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by

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Abstract

This paper considers how to structure contractual incentives between a buyer and a single supplier of raw materials when early shipments are forbidden. A leader-follower game is used to take the supplier's behavior into account in the buyer's choice of incentives. Combinations of two types of incentives that the buyer might offer are considered: (1) a fixed-value, all-or-nothing incentive and (2) an incentive that decreases in value as time elapses. Given a desired probability of on-time delivery, optimal incentives are found by specifying indifference curves for on-time delivery and assessing the expected total cost of incentive schemes along that curve. Difficulties of using incentives to achieve 100% on-time delivery are considered and three example flow time distributions are presented.

1. Introduction

Just-in-time (JIT) purchasing involves eliminating waste in the linkages between a firm and its suppliers. Usually, the procedure for eliminating waste includes reducing the amount of in-bound material held by the firm, and reducing the lot size of deliveries. This reduction in inventory and lot size requires streamlined material handling, reduction or elimination of incoming inspection, and more effective communication of requirements between buyer and supplier. A more complete description of JIT purchasing has been provided elsewhere [1,2,3, and 4].

Although the benefits achieved in the ideal scenario seem promising, JIT purchasing has proven to be difficult to implement. Research shows that a substantial portion of buyers experience problems implementing JIT purchasing. Lack of support [5], vendor related work stoppages [6,7], suppliers holding excessive inventory to ensure timely delivery [8,9,10] are some of the problems that are reported.

One of the reasons that JIT purchasing is difficult to implement is that timing is extremely critical to a buyer's ongoing economical operation; yet the supplier controls the timeliness of the deliveries. In JIT purchasing buyers depend on their suppliers to provide inputs to their production process on a very strict time schedule. Because little or no excess inventory is kept to compensate for supply uncertainties, tardy deliveries cause costly work stoppages. In order to avoid these stoppages, firms implementing JIT purchasing must create buyer-supplier relationships that insure that deliveries are as timely as possible.

Not all managers are comfortable with the supplier dependence that JIT purchasing creates. Timeliness is costly to the supplier; the supplier must exert effort and dedicate resources to insure that deliveries occur on time. Managers may be skeptical that the supplier is willing to exert the level of effort desired by the buyer. Spekman [11] described this uneasy dependence as "strategic vulnerability," the risk associated with acting as if firms are vertically integrated when they are not. A buyer's strategic vulnerability is the result of the buyer having more limited means of controlling the supplier's behavior than under vertical integration. Reducing strategic vulnerability involves providing managers with improved methods of influencing the behavior of suppliers.

A variety of methods for influencing supplier behavior are available. Historically, most U.S. firms have used competitive pressure to influence suppliers. Buyers have allocated portions of their purchases of an item to multiple suppliers. The timeliness, quality, and price of the suppliers are used to determine what proportion of the purchases are allocated to each supplier. Asanuma [12] and MacMillan [13] describe the intricate competitive structure of buyer-supplier relationships used by large Japanese firms to maintain competitive pressure during the execution of long-term contracts. Johnston and Lawrence [14] discuss the use of reciprocity as a means of controlling the behavior of suppliers. Their work is an application of Axelrod's research into the prisoner's dilemma game [15]. Axelrod finds that the "tit-for-tat" strategy is an effective, robust strategy for creating cooperation. Supplier behavior can also be controlled through contractual means. Williamson [16] suggests the creation of "self-enforcing" contracts through the use of "hostages." A hostage is something of value that is held by the buyer to insure that the supplier performs according to the contract. The contract is self-enforcing in the sense that if the supplier fails to perform, the buyer keeps the hostage as a remedy for the breach of contract. A similar approach is used by Crocker and Masten [17]. Another model of contractual control is the principal-agent problem. In the principal-agent problem, incentives are created to make the actions that are desired by the buyer be in the interest of the supplier [18]. In actual practice, nearly 50% of JIT purchasing contracts use penalties for non-performance as an incentive for on-time delivery [6]. Such incentive schemes have been formulate as a sequential game to determine the buyer's least-cost incentives and the supplier's cost-minimizing response to those incentives for two specific flow time distributions [19]. This paper also uses a sequential game to model delivery incentives. However, the results of this research are more general because the results characterize the buyer's decision for any flow time distribution.

2. Contractual incentives

This paper focuses on achieving on-time deliveries in JIT purchasing using contractual incentives. Two types of incentives are considered: (1) a fixed-value, all-or-nothing incentive and (2) an incentive that declines over time. Contractual incentives for on-time delivery can be provided as either bonuses for performance or penalties for non-performance. Mathematically, the distinction between bonuses and penalties is inconsequential. If the price specified in the contract includes a premium that is forfeited for late delivery, then a penalty is being used. If the contract price is augmented by a premium for on-time delivery, then a bonus is used. The exchange is not affected by how the incentives are labelled.

