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Reducing lead time risk through multiple sourcing: The case of stochastic demand and variable lead time

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Abstract: This paper studies a buyer sourcing a product from multiple suppliers under stochastic demand. The buyer uses a (Q,s) continuous review, reorder point, order quantity inventory control system to determine the size and timing of orders. Lead time is assumed to be deterministic and to vary linearly with the lot size, wherefore lead time and the associated stockout risk may be influenced both by varying the lot size and the number of contracted suppliers. This paper presents mathematical models for a multiple supplier single buyer integrated inventory problem with stochastic demand and variable lead time and studies the impact of the delivery structure on the risk of incurring a stockout during lead time.

Keywords: Variable lead time; Supply chain coordination; Supplier selection; Multiple sourcing; Delivery structure; Integrated inventory

Introduction

The management of risks in supply chains has received increased attention among both practitioners and researchers in recent years. Reasons for the growing importance of risk management are manifold and originate from various trends that enhance the exposure of supply chains to risks. Business concepts, such as outsourcing initiatives, global sourcing, reduced supplier bases and inventory buffers aim to improve the performance of the supply chain in a stable environment, but also increase its vulnerability to potential disruptions (see, e.g., Norman and Jansson, 2004; Hendricks and Singhal, 2005a). Empirical studies indicate that companies suffering from supply chain disruptions experience significant declines in operating performance (Hendricks and Singhal, 2005b) as well as lower stock returns and higher equity risks relative to their industry benchmarks (Hendricks and Singhal, 2005a), which illustrates the importance of controlling risks in the supply chain. To mitigate the impact of disruptions associated with various types of risks, it is necessary to coordinate the material flows in the network of organisations and to collaborate with upstream and downstream members of the supply chain to improve operations and to ensure continuity (Tang, 2006). A continuous flow of materials thereby depends on the sourcing structure, i.e. on the composition of the supplier base and the coordination of deliveries, as well as on the allocation of inventories along the supply chain.

In the area of inventory management, two main questions arise: How much inventory should be kept on hand in each product class to assure adequate supplies for customers and yet avoid unnecessary inventory investments, and how often should the inventory be replenished. In cases where delivery times and quantities or customer demand may not be predicted with certainty, inventory increases the robustness of the supply chain by balancing demand and supply and by reducing the risk of a stockout between successive deliveries, at the expense of higher inventory carrying costs. Since a variation of the sourcing structure may also impact disruption risks, both alternatives have to be considered as potential risk reduction methods.

Various publications addressed the determination of safety stocks in cases where customer demand and/or lead times are uncertain. In this context, many authors studied multiple sourcing as a means to reduce supply risks and showed that in case of stochastic lead times, contracting multiple suppliers is an appropriate measure to reduce the risk of a stockout in the period between the issue and receipt of an order. Sculli and Wu (1981), for instance, considered a continuous review inventory model with two suppliers under normally distributed lead times and assumed that the replenishment quantity is split into two portions, which are ordered simultaneously at the suppliers. In this case, the effective lead time is the minimum of the set of random variables representing the lead time of each supplier, which helps to reduce stockout risk and consequently expected total costs. Hayya et al. (1987) conducted a simulation study to estimate the effects of splitting orders between two suppliers on stockout risk and average inventory. Sculli and Shum (1990) extended the model to include multiple suppliers, and Kelle and Silver (1990a,b) considered the case of splitting replenishment orders among two or more suppliers with identical lead times following a Weibull distribution. Ramasesh et al. (1991, 1993) provided further extensions to the model and studied uniform and exponential lead times as well as identical and nonidentical suppliers. The case where demand and lead times are both stochastic was analysed by Lau and Zhao (1993), who studied the impact of order splitting among two suppliers on reducing stockout risk. The authors showed that order splitting lowers cycle inventory and that contracting a second supplier with a larger mean lead time than the first supplier may not necessarily increase expected total costs. Chiang and Benton (1994) provided a comparative analysis of single and dual sourcing practices under normally distributed demand and shifted-exponential lead times. Numerical studies indicated that dual sourcing provides a higher service level and results in higher order quantities than single sourcing. A study of order splitting from an inventory perspective under a generic lead time distribution can be found in Hill (1996), who showed that multiple sourcing reduces average stock levels. Ganeshan et al. (1999) investigated the benefits of splitting orders between a reliable and an unreliable supplier that offers a purchase price discount. Cost comparisons were used to derive the discount rates the unreliable supplier needs to provide to make splitting worthwhile for different order allocations. Order splitting between two suppliers with different lead time characteristics was also studied by Kelle and Miller (2001), who investigated its effects on stockout risk. They showed that dual sourcing can provide lower stockout risks even for a second supplier with an inferior delivery performance, and that an optimal order split leads to lower stockout risks in the case of different lead time characteristics, as compared to an equal split. Ryu and Lee (2003) considered dual sourcing models with lead time expedition cost functions and showed that these investments lead to significant savings. Sajadieh and Eshghi (2009) extended dual sourcing models and introduced order quantity-dependant lead times and unit purchase prices. Numerical results indicated that purchase quantity discounts decrease savings obtained from order splitting and result in unequal splits even if suppliers are identical. Furthermore, order splitting seems to be favourable when delivery characteristics are similar. A comprehensive overview of different alternatives of splitting orders between multiple suppliers can further be found in Thomas and Tyworth (2006).

