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A framework for comparing outsourcing strategies in multi-layered supply chains

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Abstract

The growth in the use of the Internet as one of today's main tools of business communications has drastically increased competitiveness and changed many of the existing axioms creating more complex supply chains that consist of several layers. In this paper, we develop a framework to assess the performance of these emerging types of multi-layered supply chains when coupling the outsourcing strategies, whether it is based on competitive bidding/E-bidding or long–term partnerships, with the required level of safety stock that the parent company sets to satisfy the quality of its services. In order to estimate the safety stock for each of the outsourcing strategies, the supply chain is modeled as a series of tandem queues. Based on the sojourn times that a particular order spends in process at the various levels of the chain, the lead time is estimated and, consequently, one can determine the needed safety stock as well as draw a first cut comparison for the annual cost estimates of each of the possible outsourcing options. We include an illustrative example for the application of the proposed framework as well as simulation experiments for cases when closed-form solutions of the queuing models are difficult to obtain.

Keywords: Multi-layered supply chain logistics; Safety stock; E-bidding/purchasing; Long-term partnerships; Tandem queues

1. Introduction

The globalization of manufacturing and business activities has led industries to outsource many production functions and focus more on their core competencies. This, in turn, has created complex supply chains consisting of multiple layers where vendors could spread worldwide. To remain competitive, manufacturers seek to deliver to their customers high-quality products in the right time at the right price. So, they seek globally suppliers

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who can fulfill these needs. Hence, in managing their supply chains, manufacturers have to carefully consider the many aspects that govern their performance in order to ensure the end user satisfaction.

To stay flexible, many manufacturers, who outsource, maintain their options open vis-à-vis long-term contractual basis with particular vendors. In this type of situation, the manufacturer has the flexibility of choosing the vendors according to market conditions in what is known as competitive bidding practice or E-procurement strategy. While this practice is advantageous regarding the just-in-time choice of the least-expensive and high-quality vendors, the manufacturer could be risking backlogging since these suppliers usually cater to other customers as well and serve on first-in-first-out basis. Consequently, in order to ensure a certain level of customer satisfaction, manufacturers who exercise this option have to pay close attention to the effect of randomness on the lead-times and their ramifications on the proper safety stocks and the costs involved.

In order to compare outsourcing strategies for these emerging multi-layered supply chains, this paper examines and models these types of chains that usually consist of a parent company that produces the end product and out-sources a portion of its components to several suppliers. Those suppliers in turn may outsource some of the subcomponents to other vendors and so forth creating a multi-layered chain. Our main objective is to develop a first-cut framework to assist in selecting the proper outsourcing strategies for the company's supply chain; that is competitive bidding among undedicated suppliers, or the traditional long-term partnerships. The framework is based on comparing the required safety stocks, which is a key indicator of customer satisfaction, as well as other involved costs when deciding on the outsourcing strategies. Our approach is two-fold. First, the chain is modeled as a tandem set of queues. Markovian and simulation models are introduced to compute the waiting times and consequently estimate the safety stock required for a given customer's satisfaction level. Second, for long-term partnerships (including consignment stock practice), and competitive/E-bidding strategies, we provide bounds for the safety stock of each and consequently a rough estimate for their respective annual costs. This presents the underpinning of a framework to compare the effect of these outsourcing strategies, as well as their various classes, on safety stocks and on their annual costs as two of the key performance measures of supply chain management.

This paper is organized as follows. After this introduction, we present a background section. Then, a section for problem description and the necessary preliminaries is provided. A section where we introduce the framework and its models will succeed. This section consists of several subsections. It includes a brief discussion for the possible outsourcing scenarios; an analytical model of the supply chain based on tandem queuing principles; steps of the proposed framework; a numerical example showing the application of the proposed approach to the different outsourcing strategies; and simulation experiments to compare the Markovian analytical results to non-Markovian ones. Finally, we present a section for concluding remarks.

2. Background

This section discusses some of the pertinent literature related to this article. It is basically divided into three parts. In the first part, we review articles that address comparison issues among outsourcing strategies in supply chains. The second part is dedicated to the various performance measures of supply chains showing the importance of safety stocks. In the third part, we refer to works regarding uncertainty and information-sharing effects on supply chains (specifically ''bullwhip effect'').