For simplicity of exposition, the fixed-value, all-or-nothing incentive is called a bonus (B). The buyer pays this bonus to the supplier for each on-time delivery that occurs under the contract. The supplier receives either the entire bonus B or no bonus for each delivery. The incentive that is proportional to the amount of time that a delivery is late is called a penalty (P). When a penalty is used, the buyer withholds P for each unit of time that the delivery was late. By using the bonus and penalty together, any incentive scheme that is a linear function of time can be created.

In this paper, both B and P are assumed to be non-negative. The buyer and supplier are assumed to be rational and only enter into contracts that are financially beneficial. The supplier only enters contracts where the expected revenue is at least equal to some minimum "reservation price." The reservation price is the lowest expected revenue where the supplier is still willing to trade with the buyer. If the amount that the supplier expects to receive is less than the reservation price, the supplier will choose not to sell to the buyer. A more reliable, timely supplier can expect to be paid more than a less reliable, less timely supplier. The extra revenue that the more timely supplier receives will be called a timeliness premium. This timeliness premium becomes larger as the tardiness of orders and the proportion of orders tardy decreases. The buyer does not enter a contract when a more attractive alternative exists. If the expected cost of incentives to achieve a given service level exceed the cost of holding inventory then incentives will not be used. The supplier's requirement of earning the reservation price is modelled explicitly. The buyer's option to hold inventory instead of offering incentives is not included in the model. The omission is not intended to imply that this option is not a valid respons to buyer-supplier interaction; rather, the omission reflects the focus of this paper on the incentive schemes that are included in signed contracts.

A very stylized just-in-time environment is assumed. A kanban ordering system is used. The order size is constant and known. Early shipments are forbidden. The buyer follows the JIT practice of freezing its production schedule and requirements well in advance of actual production. A long-term contract for an item is signed with a single make-to-order supplier. Multiple orders and deliveries occur under the contract. The long-term contract includes incentives for on-time delivery. The incentives are awarded after each delivery based on the timeliness of that delivery. The more closely the actual situation matches these stylized assumptions the more accurately the model indicates optimal behavior.

In selecting an incentive, the buyer must take into account how the supplier will respond. The supplier can respond to incentives by holding additional inventory or by reducing the variance of flow time. Holding additional inventory makes on-time deliveries more likely. Inventory is increased in a make-to-order operation by increasing the flow time allowance, that is, by increasing the amount of time budgeted for completing the buyer's order. Since early shipments are forbidden, increasing the flow time allowance causes the average order to be held longer in inventory prior to shipment. This response is not the most desirable one according to JIT proponents. A reduction in the variance of flow time through the implementation of JIT is preferred. In this case, both the allowance and the variance can be controlled to increase the probability of on-time delivery. Grout and Christy [20] present a model where the optimal allowance and variance are determined for uniformly distributed flow times.

Developing general results when the variance is controlled by the supplier is difficult because including the variance of flow time as a decision variable requires that the probability density function of flow time be specified. In this paper, only controlling the flow time allowance is considered. The results provided do not require that a flow time distribution be specified. However, this means that the results are a worst case scenario, since the response to incentives may be understated for suppliers that choose to reduce the variance of flow time. Where the variance is reduced, deliveries will be more timely than the model predicts.

3. Methodology

The method of analysis used in this paper is similar to the analysis used to characterize utility maximization. Sets made up of varying amounts of goods that provide the same level of satisfaction are called indifference curves. Consumers have a budget constraint that insures that the sum of the quantity times the price for the various goods they purchase do not exceed the money they have to spend. Utility is maximized by choosing a set of goods from the most preferred indifference curve. This curve typically is tangent to the budget constraint.

In this paper, bonuses and penalties can be combined at varying levels of B and P to achieve a specific probability of on-time delivery. The set of (B, P) pairs that provide a given probability of on-time delivery can be plotted to create a curve. This curve corresponds to the notion of an indifference curve in economics. These lines of equal probability of on-time delivery are considered instead of lines of equal satisfaction. This analysis differs from the economic analysis of utility maximization because no budget constraint is identified. Rather, a given probability of on-time delivery is selected, and a minimum cost incentive scheme to achieve that probability is found.

The reason that a more straightforward optimization technique is not used is because it would require that a specific probability density function of flow time be specified. This would make any results about the use of penalties and bonuses valid only for specific distributions.