A second stream of research that studies measures to reduce lead time risk assumes that lead times may be crashed to a given minimum duration at an additional cost and analyses the impact of lead time reduction efforts on the stockout risk and the expected total costs of the system. One of the first papers dealing with a variable lead time in a continuous review model is the one of Liao and Shyu (1991). The authors assumed that demand is normally distributed and showed that reducing lead time may result in lower stockout risk and consequently lower expected total costs. While Liao and Shyu (1991) assumed that the order quantity is predetermined, Ben-Daya and Raouf (1994) proposed a model that treats both lead time and order quantity as decision variables and studied the cases of a linear and an exponential lead time crashing cost-function. Ouyang et al. (1996) introduced another extension and include shortages in the model. They assumed that a certain fraction of the demand during the stockout period is backordered and that the remaining fraction results in lost sales. Chandra and Grabis (2008) assumed that reduced lead time is accompanied by increased procurement costs due to premium charges imposed by the supplier or higher transportation costs, and studied the interdependencies between a reduction in stockout risk and an increase in procurement costs. Jha and Shanker (2009) formulated an integrated inventory model with controllable lead time for items with a constant decay rate and optimised order quantity, lead time and the number of shipments under a service level constraint. Other authors studied lead time reduction in inventory models with stochastic demand and permitted further model parameters to be varied as well, such as setup costs or product quality. Examples are the models of Ouyang and Chang (2002), Ben-Daya and Hariga (2003), Zequeira et al. (2005), and Pan and Lo (2008). A continuous review model with variable, lot size-dependent lead time can finally be found in Ben-Daya and Hariga (2004) and Glock (2009, In Press a). The authors assumed that lead time varies linearly with the lot size and studied the impact of a variation in the lot size on the safety stock and the expected total costs of the system.

A closer look at the literature reviewed above reveals that previous research has mainly focused on analysing multiple sourcing in cases where lead time is stochastic, but that the case where lead time is deterministic and varying with the lot size has thus far not been studied in a setting with multiple suppliers. This is insufficient inasmuch as many real world scenarios exist where stochastic influences on the replenishment lead time are negligible (for example if buyer and supplier are located in close geographic proximity), but where the length of the lead time is primarily influenced by the quantity ordered (for example in serial production processes). If demand during lead time is assumed to be stochastic in such a setting, the buyer may influence stockout risk by splitting the replenishment order on multiple suppliers and by thus reducing the length of the individual lead times, as well as by varying order quantities and replenishment policies. To close this gap, a single item integrated inventory system consisting of multiple suppliers and a single buyer who faces stochastic demand and splits the replenishment orders among the suppliers is studied in this paper. Our work focuses explicitly on the total costs of the supply chain under study (for reviews of so-called integrated inventory models see Goyal and Gupta, 1989; Ben-Daya et al., 2008; Glock, In Press b) to examine how supply chain operations and the management of risks can be improved through coordination and collaboration among the supply chain partners (Tang, 2006; Cao et al., 2010). This also enables us to assess the impact of individual decisions on the risk and performance of the supply chain partners and helps to develop strategies that improve the competitive position of the supply chain as a whole.

The remainder of the paper is organised as follows: In the next section, the article outlines the assumptions and definitions which are used in the paper. Accordingly, Section 3 develops formal models which consider stochastic demand and variable lead time in a system with multiple suppliers. Section 4 contains a numerical study and Section 5 concludes the article.

Problem description

This paper studies the case where a buyer sources a product from multiple suppliers under stochastic demand. The buyer uses a (Q,s) continuous review, reorder point, order quantity inventory control system to determine the size and timing of orders and issues an order whenever the inventory position reaches the reorder point. Lead time is assumed to be deterministic and to vary linearly with the lot size. This functional form is representative for (serial) production processes where each product is manufactured individually and may be transported to the subsequent stage or the customer after its completion (note that this scenario is studied in many papers, see e.g. Kim and Benton, 1995; Ben-Daya and Hariga, 2004; Hsiao 2008; Glock 2009, In Press a, among others). However, we note that other production processes might be associated with different functional forms, such as a step-wise lead time-function for example, which could be representative for production processes where each batch needs a certain production time regardless of the number of units in the batch, for instance in case products are heated in an oven or treated in an immersion bath. The replenishment quantity is split evenly among the suppliers, who initiate production upon receipt of the order and deliver the production quantity to the buyer after the lead time L has elapsed. To reduce the complexity of our model, we assume that the suppliers are homogeneous, i.e. that all problem parameters are identical for the suppliers (note that this assumption is not uncommon in the literature, cf. for example Kelle and Silver, 1990b; Ramasesh et al.,1991; Chiang and Benton, 1994; Hill, 1996; Ganeshan, 1999). This scenario is representative for a variety of industries, for example for industries that produce standard mechanical components for automotive manufacturers or for commodity markets (see for example Oladi and Gilbert, 2009; Smith and Thanassoulis, 2008). Further, we consider two alternative delivery structures which are discussed in Rosenblatt et al. (1998), Park et al. (2006), Kim and Goyal (2009), Kheljani et al. (2009), and Glock (2011a, 2011b), among others, and which are illustrated exemplarily in Figure 1. In the first case (cf. part a) of Figure 1), which we term simultaneous deliveries in the following, the suppliers deliver at the same time to the buyer. In the second case (cf. part b) of Figure 1), which we term sequential deliveries, the suppliers deliver alternately, such that a shipment reaches the buyer exactly when the shipment of the supplier who has delivered previously is expected to have been used up (note that the dashed line in Figure 1 represent inventory build-up with a lower production rate).