Grieger (2003) reports that the exponential growth of electronic marketplaces (EMs) is significantly impacting the outsourcing practices in today's supply chains. He argues that further research to examine these types of practices is needed. One can infer from his argument that long-term partnerships between entities of a supply chain is not the only viable option that is available to firms at the present environment. In essence, Greiger is calling for considering other outsourcing strategies such as competitive/E-bidding when selecting a supply chain's vendors. Earlier, Peleg et al. (2000) compare short-term procurement strategies versus long-term contracts as well as a strategy that is based on combination of both. Their findings suggest that no strategy is generally superior to the others. They report that the dominance of a particular strategy depends on the specifics of the case; mainly cost distribution and length of terms negotiated. Weele (2000) presents interesting insights into purchasing and supply chain management, where the pros and cons of competitive bidding practices of EMs versus the more traditional long-term partnerships between the vendors and the buyers are compared. Among the strategies discussed in his book are those of global versus local sourcing, single versus multiple sourcing, partnerships or competitive bidding, and buying on contract or buying on the spot basis. In essence the comparisons drawn are between the benefits of the long-term contractual supply chains and the emerging ones with undedicated vendors. In both types of these supply chains there are common measures of performance. However, some may be more important than the others based on the supply chain particulars. Poirier and Bauer (2001) in their text "E-supply Chain" echo similar themes of these measures as those reported by Weele in Weele (2000).

On the front of measuring the performance of supply chains, Otto and Kotzab (2003) describe the pertinent standard problems, solutions, and performance metrics. They discuss six perspectives for evaluating supply chains, ranging from system dynamics, operations research, and logistics to marketing, organization, and strategy perspectives. In most of these perspectives, stock-outs, service level, lead-times, and customer satisfaction have been identified as leading performance indicators of successful supply chains. As one can see, all of the aforementioned indicators could be linked to safety stocks. If the end users maintain relatively large amounts of safety stocks, they can attenuate the effect of lead-times excesses, protect against shortages, and maintain high service level. (One may argue that a large safety stock increases inventory costs, but on the other hand, the company could benefit from competitive pricing; therefore, this increase in holding expenses is outweighed.)

Uncertainty is one of the most important problems that a supply chain faces. Forrester (1960) reports that the distortion of demand can accumulate considerably upstream the supply chain (which is known as the bullwhip effect or variance acceleration). This phenomenon is a major cause of difficulty for materials planning, materials ordering, and production planning. To measure the quantity of the bullwhip effect, Metters (1997) expresses its significance in monetary term. He states that only eliminating the seasonal bullwhip effect could increase the product profitability by 10–20%. Chen et al. (2000) propose a model to quantify the bullwhip effect by considering the variance of the orders placed by the retailer to the manufacturer relative to the variance of the demand faced by the retailer. One of the methods that are proposed to reduce the bullwhip effect is information sharing. Along the same lines of Chen et al. (2000), Srinagesh et al. (1999) study the partial and complete information sharing in a two-echelon supply chain model under three situations: (1) the supplier receives no advanced information about the demand except past data, (2) the supplier knows the $(\boldsymbol{s}, \boldsymbol{S})$ policy used by the retailer, and (3) the supplier has complete information about the state of the retailer. The results show that the model with additional information performed better than the model with restricted information. Hau et al. (2000) examine the benefits of the information in a two-leveled supply chain. They consider two supply chain models, with and without information sharing. They also present numerical examples to illustrate that the information sharing could reduce the inventory and save cost. Kalchschmidt et al. (2003) report similar conclusions regarding the importance of modeling and information sharing on the performance of multi-echelons supply chains. They emphasize the fact that information sharing can "dramatically" improve performance. Rau et al. (2003) echo comparable findings while studying multi-echelon supply chains of deteriorating items. They demonstrate that an integrated approach strategy yields lower cost as compared to separately making decisions for each echelon. Finally, in a review paper on multiple-supplier chains by Minner (2003), the value of information sharing and the use of modern technologies in this vein have been reiterated. He states that the low cost of information sharing via the Internet is an asset in managing supply chain through the emerging E-procurement practices.

To conclude, the previous discussion shows the interest of the community in the performance of supply chains and the inventory levels kept, the importance of information sharing between the different layers in reducing the bullwhip effect that results from uncertainty, and the impact of EMs on competitive bidding strategies among vendors versus long-term partnerships between the components of the chain. However, insufficient attention has been given in estimating the safety stock and its effects on supply chains where information sharing is limited or not at all available, in particular in chains with competitive bidding strategies. Providing a framework to help the decision-maker to gauge the effect of safety stock levels and annual costs when comparing between competitive bidding strategies and long-term partnerships is what motivated our work.