In the analysis, the supplier's minimum cost is found using calculus. The result is essentially that of the newsvendor problem, but finding the optimal allowance here is not possible without specifying the probability density function of flow time. However, the bonus or penalty required to achieve a given probability of on-time delivery can be characterized. This information is used to create the expression of the buyer's cost that always has the same probability of on-time delivery, without specifying the probability density function.

4. The model

The majority of cost parameters used in modeling delivery behavior are those which are commonly used in inventory theory. The definitions of cost parameters vary slightly from one inventory researcher to another, so the cost parameters that are used are defined below.

4.1. Buyer and supplier costs

The supplier faces two relevant costs. The cost of finishing the order early, and the cost of finishing the order late. When early shipments are forbidden, the cost of finishing early is the cost associated with holding the order as finished goods inventory until the delivery due date. The holding cost rate α is assumed to be positive, based upon a fixed order size, and computed for the time items are held as finished goods only. A fixed order size is assumed to avoid unnecessary complications, and Grout [21] shows that order size does not affect the delivery incentive problem. Only finished goods holding costs are considered, work-in-process holding costs are assumed to be unaffected by the prohibition of early shipment. These holding costs are reduced by bonus payments by the buyer when deliveries occur on-time. The buyer pays the supplier a bonus of B only when delivery occurs on the due date. When shipments arrive late the bonus is not paid.

The cost of finishing an order late involves two components: the cost of tardiness, and the cost of penalties levied by the buyer. Both costs are assumed to be positive and proportional to the amount of time that the order is tardy. The tardiness cost per unit of time is β. This cost does not include estimated costs of lost goodwill and buyer inconvenience like stockout costs in traditional inventory theory. Rather, the tardiness cost includes only the costs of the status tracking, rescheduling, and communication with the buyer associated with not meeting the due date. The cost of lost goodwill and buyer inconvenience are presumed to be incorporated into the buyer's choice of penalty P. The parameter β is assumed to be a constant. The per- unit-time penalty P is a decision variable that is assumed to be controlled by the buyer.

The buyer's cost is the contract price C plus the marginal cost of incentives, or timeliness premium. The supplier is assumed to require a reward for increased timeliness. The timeliness premium is assumed to increase as the probability of on-time delivery increases. Without this assumption the buyer could achieve a higher probability of on-time delivery and still pay only the reservation price by manipulating the incentives and the contract price of the goods. The relationship of the bonus, penalty, contract price, and reservation price is presented in detail later in this paper.

Another cost to the buyer is the cost of stock outs when deliveries are late. This cost decreases as timeliness increases. Were this cost zero or negative, there would not be a timeliness problem. The stock out cost is relevant in choosing the optimal probability of on-time delivery; however, in this analysis, choosing the best probability of on-time delivery is not addressed. Rather, once management has selected a desired probability, this analysis indicates the minimum cost incentive scheme to achieve it.

The following notation is be used:

$X_s(A) =$ supplier's expected total relevant cost as a function of the allowance

$X_b(B,P) =$ buyer's expected total relevant cost as a function of the bonus and penalty

$\alpha =$ holding cost per order per period of time

$\beta =$ tardy cost per order per period of time

$A =$ the allowance, the time budgeted for the completion of the order

$A_0 =$ the baseline allowance, the time budgeted for the completion of the order when no incentives are offered

$F =$ the flow time, the random variable of how long it actually takes to complete the order

$g(F) =$ the probability density function of the flow time

$G(A) =$ The cumulative distribution function of the flow time distribution at A

$C =$ the contract price, the price paid per order as specified in the contract regardless of when it is delivered

$R =$ the reservation price, the minimum expected revenue where the supplier is willing to trade with the buyer.

The amount of time finished goods are held can be expressed as

$$\begin{cases} 0, & \text{if } A \leq F; \\ A - F, & \text{if } A > F. \end{cases}$$

The amount of time orders are tardy is

$$\begin{cases} F - A & \text{if } A < F; \\ 0 & \text{if } A \geq F. \end{cases}$$

4.2. The supplier's cost function

The supplier's expected cost as a function of the allowance $X_s(A)$ can now be stated:

$$X_s(A) = \alpha \cdot \int_0^A (A - F) \cdot g(F)dF + (\beta + P) \cdot \int_A^\infty (F - A) \cdot g(F)dF - B \cdot \int_0^A g(F)dF. \quad (1)$$

The first term is the expected holding cost, the second term is the expected tardy and penalty costs, and the third term is the expected bonus that is received.

