries and reduce the variability of the demand process. Janssen et al. (2000) take this approach, shipping each order in several shipments. While this approach will tend to increase transportation costs, it may reduce system inventory by providing advance information to the producer about future production needs.

Another approach is to try to exploit the cost-performance differences in modes of transportation. That is, by intelligently specifying a mixture of different modes, a firm may be able to receive the service benefits of a fast, reliable supplier, while enjoying some of the cost benefits of a more economical, but less reliable mode. Many of the studies pursuing this line of research, which have been reviewed elsewhere by Minner (2003), indicate that the differences in lead time performance across modes are large enough such that the probability of the slow mode arriving before the fast mode is very small or even zero. As such, the statistical machinery that is developed to find the effective lead time is unnecessary.

Finally, some researchers have investigated the policy of making firm, periodic, long-term transportation commitments to absorb some of the demand variability at the consumer-facing point in the supply chain (see, for example, Thomas and Hackman, 2003; Henig et al., 1997). The potential economic benefit is the reduction in freight rates that carriers might offer for the long-term commitment of traffic and the reduction in variability inflicted on the transportation system.

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