3. Problem description

In order to compare the outsourcing strategies of undedicated vendors (competitive bidding) to the ones with long-term partnerships vis-à-vis their safety stock levels, we consider a multi-layered supply chain where a parent company outsources subcomponents to several suppliers who in turn subcontract components to other vendors and so forth forming arborescence-like chain. We postulate further that the vendors and the supplier of the chain follow the same pattern of ordering; that is, they outsource to others who follow the same philosophy as that of the parent company (that is long-term partnership or competitive bidding where the basis in the latter is on first-come-first-served). In case of competitive bidding, it is also presumed that some historical data about these temporary partners in the chain are known. One of the main objectives is to determine the safety stock, "s," for the parent company that satisfies certain level of performance. More clearly, for the different outsourcing options, the parent company wishes to know the safety stock level that should be available during lead-time in order to keep the probability of shortage below a certain stipulated level. When we have determined the safety stocks for the various scenarios, then we can compare them as they relate to the performance level. This offers the decision-maker a means whereby the expected saving potential of competitive bidding as opposed to the reduced inventory levels that long-term partnerships render can be quantitatively measured.

The problem of multi-layered supply chain can be modeled as an open queuing network. When the safety stock reaches a stipulated level, the parent company places the order to the next level downstream. We assume that upon the receipt of the order, it is passed along immediately until it reaches the first layer where it joins the queue of jobs. Then, this particular order proceeds to the subsequent layer and waits its turn of processing until it reaches the parent company. As one can see, the lead-time will be the longest sojourn time (flow time) that it takes a batch of certain components to travel through the different layers of its branch until it reaches the parent company.

To clarify, let us consider a branch of a multi-layered chain as shown in Fig. 1. As mentioned before, when the parent company places an order, it is passed down to the first layer of the chain. Then, it travels back upward as it is being processed by suppliers upstream. If the suppliers are not retained on consignment basis, it is reasonable to assume that they do not hold the requested parts in stock. Noting that supplier n, Fig. 1, is where the order will start to be processed; one can see that the waiting time in this tandem set of queues is equivalent to the lead-time. Hence, estimating the sojourn time and its variance provide the means for the parent company to determine the proper safety stock as will be shown in the following sections. The following sections illustrate how to estimate the differences between

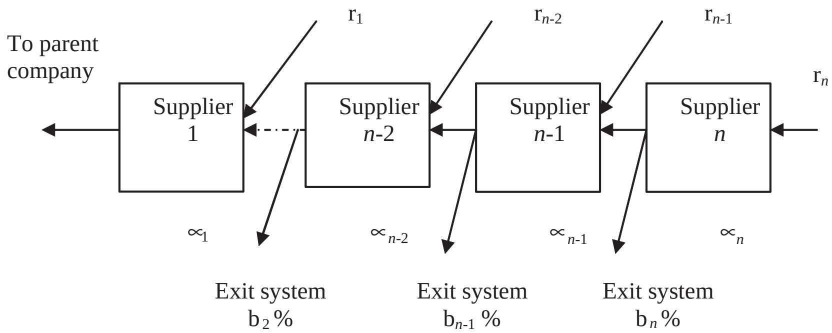

Fig. 1. Branch of a multi-layered supply chain model.

safety stocks in the various types of chains, those which are competitive bidding based and the ones with long-term partnerships.

4. The framework

As mentioned prior, one of the main objectives of this work is to determine the level of safety stock that meets management's customer satisfaction measure. Therefore, having a proper expectation for the demand during the lead-time period is a key to a good estimate of the safety stock level. It is common that companies have reasonable forecasts for the demand. Silver et al. (1998) present a popular formula for computing the safety stock. It is as follows:

$$s = E(X) + z\sigma_x, \tag{1}$$

where

$$E(X) = DL.$$

Note that D is the expected annual demand (in units), L is the expected lead-time, σ_x is the estimate of the standard deviation of forecasts errors which stems from both lead-time estimates and demand expectation during this period, and z is a factor that depends on the company's level needed for customer satisfaction.

As can be seen from Eq. (1), having a good estimate for the lead-time and its variance is essential in determining the proper safety stock for the different scenarios: the undedicated vendors and the dedicated ones. To estimate these parameters, in the succeeding subsections we present a queuing model based on Markovian assumptions, and then simulation analysis for non-Markovian cases. But before this, we briefly discuss the types of outsourcing scenarios considered.