Figure 1

Apart from the assumptions already stated, we assume the following hereafter:

1. Demand per unit of time follows a normal distribution with mean D and standard deviation σ. Thus, demand during lead time, x, has the probability density function f(x) with mean DL(Q,n) and standard deviation $\sigma\sqrt{L(Q,n)}$.
2. Lead time is proportional to the lot size produced by the supplier and consists of processing time and a fixed delay due to transportation or nonproductive time (see Ben-Daya and Hariga, 2004). Lead time may thus be calculated as L(Q,n) = Q/(nP)+b.
3. Unsatisfied demand at the buyer is backordered.
4. The focus is on the total costs of the system, since we assume that the suppliers will pass on savings or increases in cost to the buyer. Transfer payments between the suppliers and the buyer are not considered.
5. The supplier handling and material receiving costs encompass all costs associated with the management of the supplier base and the receipt of incoming deliveries. The supplier handling costs are assumed to vary with the number of contracted supplier with a constant, increasing or decreasing incremental cost trend and are calculated as an^t with a and t as specific cost parameters (see Thomas and Tyworth, 2006). The material receiving costs are incurred with every receipt of a delivery, regardless of whether it is sent from a single or multiple suppliers (see Kelle et al., 2007). Thus, the entire supplier handling and material receiving costs amount to $an^t + Y$ in case of simultaneous deliveries and $an^t + nY$ in case of sequential deliveries.

In addition, the following terminology is used:
A = ordering costs per order
a = cost parameter of the supplier handling cost function
b = fixed delay factor
C(n) = supplier handling and material receiving costs
D = demand rate in units per unit time
h_b = unit inventory carrying charges per unit of time at the buyer
h_v = unit inventory carrying charges per unit of time at the suppliers
K = setup and transportation costs per production lot at the supplier
L = lead time
n = number of suppliers
n_{min} = minimum number of suppliers the buyer needs to contract
$\hat{n}$ = $n_{min} - 1$
k = safety factor
p = inverse production rate, i.e. p = 1/P
P = production rate in units per unit time
π = backorder costs per unit backordered
Q = order quantity
q = production quantity of supplier i
r = reorder point
S = safety stock
t = cost parameter of the supplier handling cost function
σ = standard deviation of demand
x = lead time demand
Y = receiving costs per delivery

Definitions
[ε] denotes rounding a non-integer value ε to the nearest integer
$\lceil \varepsilon \rceil$ denotes rounding a non-integer value ε up to the next integer
|ε| the absolute value of ε, i.e. $|\varepsilon| = \sqrt{\varepsilon^2}$
SEQ model that considers sequential deliveries from the suppliers
SIM model that considers simultaneous deliveries from the suppliers

Model development

Simultaneous deliveries

First, we consider the case where the buyer places orders simultaneously at the suppliers. In this case, it can be easily shown that it is optimal to order an equal quantity at each of the suppliers. If q denotes the production quantity of supplier i and n the number of suppliers, it follows that q(Q,n) = Q/n. As can be seen in Figure 1, the suppliers initiate production with a delay of b time units after receipt of the order and deliver a batch of size Q/n to the buyer as soon as the batch has been finished. Inventory per lot at supplier i may thus be calculated as $Q^2/(2Pn^2)$. The total costs of supplier i are consequently given as:

$$(1) \quad \frac{QDh_v}{2Pn^2} + \frac{KD}{Q}$$

The buyer, in turn, incurs ordering costs, supplier handling and material receiving costs, inventory carrying costs and backorder costs. To calculate the inventory carrying costs, we use the common approximation of Hadley and Whitin (1963), who showed that the average inventory may be expressed as Q/2 + S. The backorder costs per cycle may be derived by calculating the expected shortage, which is:

(2) $$s(r, L(Q,n)) = \int_r^{\infty} (x - r) f(x) dx$$

The sum of inventory carrying costs, ordering costs, supplier handling and material receiving costs and backorder costs per unit time amounts to:

(3) $$\frac{(A + C(n))D}{Q} + h_b\left(\frac{Q}{2} + S\right) + \frac{\pi D}{Q} s(r, L(Q,n))$$

The system's expected total costs per unit of time may now be calculated as the sum of (1) and (3), whereby (1) has to be summed up over all suppliers:

(4) $$ETC = (A + nK + C(n))\frac{D}{Q} + \frac{Q}{2}\left(h_b + \frac{Dh_v}{Pn}\right) + Sh_b + \frac{\pi D}{Q} s(r, L(Q,n))$$

Before deriving a solution for the model, it is beneficial to substitute the reorder point r in (4) by the safety factor k. This can be done by transforming the normal probability density function in (2) into a standard normal probability density function and by substituting r by $k\sigma\sqrt{L(Q,n)}$ + μ, with μ being the expected demand during lead time, DL(Q,n). The safety stock, in turn, equals the difference between the reorder point and the expected demand during lead time, r – DL(Q,n). Using the expression introduced above leads to:

(5) $$S = k\sigma\sqrt{L(Q,n)} = k\sigma\sqrt{pq(Q,n) + b}$$

It follows that:

(6)

$$ETC = (A + nK + C(n))\frac{D}{Q} + \frac{Q}{2}\left(h_b + \frac{Dh_v}{Pn}\right) + k\sigma\sqrt{pq(Q,n) + b}h_b + \frac{\pi D}{Q}\sigma\sqrt{pq(Q,n) + b}\psi(k)$$

where $\psi(k) = \int_k^{\infty}(z - k)f(z)dz$ and $f(z)$ is the standard normal probability density function. To simplify notation, let G(n) = A + nK + C(n) and H(n) = $h_b + \frac{Dh_v}{Pn}$. Consequently, the expected total costs can be rewritten as:

(7) $$ETC = G(n)\frac{D}{Q} + \frac{Q}{2}H(n) + k\sigma\sqrt{pq(Q,n) + b}h_b + \frac{\pi D}{Q}\sigma\sqrt{pq(Q,n) + b}\psi(k)$$

When searching for optimal values for Q, k and n, it has to be considered that the delivery quantity needs to be large enough to exceed the reorder point reduced by the safety stock, i.e. R – S < Q has to hold. In other words, the time to produce the lot at the suppliers has to be shorter than the expected consumption time of the lot at the buyer. If this condition is not met, planned shortages may occur, since the suppliers are assumed to deliver after the buyer is expected to have run out of material. As the production time of supplier i depends on both Q and n, and the expected consumption time of the buyer is dependent on Q, it is obvious that the condition formulated above has to be considered when finding values for Q and n.