Leibniz's rule is applied to $X_s(A)$ to find the first derivative with respect to A. The minimum cost is achieved by selecting an allowance that satisfies the following equation:

$$\frac{\beta + P}{\alpha + \beta + P} + \frac{B}{\alpha + \beta + P} \cdot g(A) = G(A). \quad (2)$$

If the contract does not use incentives, in which case $P = 0$ and $B = 0$, then (2) is the standard newsvendor result:

$$\frac{\beta}{\alpha + \beta} = G(A). \quad (3)$$

The expected cost of setting the allowance too long must be balanced with the expected cost of setting the allowance too short. In JIT purchasing, the cost of setting the allowance too long is the holding cost (α) of orders that cannot be shipped until the due date. The cost of setting the allowance too short is the tardiness cost (β) that is incurred when orders are not delivered on-time.

This case, where incentives are not used, provides a baseline for the probability of on-time delivery and the cost of incentives to achieve more timely delivery. The allowance that satisfies (3) is A_0.

Suppose that the buyer wanted to achieve a particular probability of on-time delivery $G(A) = k$. By substituting k for $G(A)$ in (2), a manager can solve for either the bonus B_k or penalty P_k necessary to achieve k, or

$$B_k = \frac{k\alpha - (1-k)(\beta + P)}{g(A)}, \tag{4}$$

$$P_k = \frac{(\alpha + \beta)k - \beta - B \cdot g(A)}{1-k}. \tag{5}$$

Either of these equations can be used to plot the line of equal probability of on-time delivery for various combinations of B and P. Figure 1 shows a curve for a uniform distribution. The negative slope of these lines is expected since increasing P in (4) results in smaller values of B_k. The horizontal line at 100% probability of on-time delivery is also expected. When deliveries are always on-time, the supplier is never charged the penalty. Since the penalty is not incurred, the value of P is irrelevant when the probability of on-time delivery is 100%. The uniform distribution has special properties that make 100% on-time delivery possible. For other distributions, 100% on-time delivery may not be achievable.

— insert Figure 1 about here —

4.3. Difficulty achieving 100 percent on-time delivery

Equations B_k and P_k provide new insight into the task of achieving 100% on-time delivery. There are at least three conditions that make 100% on-time delivery impossible:

(1) a flow time distribution with infinitely long upper tail, (2) using only per-time-period incentives, and (3) a flow time distribution that ends at zero.

Failure to achieve 100% on-time delivery could be the result of having a flow time distribution that has an infinitely long upper tail. Because the tail is infinitely long, any finite allowance selected by the supplier will result in less than 100% on-time delivery.

The second condition that would make 100% on-time delivery impossible is the use of only a per-time-period incentive like the penalty P. Even if the flow time distribution has finite tails and P is very large, 100% on-time delivery will not occur. Penalties alone cannot be used to achieve 100% on-time delivery since the equation for P_k, (5), is undefined when $k = 1$. The supplier's optimal probability of on-time delivery is less than one any time that $B = 0$ and α is positive:

$$\frac{\beta + P}{\alpha + \beta + P} = G(A). \tag{6}$$

The third condition that would make 100% on-time delivery impossible is that the tails of the finite distribution of flow time occur where the probability density function takes on the value zero. When $k = 1$,

$$B_k = \frac{\alpha}{g(A)}. \tag{7}$$

If the probability density function $g(A)$ equals zero at the upper bound of the distribution then B_k is undefined. Consider an example using the triangular distribution. Let a, b, and c represent the lower bound, mode, and upper bound of a triangular distribution respectively. The probability density function for points above the mode is

$$g(A) = \frac{2(c - A)}{(c - b)(c - a)}. \tag{8}$$

When $k = 1$,

$$B_k = \frac{\alpha}{g(A)} = \frac{\alpha(c - b)(c - a)}{2(c - A)}. \tag{9}$$

One hundred percent on-time delivery implies that the flow time allowance equals the upper bound of the distribution, $A = c$; therefore, B_k is undefined. As k increases approaching 1, B_k increases toward infinity.

Now consider the case where none of these three conditions hold. In order to achieve 100% on-time delivery, a fixed-value incentive like the bonus B must be used and the flow time distribution of the supplier must be finite and end with a "step" ($g(A) > 0$ when $k = 1$).

The three conditions discussed imply that 100% on-time delivery may not be a realistic aspiration in every delivery situations. The purpose of this paper is to provide insights into achieving timeliness, not to discourage such achievements. This discussion of the difficulties of achieving 100% on-time delivery is intended to identify the limitation of using incentive schemes with cost minimizing suppliers.