4.1. Outsourcing scenarios

The acceleration of variance through the layers of the supply chain contributes significantly to the increase of safety stock, in particular when the Markovian assumption is imposed, and no significant information sharing is available. (Therefore, a Markovian model provides a conservative estimate for the safety stock amount.) This situation is more prevalent when the company resorts to competitive bidding practice as opposed to long-term partnerships. As will be shown in the numerical example, the components of Eq. (1) for the safety stock include, in addition to the expected value of the demand during lead-time and its expected error as a function of the variances, the extra errors in estimating the lead-time stemming from variability which is mainly attributed to lack of information particularly in case of competitive bidding. This variability can be expressed as a function of the variances of the flow time at the different layers of the supply chain. On the other hand, if the company resorts to long-term partnerships where information sharing or preemption exists, it can be argued that the variance in the lead-time can be contractually reduced if not all together eliminated. In the following, we present the most common scenarios of long-term partnerships and that of competitive bidding as they relate to safety stock determination.

4.1.1. Consignment stock practice

Hill (1988, 1999) investigates the effects of integrating a single vendor with a single buyer production-inventory policy showing the advantages of this type of practice. Motivated by his findings, Valentini and Zavanella (2003) present one of the early analytical case studies regarding consignment stock practice. In their article, a clear listing of these practice guidelines is given (an extension of their work appeared in Abdel-Malek et al. (2002)). It is reported that in this type of supply chain the vendors are responsible for maintaining the safety stock (usually at the vendors' expense). Therefore, one can argue that the annual cost differential, ceterisparibus, is based on the variable cost. That is

$$K_s = C_s D, \tag{2}$$

where K_s is the expected annual cost differential, C_s is the cost of buying the items on consignment stock basis, and D is the annual demand.

4.1.2. Long-term partnership with information sharing

A significant portion of the literature in the area of supply chain management reports favorably on the value of long-term partnerships along the supply chain and how information sharing among the chain layers helps in reducing inventory (bullwhip effect). Therefore, depending on the type of contract between the partners, the level of safety stock is determined. Two possible scenarios present the upper and the lower bounds for the safety stock in this type of partnership. The contract may stipulate that the suppliers preempt all other works and respond to the buyer's request. In this case the buyer's (the parent company) safety stock should only consider the variability of the demand during lead-time. In the other scenario, the suppliers operate on first-come-first-served basis, but, because of the long-term partnership relation, the manufacturer knows the expected lead-time and therefore the suppliers are expected to deliver during that stipulated lead-time. Hence, in the first scenario,

$$K_{\mathrm{LP}} = C_{\mathrm{LP}} D + I C_{\mathrm{LP}} z \sigma_{x\mathrm{LP}}, \tag{3}$$

where K_{LP} is the expected annual cost differential, C_{LP} is the variable cost for long-term partnership with preemption option, $\sigma_{x\mathrm{LP}}$ is the standard deviation of the demand during lead-time, and I is the inventory carrying cost rate per year.

The other scenario will present the upper bound of the cost for long-term partnership. In this case it is given by

$$K_{\mathrm{LL}} = C_{\mathrm{LL}} D + I C_{\mathrm{LL}} [E(X) + z \sigma_{x\mathrm{LP}}], \tag{4}$$

where K_{LL} is the expected annual cost differential, C_{LL} is the variable cost for this type of long-term partnership and it is assumed to be smaller than C_{LP}.

What is expressed in the term between brackets of Eq. (4) is that the agreement between the suppliers and the parent company stipulates that the latter is responsible for maintaining the inventory during the expected lead-time, but not its variance, plus the variance of the demand during lead-time.

4.1.3. Competitive bidding/E-bidding

In this situation, the suppliers are not bound by long-term agreements with the parent company. Therefore, the parent company is responsible for the uncertainty in the whole chain. Hence, the annual cost in this case is obtained by modifying Eq. (4) as

$$K_{\mathrm{b}} = C_{\mathrm{b}} D + I C_{\mathrm{b}} [E(X) + z \sigma_{x\mathrm{b}}], \tag{5}$$

where K_{b} is the expected annual cost, C_{b} is the variable cost per unit for competitive pricing, $\sigma_{x\mathrm{b}}$ is the standard deviation of variability stemming from those of demand during lead-time, as well as the lead-time and its variability (see the following sections for more details).

As can be seen, the difference between the annual costs of these scenarios mainly emanates from the variable costs and the carrying cost of inventories as safety stocks (as mentioned before, we assume that all other parameters are equal and if not, the models can be easily adjusted to accommodate the differences). The following sections illustrate more how to estimate the variability in the chain. We begin by presenting the Markovian model to show how to estimate the lead-time and the variance in such chains. An illustrative example shall follow after presenting the framework steps. Then, as stated before, we run simulation experiments for non-Markovian models (normal distribution).