Hadley and Whitin (1963) and Ben-Daya and Hariga (2004) suggested that an optimal solution to their models can be found by calculating partial derivatives of the respective objective functions with respect to Q and k. However, since the values of Q and n are restricted in the present case, it would be necessary to derive the Karush-Kuhn-Tucker (KKT) conditions to guarantee optimality (see e.g. Hillier and Lieberman, 2001). Since the objective function (7) is too complex to derive the KKT conditions and since convexity of (7) in Q cannot be proved, we used the NMinimize-Function of the software package Mathematica 7.0 (Wolfram Research, Inc.) to derive a solution for the problem. The NMinimize-function contains several methods for solving constrained and unconstrained global optimisation problems, such as genetic algorithms, simulated annealing or the simplex method. Using a standard software package has several advantages, especially for practitioners. On the one hand, results may be easily obtained and reproduced without the need to develop sophisticated solution mechanisms, and further the user may benefit from advances in optimisation theory which may be included in future release versions of the software package. Numerical results for the problem are presented in Section 4.

Sequential deliveries

As can be inferred from Figure 1, for a given lot size and a given number of suppliers, the total costs of supplier i are identical for both the cases of simultaneous and sequential deliveries. Consequently, the total costs of supplier i equal those given in (1). However, two major aspects are different in this model as compared to the case of simultaneous deliveries. First, for given values of Q, n, and k, the average inventory at the buyer is reduced to $Q/(2n) + S$ due to the fact that the buyer does not receive deliveries of size Q, but more frequent deliveries of size Q/n, which reduces the expected maximum inventory in the system. Second, the expected shortage and total shortage costs may have to be calculated differently in this case, depending on the values of P, D, n and b. First, consider the case where $Q/(nD) \geq Q/(nP)+b$. In this case, as can be seen in part b) of Figure 1 (cf. the bold lines), an order is placed at one of the suppliers as soon as the inventory level reaches the reorder point. The supplier initiates production after a delay time b and delivers the order once the production lot q has been completed. As soon as the inventory level reaches the reorder point again, an order is placed at one of the other suppliers. It is obvious that in this case, both safety stock and expected shortages may be calculated as in expression (7). Thereby the expected shortage, which occurs in every delivery cycle, has to be multiplied with n. However, in case $Q/(nD) < Q/(nP)+b$ (cf. the dotted lines in part b) of Figure 1), the problem arises that the time to produce a lot of size q at one of the suppliers exceeds the average consumption time of this lot. To avoid excessive shortages, it is necessary to place an order at the suppliers in an earlier consumption cycle, which results in overlapping production phases. The major problem with this practice is that the model of Hadley and Whitin (1963) requires in its original form that there is never more than one order outstanding at a time, wherefore further assumptions are necessary to assure that the formulation introduced above may still be used in this case. As was shown by Hadley and Whitin (1963), their approximation is applicable for any number of orders outstanding if the probability of the lead time demand exceeding $r + (n_{min}-1)Q/n$ is low, which implies that after the arrival of a shipment, the probability is low that there are still backorders on the books, i.e. that the shipment is not able to remove all the backorders and inventory after the shipment does not exceed the reorder point. Further, it is required that the backorder costs are independent of the length of the stock-out period and that the contribution of the expected number of backorders to the inventory carrying charge is negligible. To assure that the approximation introduced above may still be used in case Q/(nD) < Q/(nP)+b, we assume in the following that these prerequisites are met.

The following example illustrates how the expected number of backorders may be calculated. Assume that the buyer orders a lot of size q at supplier i at time 0. Supplier i initiates production after the delay time b and finishes the lot at time pq + b. However, due to q/D < q/P+b, it is necessary that the buyer receives further shipments during the lead time L to avoid planned shortages. The number of deliveries the buyer needs to receive during the lead time L to avoid planned shortages may be calculated as $\hat{n} = n_{min} - 1$, whereby n_{min} is the minimal number of suppliers the buyer needs to contract. n_{min}, in turn, may be calculated by considering that the production quantity of supplier i needs to be large enough to exceed the reorder point reduced by the safety stock, i.e. R – S < Q/n. It follows that:

$$(8) \qquad n_{\min} > D\left(\frac{1}{P} + \frac{nb}{Q}\right)$$

The actual n_{min} is the smallest integer number for which inequation (8) is satisfied. The expected shortage may now be determined by calculating the expected demand during lead time exceeding the reorder point r and the number of shipments the buyer receives during the lead time:

$$(9) \qquad s(r, L(Q,n)) = \int_{r+Z}^{\infty} (x - Z - r)\, f(x) dx \quad \text{where } Z = q(Q,n)\hat{n}$$

Note that in case Q/(nD) ≥ Q/(nP)+b, $\hat{n}$ equals 0 and expression (9) reduces to (2). The safety stock now equals the sum of the reorder point and the delivery quantity Z, reduced by the expected demand during lead time, i.e. S = r + Z – DL(Q,n). Considering that r = $k\sigma\sqrt{L(Q,n)}$ + μ – Z, it becomes obvious that the safety stock equals the one given in (5).
The system's expected total costs for both the cases Q/(nD) ≥ Q/(nP)+b and Q/(nD) < Q/(nP)+b may now be calculated as follows:

(10)

$$ETC = (A + nK + C(n))\frac{D}{Q} + \frac{Q}{2}\left(\frac{h_b}{n} + \frac{Dh_v}{Pn}\right) + k\sigma\sqrt{pq(Q,n) + b}\,h_b + \frac{\pi nD}{Q}\sigma\sqrt{pq(Q,n) + b}\,\psi(k)$$

Substituting G(n) = (A + nK + C(n)) and H(n) = $\left(\frac{h_b}{n} + \frac{Dh_v}{nP}\right)$, the expected total costs can be rewritten as:

$$(11) \quad ETC = G(n)\frac{D}{Q} + \frac{Q}{2}H(n) + k\sigma\sqrt{pq(Q,n) + b}\,h_b + \frac{\pi nD}{Q}\sigma\sqrt{pq(Q,n) + b}\,\psi(k)$$

To find a solution for Q, k and n that minimises the expected total costs, we again used the NMinimize-function of the software package Mathematica 7.0 and assumed that the condition R – S < Q/n has to be satisfied.