4.2. The Markovian model

Without loss of generality, assume that the branch shown in Fig. 1 is the one that has the longest lead-time in the considered supply chain. If the suppliers are not dedicated to a particular product, then what they produce does not necessarily follow the same path. That is, at each layer a percentage of the jobs could leave the system and also additional jobs may join in. Hence, if we start from the bottommost supplier (supplier n), then for any supplier i, defining r_i as orders for the jobs that supplier i receives from other sources other than supplier $i+1$, μ_i as the service rate of supplier i, and b_i as the portion of finished subparts that are not delivered to supplier $i-1$, one can express the sojourn time and its variance as follows (see Ross, 1997).

$$L = \sum_{i=1}^{n} L_{n-(i-1)} = \sum_{i=1}^{n} \left[\frac{1}{\mu_{n-(i-1)} - \lambda_{n-(i-1)}} \right], \tag{6}$$

$$V(L) = \sum_{i=1}^{n} \left[\frac{1}{\mu_{n-(i-1)} - \lambda_{n-(i-1)}} \right]^2. \tag{7}$$

Note that

$$\lambda_i = r_i + \lambda_{i+1} - \frac{(b_{i+1}\,\lambda_{i+1})}{100}, \tag{8}$$

where r_i is the mean arrival rate that an order arrive to the system at supplier i, b_{i+1} the percentage of orders that exit the system after being served by supplier $i+1$ (note that $b_1 = 100\%$ and $r_n = \lambda_n$).

Thus, estimating the lead-time L and its variance $V(L)$ enables us to compute the second term of both Eqs. (4) and (5), which is concerned with the various sources of variability in case of long-term partnership and competitive bidding (mainly E(X) and σ_{xb}, as will be shown in the numerical example).

The following subsection formalizes our approach. It describes the framework in a step-by-step fashion.

4.3. Steps of the framework

Initialization

- Obtain the average annual demands of the items under consideration, D, and their standard deviation, σ_x, customer service level desired, z, and purchase cost per unit for each of the available outsourcing options, C, as well as the operating inventory carry cost rate per year, I.
- For each supplier find:
  - number of orders that supplier i receives from all sources, r_i, λ_i (see Eq. (8));
  - service rate μ_i (average processing time per order);
  - percentage of finished subparts that are not delivered to supplier $i-1$, b_i.

Steps

Step 1: Using Eqs. (6) and (7), for each branch of the supply chain, calculate the expected total lead-time L and its variance $V(L)$.
Step 2: Using the information obtained from Step 1 and Eq. (1), compute the required safety stock, s, that the parent company needs for each outsourcing strategy.
Step 3: Calculate the costs for the different outsourcing strategies using the proper Eqs. (2)–(5).
Step 4: For each item outsourced, decide on the outsourcing option that optimizes the cost obtained in Step 3.

4.4. Numerical example

Consider a multi-layered supply chain where the branch that has the longest lead-time is similar to that exhibited in Fig. 1. As can be seen, this branch consists of a parent company and four supply layers. These four suppliers (one at each supply layer) may have different arrival and service rates of orders. As one can see from Eq. (6), different arrival and service rates can be assumed in the Markovian case. However, for comparison purposes, when simulating other probability distribution cases, it is assumed that the ratio of the arrival rate (λ) to the service rate (μ), or ρ, is constant. (Note that ρ is the utilization factor of each supplier, and $\rho < 1$.) The following parameters are used in this example. The units of r_i and μ_i are both orders/week.

Supplier 1: $r_1 = 4.08$, $\mu_1 = 14.00$, and $b_1 = 100\%$,
Supplier 2: $r_2 = 0.36$, $\mu_2 = 9.00$, and $b_2 = 20\%$,
Supplier 3: $r_3 = 2.10$, $\mu_3 = 12.00$, and $b_3 = 30\%$,
Supplier 4: $r_4 = 6.00$, $\mu_4 = 10.00$, and $b_4 = 15\%$.

The company would like to explore the price thresholds at which each of the aforementioned outsourcing strategies become more attractive from costs point of view. The parent company aims at having a customer service level of 95%. The annual demand of the part is normally distributed with an average of 10,000 U and a standard deviation of 400 U. The inventory carrying cost rate is 10% and the company is currently toward the end of a contract based on consignment stock for this component, where the price per unit is \$4.00, and it is being debated what outsourcing strategy the company should follow next.