Effects of the decision variables on the safety stock and risk

In the models developed in this paper, two of the buyer's decision variables directly influence lead time and thus the risk of incurring a stockout, which also affects safety stock: the order quantity Q and the number of suppliers n. Furthermore, the buyer has to decide on the desired service level, which is determined by the safety factor and the alternative delivery structures, and which, in turn, affects available stocks and stockout risk. The effect of the variables on the safety stock of the system and the risk of incurring a stockout during lead time will be discussed in the following:

The impact of a variation of Q on the level of safety stock kept at the buyer for the case of a lot size-dependent lead time has been analysed by Kim and Benton (1995). The authors differentiated between an order frequency effect and a lead time effect: The order frequency effect refers to the fact that a reduction in Q leads to an increase in the order frequency D/Q, which in turn exposes the system to the risk of stockouts more often. Consequently, for a fixed lead time, a reduction in the lot size increases the safety stock S to control the occurrence of stockouts, and vice versa. The lead time effect, in contrast, describes a negative correlation between the length of the lead time and the uncertainty in demand during lead time. Thus, with a decreasing lot size, lead time is shortened, which leads to a lower demand uncertainty and a lower safety stock for a given order frequency. The interrelations described by Kim and Benton (1995) are also valid for the model developed in this paper.

Taking a closer look at the number of suppliers, an increase in n entails a smaller production lot size q at supplier i if Q remains constant. This, in turn, leads to a similar lead time effect than the one described above. In case of model SIM, the order frequency effect is not directly influenced by a variation in the number of suppliers if the order quantity Q remains constant. In model SEQ, however, an increase in the number of suppliers reduces the order cycle, which leads to a higher order frequency and the order frequency effect described above. Moreover, since an increase in n reduces inventory at the suppliers and at the buyer in case of a sequential delivery, we may assume that the order quantity Q is increased, which again leads to the order frequency effect.

The safety factor k, in turn, also influences safety stock and the risk of running out of stock. If the system aims on reducing the probability of incurring a stockout during lead time, a higher safety stock needs to be kept, which increases k. Ceteris paribus, this leads to higher inventory in the system, and thus induces the order frequency and lead time effect.

Finally, it is obvious that also the delivery structure influences the inventory position of the buyer. For a given lead time, a given safety factor and a given number of suppliers, sequential deliveries lead to lower inventory carrying costs at the buyer. This in turn favours higher order quantities, which may indirectly bring about the order frequency and lead time effects.

Clearly, a variation in Q, k or n influences the expected total costs in a variety of ways, and the delivery structure also has a significant impact on the expected total costs of the system. To gain further insights into the model behaviour and into the impact of the delivery structure on the expected total costs of the system, a simulation study was conducted whose results will be presented in the next section.

Simulation study

An analysis of equations (6) and (10) indicates that sequential deliveries result in lower costs for cycle inventory, at the expense of potentially higher shortage costs as compared to simultaneous deliveries, which may have a significant impact on sourcing decisions and the associated stockout risk. Before analysing the effects of the problem parameters and the inventory structure on the expected total cost and the risk in detail, a simple example illustrates the behaviour of the models developed in this paper. Consider a two-stage supply chain with the input parameters given in Table 1. Computing order quantities, numbers of contracted suppliers, service levels and expected total costs for both supply modes, sequential deliveries lead to higher order quantities as well as a higher number of suppliers. Further, sequential deliveries result in lower costs and a higher service level as compared to simultaneous deliveries (cf. Table 2).

Table 1

The effects of varying the different input parameters on the order quantity, the number of suppliers, the service levels and the expected total costs for both supply modes are illustrated in Table 2. Higher demand rates result in increasing order quantities, safety stocks and service levels for both supply modes which is associated with higher expected total costs. Higher production rates, in contrast to demand rates, lead to lower costs, especially for simultaneous deliveries, but have mixed effects on the other parameters. For sequential deliveries, the order quantity increases, whereas safety stock and service level decrease. In the case of simultaneous deliveries, similar effects can be observed for a constant number of suppliers. A higher standard deviation of demand induces higher safety stocks and higher total costs. An increase in the ordering costs leads to increasing order quantities and higher total costs especially for simultaneous deliveries and an increasing number of suppliers for sequential deliveries. The results for various parameters of supplier handling costs show that cost increases have only little influence on simultaneous deliveries, but that they result in smaller order quantities and a decreasing number of suppliers for sequential deliveries where usually more suppliers are used and consequently supplier handling costs are more important. Higher receiving costs also have little influences on simultaneous deliveries where all partial deliveries are stored at the same time, but lead to higher order quantities and costs in the case of sequential deliveries.

Table 2

Lower setup and transportation costs for suppliers lead to smaller lot sizes and lower expected total costs for both delivery modes. Increasing inventory holding costs induce lower order quantities, lower safety stocks and higher expected total costs. Service levels, however, decline if the buyer's inventory holding costs increase and rise if the suppliers' inventory holding costs increase. Higher backorder costs lead to slightly lower order quantities and higher safety stocks, service levels and costs. Increasing delay time induces higher cycle and safety inventories as well as increases in expected total costs.