The readers are reminded that although the parent company usually places the order to supplier 1, the queuing system assumes that supplier 1 will pass the orders to supplier 2 and so forth. Assuming that the order processing times are negligible, it is possible to view the supply chain model as if the parent company places the order directly to supplier 4. The physical flow of the supplies (subparts or subcomponents) will be from supplier 4 → supplier 3 → supplier 2 → supplier 1 → parent company.

In order to compare the various options, we follow the steps of the framework given in Section 4.3 and begin by estimating the total lead-time and its variance using Eqs. (6) and (7).

At supplier $i = 4$,

$$\lambda_4 = r_4 = 6.00,$$

$$L_4 = \frac{1}{\mu_4 - \lambda_4} = \frac{1}{10.00 - 6.00} = 0.2500.$$

At supplier $i = 3$

$$\lambda_3 = r_3 + \lambda_4 - \frac{(b_4\,\lambda_4)}{100} = 2.10 + 6.00 - \frac{(15 \times 6.00)}{100} = 7.20,$$

$$L_3 = \frac{1}{\mu_3 - \lambda_3} = \frac{1}{12.00 - 7.20} = 0.2083.$$

Similarly, one can proceed and obtain L_2 and L_1. They are 0.2777 and 0.1786, respectively. Hence, the expected lead-time is

$$L = \sum_{i=1}^{4} L_i = 0.9146 \text{ weeks}$$

And, the variance of the total lead-time ($V(L)$) calculated using Eq. (7) is

$$V(L) = \sum_{i=1}^{4} L_i^2 = 0.2149.$$

From the variance, the standard deviation can then be calculated:

$$\mathrm{SD}(L) = \sqrt{V(L)} = 0.4635.$$

Hence, the safety stock that the parent company needs (s) can be calculated for the different outsourcing strategies, and consequently the expected annual costs for each.

Expected demand during lead-time, $E(X)$:

$$E(X) = \left(L\frac{\text{average annual demand}}{52}\right) = 0.915\frac{10,000}{52} = 175.96 \text{ U}.$$

And, the variance during lead-time is

$$\sigma_{xb}^2 = \left(L\frac{\text{demand variance}}{52}\right) + \left[\left(\frac{\text{average annual demand}}{52}\right)^2 V(L)\right] = \left(0.915\frac{(400)^2}{52}\right) + \left[\left(\frac{10,000}{52}\right)^2 0.2149\right] = 10,762.88,$$

$$\sigma_{xb} = 103.74 \text{ U}.$$

Thus, the required safety stocks that the parent company is charged for in cases of consignment stock, lower and upper bounds for long-term partnerships, and competitive bidding, respectively, are:

(i) The consignment stock: As mentioned prior, the safety stock here is zero. Using Eq. (2), the annual cost indictor for the platform is $K_s = 4 \times 10{,}000 = \$40{,}000$.
(ii) The lower bound for long-term partnership: In this situation, as described before, the parent company is responsible for only the fluctuation of the demand during the lead-time, which is given by $z\sigma_{x\mathrm{LP}}$. Thus, for the considered example, the safety stock, $s_{\mathrm{LP}} = 104$ U, and using Eq. (3), the threshold of the cost per unit as compared to the consignment stock that is given in (i) stock is $C_{\mathrm{LP}} < 0.998C_s$.
(iii) The upper bound for long-term partnership: Following similar arguments as before, one obtains $s_{\mathrm{LL}} = 104 + 176 = 280$ (note that in this case the parent company is responsible for inventory during lead-time plus demand fluctuation). Using Eq. (4), the variable cost in this case as compared to that of the consignment stock is $C_{\mathrm{LL}} < 0.996\ C_s$.
(iv) The competitive bidding/E-bidding strategy: In this case, as mentioned earlier the parent company is responsible for the uncertainty in the chain which amounts to

$$S_b = E(X) + z\,\sigma_x = 175.96 + 170.65 = 347\ \mathrm{U}.$$

Using Eq. (5), it can be shown that the unit cost in the competitive bidding case as opposed to that of consignment is given by $C_b < 0.994C_s$.

Having found the cost thresholds for the different outsourcing strategies, one can follow the same approach for the second longest lead-time, and decide independently on the purchasing option, which is suitable for the component under consideration. Proceeding successively in the same fashion, the impact of the safety stock of each component can be assessed and consequently the proper outsourcing strategy for each can be obtained.

4.5. *Simulation experiments*

The example given before considers Markovian tandem queues when evaluating the lead-times (sojourn times). In general, the Markovian assumption renders conservative estimates for the performance measures of queuing systems. That is, the lead-time estimates are usually larger than those when other probability distributions are considered (note that the exponential distribution is utilized under the Markovian assumption). In this section, we develop simulation experiments to test the effect of the various governing parameters of the supply chains on the safety stock when the probability distribution function is normal as opposed to exponential.

A multi-layered supply chain system similar to the one considered in the previous numerical example is tested. The average annual demand of the part and its standard deviation are 10,000 and 400 U, respectively. We vary the number of supply layers between two and eight. In each experiment, while the average arrival rate (λ) of orders and the average service rate (μ) of the supplier may vary, the utilization (load) factor is kept constant. The utilization factors used in these experiments are 0.2, 0.4, 0.6, and 0.8. To validate the formulae obtained before and compare the results to non-Markovian queues, two multi-layered supply chain models are investigated: (1) the ‘‘Markovian’’ multi-layered supply chain model, and (2) the ‘‘normal’’ multi-layered supply chain model. As mentioned prior, the rest of the assumptions are similar to those described earlier in the numerical example.

From the sojourn times (lead-times) and their standard deviations that are yielded by the experiments, the safety stock levels required to obtain the desired 95% customer service level are estimated for various utilization (load) factors and supply layers as shown in Tables 1 and 2. The results show that the safety stock level increases with the utilization (load) factor in both the ‘‘Markovian’’ and ‘‘normal’’ supply chain models. Within the same load factor, increasing the number of supply layers also causes the safety stock to increase. In both tables, it can be seen that the safety stock levels under the Markovian

Table 1
Safety stock estimation based on Markovian assumption

No. of layers	Utilization (load) factor			
	0.2	0.4	0.6	0.8
2	75.79	82.88	120.20	215.45
3	89.39	99.84	156.12	260.94
4	98.54	111.08	171.05	288.28
5	107.84	126.45	190.12	324.61
6	115.07	136.84	203.11	346.18
7	119.44	143.52	220.10	380.95
8	125.69	155.27	226.18	397.76

Table 2
Safety stock estimation based on normal distribution assumption

No. of layers	Utilization (load) factor			
	0.2	0.4	0.6	0.8
2	72.21	73.32	95.99	159.91
3	84.75	88.23	124.71	194.81
4	92.79	98.54	137.27	218.52
5	101.50	111.05	152.35	247.42
6	109.05	121.19	170.90	277.49
7	113.81	126.46	181.95	290.36
8	119.44	137.31	182.27	305.66

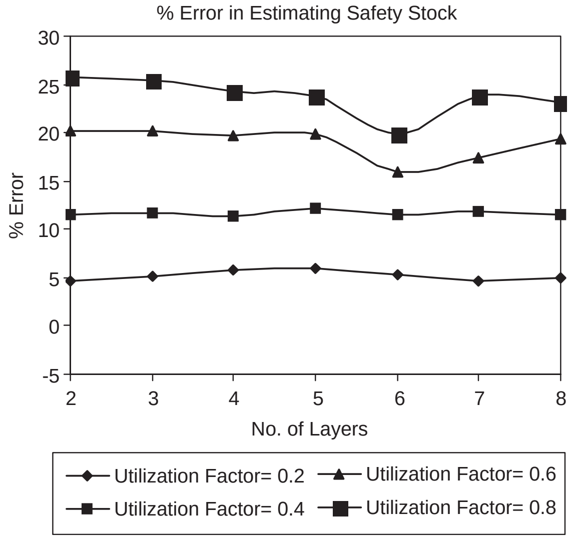

Fig. 2. Plots of the percent error of estimation versus the number of supply layers for various load factors.

assumptions are consistently higher than those under the normal probability distribution assumption (as should be the case). By comparing the percent error in estimating the safety stock (between the "Markovian" and the "normal" models), it is found that the percentage increases with the load factor and the maximum increase in the safety stock is approximately 26%, see Fig. 2.

5. Concluding remarks

In this paper we proposed a framework to compare outsourcing strategies in multi-layered supply chains. The framework considers the safety stock level, which is known to be a key performance indicator, as one of the important measures in comparing the annual costs of the outsourcing strategy options available to management. Among the motivation for developing the aforementioned framework is the increase in electronic practice via the Internet that has led many companies to consider competitive bidding as opposed to long-term partnerships as was more common in the recent past.