To gain further insights into the behaviour of the models, we conducted a simulation study where we computed results for a set of 1,500 randomly generated problem instances. To generate the parameter values, the ranges presented in Table 3 were employed. An evaluation of the results showed that sequential deliveries (model SEQ) outperformed the model where all suppliers deliver simultaneously to the buyer (model SIM) in 99.9% of the problem instances we studied, and that sequential deliveries led to 16.94% lower expected total costs on average as compared to the other delivery structure. However, as Table 4 illustrates, model SIM may also lead to better results than model SEQ. The backorder quantity, which we use as a measure for the risk incurred in the system (for alternative measures to assess risk in logistic systems, the reader is referred to Chopra and Meindl (2007)), was higher for model SIM for 71.93% of the cases studied. On average, the backorder quantity was 4.38% lower in case of model SEQ as compared to model SIM. Finally, the number of suppliers was higher for the case of sequential deliveries in 96.20% of all problem instances and equal for all remaining data sets.

Table 3

Table 4

In a second step, we analysed the influence of the problem parameters on the relative advantage of the two delivery structures proposed in this paper. For this purpose, we conducted a regression analysis between the problem parameters and the ratio of the expected total costs of both structures as given by the quotient of (7) and (11). The results of the regression analysis with the problem parameters as independent variables and the ratio of the expected total costs as the dependent variable are given in Table 5. As can be seen, a statistically relevant relationship (with Sig. < 0.05) could be found between all problem parameters and the ratio of the expected total costs, with the exception of K, a and π.

Table 5

The results may be interpreted as follows: A higher demand rate or a lower production rate leads to a higher value for the ratio of (7) to (11) and consequently lower relative expected total costs for the case of sequential deliveries. This may be explained by the fact that both an increase in D and a decrease in P, ceteris paribus, lead to a higher value of n_{min}, i.e. a higher minimum number of suppliers the buyer needs to contract. In case the suppliers deliver sequentially to the buyer, an increase in the number of suppliers reduces inventory carrying costs both at the buyer and at the suppliers, whereas in case of simultaneous deliveries, inventory is only reduced at the suppliers. As a consequence, a higher value for n_{min} results in an increase in the supplier handling costs for both delivery structures, but in a higher reduction in inventory in case suppliers deliver sequentially. This explains why the relative advantage of model SEQ increases in n_{min}.

A second effect that could be identified is that a reduction in receiving costs increases the relative advantage of sequential deliveries. The relationship between Y and the cost ratio can be explained by the fact that in case of model SEQ, more batches are delivered to the buyer, wherefore receiving costs occur more often. If Y is high, the fixed costs for receiving orders are high in case of sequential deliveries, which leads to a higher order quantity and a reduction in the number of contracted suppliers. Both effects reduce the relative advantage of sequential deliveries since simultaneous deliveries lead to scale effects in the receiving department. The ordering costs obviously have an opposite effect.

The impact of h_b on the relative advantage of both delivery structures may be explained by the fact that in case of sequential deliveries, inventory is reduced at the buyer, wherefore this delivery structure is especially beneficial in case inventory carrying costs at the buyer are high. In contrast, since more suppliers are contracted in case of model SEQ as compared to model SIM, more inventory has to be kept at the suppliers. Consequently, as h_v increases, the relative advantage of model SEQ is reduced.

A last effect that could be identified is that an increase in b increases the relative advantage of model SEQ. This result is caused by the fact that in case of sequential deliveries, the buyer incurs a smaller stockout risk per delivery, but faces this stockout risk more often. Obviously, higher values for b reduce the overall risk stronger in case of model SEQ as compared to model SIM, which necessitates a lower adjustment of the other model parameters and consequently increases the advantage of this delivery structure.

To assess the risk behaviour of both models, we conducted a second regression analysis with the problem parameters as independent variables and the ratio of the backorder quantities as the dependent variable. The results are presented in Table 6.

Table 6

The results illustrate that P, Y, h_b, h_v, π and b had a significant influence on the ratio of the backorder quantities, while the influence of the other parameters was very small or statistically insignificant. As can be seen, an increase in P leads to a relatively higher amount of backorders in the case of simultaneous deliveries. Again, this may be explained by the influence of P on n_{min}, which may reduce the number of suppliers and entail that the buyer incurs a higher stockout risk per delivery which he/she faces less often. As indicated above, this may reduce the overall stockout risk.

A second aspect that could be identified is that a reduction in Y leads to a relatively higher amount of backorders in the case of simultaneous deliveries. This may again be explained by the order frequency effect: If Y adopts a high value, the number of suppliers is restricted stronger in model SEQ, which results in higher production quantities, longer lead times and consequently higher backorder quantities. Obviously, this is a result of the scale effects the company realises in model SIM, where deliveries are received at the same time and where the workload in the receiving department can be reduced. The influence of h_b and h_v may be explained analogous. An increase in the backorder costs also has a stronger impact on the backorder quantity in the case of sequential deliveries. This is due to the fact that lead time was on average slightly higher in model SEQ than in model SIM, wherefore an increase in π necessitated a larger reduction of lead time in this case. Further, backorders occur n times per lot in case of model SEQ, which intensifies this effect. The influence of b on the backorder quantities of both models finally has already been explained above.

Conclusion

The purpose of this paper was to investigate the impact of the delivery structure and the number of suppliers on the expected total costs of the supply chain and the risk of incurring a stockout.

The contribution of the paper is twofold: First, it extends prior works on integrated inventory models to consider multiple suppliers and the supplier selection decision in a setting with stochastic demand and variable lead time, and second it studies how multiple sourcing influences the risk of incurring a stockout in case of a deterministic lead time and stochastic demand. Both aspects have not been analysed in the literature before.