The developed framework provides a datum for comparing outsourcing strategies of multi-layered supply chains, where consignment stock, long-term partnership contracts, and/or competitive bidding/E-bidding strategies could be practiced. In order to estimate the required level of safety stock, the supply chain is modeled as a set of tandem queues and the lead-times (sojourn times) are computed by using both Markovian closed-form expressions and simulation experiments. Using the results of these models, the annual costs for each of the possible outsourcing strategies are estimated. One has to mention that the Markovian analysis, as expected, yields a more conservative estimate for the safety stock (about 15% more, on the average).

The framework has focused on two major aspects regarding the cost components of the outsourcing policy: the variable cost and the safety stock carrying cost. Nevertheless, other costs can be included in the comparison, such as that of quality, reliability, and dependability. Using activity-based costing (ABC), these costs can be factored in the variable cost.

Our analysis shows that the length of the lead-time, its variance, and the inventory carrying cost are among the decisive factors against competitive bidding strategies. If the variable cost differential between this strategy and that of the long-term partnership is not significant, the gains achieved from reduction in price and flexibility can be dissipated by the increased inventory cost of the safety stock. Particularly, this is more prevalent in cases when the layers of the supply chain increase in number and the available vendors for the item being outsourced operate on high load factors (busy).

In short, the approach proposed here provides the decision-maker with the means for a first cut evaluation scheme to compare the available outsourcing strategies. Henceforth, he/she can pursue further analysis of the particulars of the outsourcing strategy to be considered for implementation in the supply chain.

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References

Abdel-Malek, L., Valentini, G., Zavanella, L., 2002. Managing stocks in supply chains modeling and issues. In: Stefan, S., Maria, G. (Eds.), Cost Management in Supply Chains. Physica-Verlag, Wurzburg (Wien), pp. 325–335.

Chen, F., Drezner, Z., Ryan, J.K., Simchi-levi, D., 2000. Quantifying the bullwhip effect in a simple supply chain: The impact of forecasting, lead-times, and information. Management Science 46 (3), 436–443.

Forrester, J.W., 1960. Industrial Dynamics. MIT Press, Cambridge, MA.

Grieger, M., 2003. Electronic marketplaces: A literature review and a call for supply chain management research. European Journal of Operational Research 144, 280–294.

Hau, L.L., So, K.C., Tang, C.S., 2000. The value of information sharing in a two-level supply chain. Management Science 46 (5), 626–643.

Hill, R.M., 1988. The Single-vendor single-buyer integrated production-inventory model with a generalised policy. European Journal of Operational Research 97, 493–499.

Hill, R.M., 1999. The optimal production and shipment policy for the single-vendor single-buyer integrated production-inventory model. International Journal of Production Research 37, 2463–2475.

Kalchschmidt, M., Zotteri, G., Verganti, R., 2003. Inventory management in a multi-echelon spare parts supply chain. International Journal of Production Economics 81–82, 397–413.

Metters, R., 1997. Quantifying the bullwhip effect in supply chain. Journal of Operations Management 15, 89–100.

Minner, S., 2003. Multiple-supplier inventory models in supply chain management. International Journal of Production Economics 81–82, 265–279.

Otto, A., Kotzab, H., 2003. Does supply chain management really pay? Six perspectives to measure the performance of managing a supply chain. European Journal of Operational Research 144, 306–320.

Peleg, B., Lee, H.L., Hausman, W.H., 2000. Short-term e-procurement strategies versus long-term contracts. Journal of Operations Management 11 (4), 458–479.

Poirier, C.C., Bauer, M.J., 2001. E-supply Chain: Using the Internet to Revolutionize Your Business. Berrett-Koehler Publishers Inc., San Francisco.

Rau, H., Wu, M.Y., Wee, H.M., 2003. Integrated inventory model for deteriorating items under a multi–echelon supply chain environment. International Journal of Production Economics 86, 155–168.

Ross, S.M., 1997. Introduction to Probability Models. Academic Press, New York.

Silver, E.A., Pyke, D.F., Peterson, R., 1998. Inventory Management and Production Planning and Scheduling. Wiley, New York.

Srinagesh, G., Kapuscinski, R., Tayur, S., 1999. Value of information in capacitated supply chains. Management Science 45 (1), 16–24.

Valentini, G., Zavanella, L., 2003. The consignment stock of inventories: Industrial case and performance analysis. International Journal of Production Economics 81–82 (11), 215–224.

Weele, A.V., 2000. Purchasing and Supply Chain Management: Analysis, Planning and Practice. Thomson Learning, London.