The results of the paper indicate that a delivery structure with sequential deliveries outperforms the case where suppliers deliver simultaneously to the buyer in most cases, although the risk of incurring a stockout is not necessarily lower in case of sequential deliveries. Based on our simulation study, we conclude that sequential deliveries are especially beneficial in case a) the buyer faces small suppliers and consequently needs to receive products from a large number of sources to satisfy demand, b) receiving efforts for the considered products or materials and associated expenditures at the buyer are low, c) fixed lead time components are high as compared to order quantity-dependant lead time components and d) inventory carrying costs at the buyer are high whereas inventory carrying costs at the suppliers are low. Table 7 summarises factors that influence the relative advantage of delivery structure SEQ.

Table 7

If one or more of these conditions are not met, the relative advantage of sequential deliveries decreases, although this delivery structure may still lead to lower expected total costs than the case of simultaneous deliveries. The question which delivery structure is better in a certain scenario depends on the problem parameters, although we were able to identify cost tendencies. The implications for practitioners clearly are that in case the conditions mentioned above are met, a sequential delivery structure should be implemented to reduce the total costs of ordering and receiving the product. In cases where some or all of these conditions are not met, choosing a delivery structure with simultaneous deliveries results in a lower increase in expected total costs. In addition, if we assume that situations may arise where companies try to minimise the number of shipments they receive, for example because limited resources are available in the receiving area of the company (for further examples, the reader is refereed to Gardner and Dannenbring, 1979; Schneider and Rinks, 1989; Ellram and Siferd, 1993), it may be beneficial to implement simultaneous deliveries. Cases with limited receiving resources may be interpreted as a restriction on the number of shipments a company is able to receive. In such a situation, a company may search for cost-optimal solutions without investing in new resources. Thus, it may be beneficial to implement a simultaneous delivery strategy with an optimal parameter setting as compared to a sequential strategy with a non-optimal parameter setting caused by this restriction. Further, the costs of receiving shipments may be difficult to estimate in practical situations. In such a case, if the costs of model SIM and model SEQ are close to each other, the company may decide to implement model SIM to reduce work in the receiving department without explicitly estimating receiving costs (which, in turn, may also be associated with costs). We conclude that there are situations where a company may want to implement a SIM policy although it leads to (slightly) higher total costs than model SEQ.

One limitation of our work clearly is the focus on homogeneous suppliers, which restricts its applicability to industries with homogeneous mass products, i.e. markets which are characterised by almost perfect competition. Consequently, future research could concentrate on studying heterogeneous suppliers in a multiple sourcing environment and analyse parameters which influence the question of how many and which suppliers to select. A heuristic method for selecting suppliers in an integrated inventory model, which, however, is only applicable to cases where demand is deterministic, can be found in Glock (2011a). Further extensions may include the study of batch shipments, which have also been shown to reduce stockout risk (see e.g. Ben-Daya and Hariga, 2004), or other types of risks, such as uncertain lead times or product quality.

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Table Captions

Figures Captions

Tables and Figures

Example data

D	=	150	demand rate in units per unit time
P	=	160	production rate in units per unit time
σ	=	10	standard deviation of demand
A	=	75	ordering costs per order
a	=	8	first cost parameter of the supplier handling cost function
t	=	1.75	second cost parameter of the supplier handling cost function
Y	=	150	receiving costs per delivery
K	=	300	setup and transportation costs per production lot at the supplier
h_b	=	6	unit inventory carrying charges per unit of time at the buyer
h_v	=	3	unit inventory carrying charges per unit of time at the vendors
π	=	100	backorder costs per unit backordered
b	=	0.1	fixed delay factor

Table 1: Sample data set.

Effects of the key model parameters

		Simultaneous Deliveries					Sequential Deliveries				
		Q	n	SS	SL	ETC	Q	n	SS	SL	ETC
D	150	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	250	223	2	14	94.65	1994.33	593	4	18	96.44	1754.66
	350	315	3	14	94.60	2706.26	649	4	20	97.22	2224.60
P	160	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	260	141	1	13	94.36	1208.79	542	4	13	94.58	1163.66
	360	146	1	11	94.16	1162.05	562	4	11	94.38	1118.50
σ	5	185	2	6	92.60	1422.59	511	4	8	94.89	1198.25
	10	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	20	181	2	24	92.76	1562.59	493	4	31	95.07	1372.67
A	50	181	2	12	92.76	1448.71	376	3	15	94.99	1248.84
	75	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	100	186	2	12	92.56	1489.61	634	5	15	94.93	1262.93
a	4	182	2	12	92.72	1458.26	746	6	15	95.03	1240.35
	8	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	12	185	2	12	92.60	1480.28	383	3	15	94.89	1269.54
t	1.5	183	2	12	92.68	1465.81	875	7	15	95.00	1245.22
	1.75	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56

	2	184	2	12	92.64	1473.47	382	3	15	94.91	1265.59
Y	100	178	2	12	92.88	1427.79	478	4	15	95.22	1195.51
	150	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	200	189	2	12	92.44	1509.62	530	4	16	94.70	1314.53
K	200	160	2	12	93.60	1294.64	449	4	15	95.51	1130.80
	300	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	400	240	1	17	90.40	1587.78	555	4	16	94.45	1369.81
h_b	4	215	2	14	94.27	1245.98	575	4	18	96.17	1089.18
	6	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	8	163	2	11	91.31	1664.26	456	4	14	93.92	1405.62
h_v	1	240	1	17	90.40	1300.28	567	4	16	94.33	1131.40
	3	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	5	173	2	12	93.08	1552.74	460	4	15	95.40	1369.32
π	50	185	2	9	85.20	1452.96	510	4	12	89.80	1239.08
	100	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	150	183	2	14	95.12	1477.90	502	4	17	96.65	1265.86
b	0.01	131	1	15	94.76	1299.12	503	4	15	94.97	1250.50
	0.10	183	2	12	92.68	1469.32	505	4	15	94.95	1256.56
	1.00	283	2	17	88.68	1639.18	516	4	22	98.84	1305.04

Table 2: Results for the sample data set.

Parameter ranges for simulation			
D	75	-	500
P	75	-	500
σ	5	-	20
A	50	-	200
a	5	-	10
t	0.5	-	2.0
Y	100	-	250
K	100	-	500
h_b	3	-	8
h_v	1	-	6
π	25	-	150

b	0.01	-	1.00

Table 3: Parameter ranges employed in the generation of the random data sets.

Example 1	**a**	**A**	**b**	**D**	**h_b**	**h_v**	**K**	**P**	**π**
	7.66	151.31	0.29	427.96	3.93	5.67	131.00	146.41	86.56
Example 2	**a**	**A**	**b**	**D**	**h_b**	**h_v**	**K**	**P**	**π**
	8.10	70.61	0.05	233.90	7.84	3.24	459.40	355.83	115.01

σ	**t**	**Y**	**ETC SIM**	**ETC SEQ**
14.95	1.37	219.47	2720.13	2749.43
σ	**t**	**Y**	**ETC SIM**	**ETC SEQ**
11.70	1.50	185.51	1977.56	1915.23

Table 4: Illustration of the relative advantage of model SIM and model SEQ.

	Standardized Beta	**t**	**Sig.**
D	0.523	40.951	0.000
P	-0.226	-17.669	0.000
σ	-0.081	-6.323	0.000
A	0.139	10.833	0.000
a	-0.007	-0.513	0.608
t	-0.098	-7.693	0.000
K	-0.001	0.114	0.909
Y	-0.204	-15.985	0.000
h_b	0.259	20.180	0.000
h_v	-0.275	-21.509	0.000
π	-0.022	-1.745	0.081
b	0.471	36.839	0.000

Table 5: Results of the regression analysis for the ratio of the expected total costs.

	Standardized Beta	**t**	**Sig.**

D	-0.031	-1.505	-0.132
P	0.098	4.759	0.000
σ	-0.009	4.759	0.680
A	0.043	2.086	0.037
a	0.034	1.631	0.103
t	-0.051	-2.450	0.014
K	0.045	2.189	0.029
Y	-0.161	-7.085	0.000
h_b	0.103	4.960	0.000
h_v	0.154	7.456	0.000
π	-0.228	-10.998	0.000
b	0.494	23.894	0.000

Table 6: Results of the regression analysis for the ratio of the backorder quantities.

	Production conditions and parameter setting	Relative advantage of a SEQ delivery structure $RA_{SEQ} = ETC_{SIM} / ETC_{SEQ}$
a)	Large number of small suppliers needs to be contracted	****
b)	Lead time is more dependant of fixed components	***
c)	Inventory carrying costs at the buyer are high compared to the suppliers	**
d)	Low expenses for receiving of material- or product-shipments	*
(Note that * denotes the strenght of correlation between the relevant parameter and the relative advantage)		

Table 7: Factors that influence the relative advantage of delivery structure SEQ.

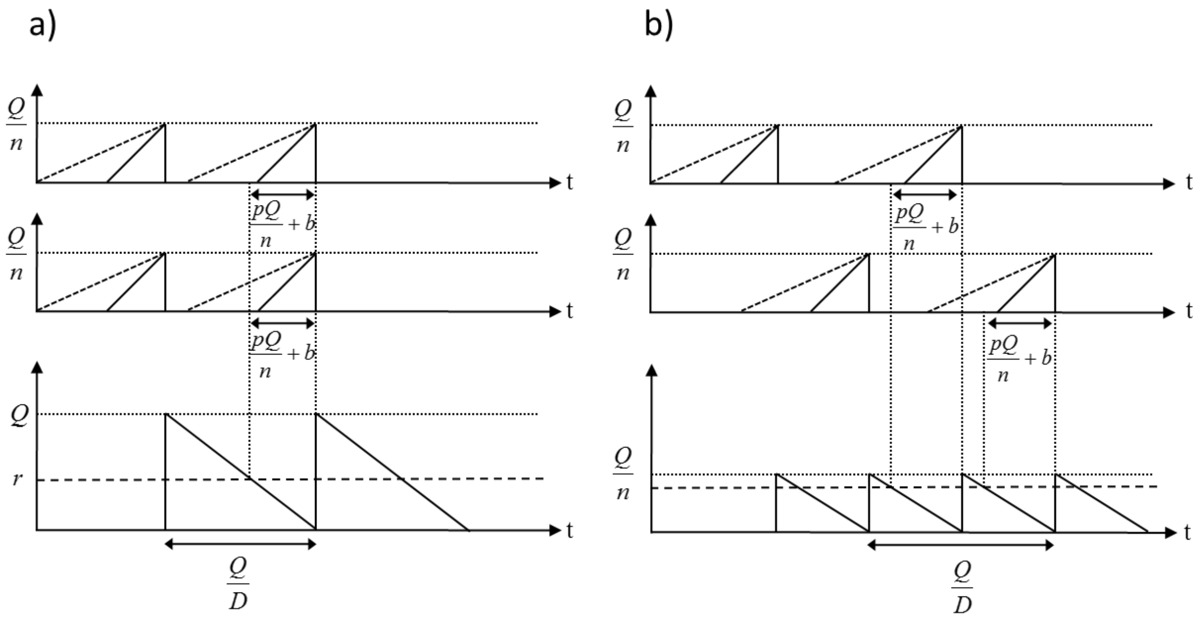

Figure 1. Alternative delivery structures for a system with two suppliers and a single buyer.