4.4. The buyer's cost function

In order to determine an optimal incentive scheme for on-time delivery, the buyer's cost of choosing a given scheme must be found. The buyer's cost function depends on B and P. It is clear that any bonus the buyer pays the supplier increases the buyer's costs. It is not as apparent that charging the supplier a penalty costs the buyer more. The use of penalties reduce the supplier's profit. If the penalty is large enough to reduce profits below an acceptable level, the supplier will do business elsewhere. The supplier only enters into contracts that do not have excessive penalties. If the buyer has been buying the item for the lowest possible price (the reservation price), any penalty that is included in the contract must be offset by an increase in price to compensate for the expected value of the penalty. This logic can be expressed as follows:

$$C + B \cdot \int_0^{A_0} g(F)dF - P \cdot \int_{A_0}^{\infty} (F - A_0) \cdot g(F)dF = R. \tag{10}$$

Equation (10) insures that if the supplier's delivery timeliness remains unchanged when incentives are used, then the supplier still receives the reservation price. Recall that

A_0 is the allowance when no incentives are offered. Rearranging terms yields

$$C = R - B \cdot \int_0^{A_0} g(F)dF + P \cdot \int_{A_0}^{\infty} (F - A_0) \cdot g(F)dF. \tag{11}$$

The buyer's expected relevant cost $X_b(B, P)$ is

$$X_b(B, P) = C + B \cdot \int_0^{A} g(F)dF - P \cdot \int_{A}^{\infty} (F - A) \cdot g(F)dF. \tag{12}$$

or, substituting (11) for C,

$$X_b(B, P) = R + B \cdot \int_{A_0}^{A} g(F)dF + P \left[\int_{A_0}^{\infty} (F - A_0) \cdot g(F)dF - \int_{A}^{\infty} (F - A) \cdot g(F)dF \right]. \tag{13}$$

The second term is the expected bonus payments that the buyer gives to the supplier for more timely deliveries. The third term is the expected marginal cost of imposing a penalty for late deliveries. The sum of these two terms is the timeliness premium discussed above.

The buyer wants to minimize $X_b(B, P)$. To do so using calculus requires that $g(F)$ be specified so that A can be stated as a function of B and P. For a particular probability density function, these steps are not conceptually difficult (although some distributions are computationally tedious). An example for the uniform and exponential distributions using a similar cost function where only B is used is given by Grout and Christy [19]. Insights that are true regardless of the flow time distribution are provided here. Consequently, minimizing $X_b(B, P)$ is accomplished by using an economic indifference curve approach to avoid specifying $g(F)$.

Suppose that the desired probability of on-time delivery is k. Equations (4) or (5) can be used to determine the bonus or penalty required to achieve k. Let B in equation (13) be B_k as shown in (4). Then $X_b(B, P)$ can be restated as follows:

$$\begin{aligned} X_b(P, k) = &R + \frac{k\alpha - (1-k)(\beta + P)}{g(A)} \cdot \int_{A_0}^{A} g(F)dF + \\ &P \left[\int_{A_0}^{\infty} (F - A_0) \cdot g(F)dF - \int_{A}^{\infty} (F - A) \cdot g(F)dF \right]. \end{aligned} \tag{14}$$

Note that this equation is now a function of P and k. For a specific value of k, as P varies B changes so that the probability of on-time delivery is maintained at k. Also notice that maintaining the same probability of on-time delivery implies that the allowance A remains constant as P varies. Equation (14) is the buyer's expected cost function along a line of equal probability of on-time delivery. Minimizing this function with respect to P indicates the optimal incentive scheme. Taking the first derivative of (14) yields

$$\frac{\partial X_b(P,k)}{\partial P} = \int_{A_0}^{\infty} (F - A_0) \cdot g(F)dF - \int_{A}^{\infty} (F - A) \cdot g(F)dF - \frac{(1-k)}{g(A)} \cdot \int_{A_0}^{A} g(F)dF. \quad (15)$$

An important feature of this result is that it does not contain P. Equation (13) is linear in P. The implication of this is that the lines of equal probability of on-time delivery are straight lines. Thus, the typical solution to the economic version of the problem, a point of tangency, does not hold for this delivery incentive problem. Rather, the solution is a corner point. Either $B \geq 0$ and $P = 0$, or $B = 0$ and $P \geq 0$ is optimal. Using both incentives, $B > 0$ and $P > 0$, is optimal only in the alternate optima case. When this occurs, any combination of incentives on the line of equal probability results in the same expected cost to the buyer.

Which type of incentive should be used? In a specific instance where it is appropriate to seek 100% on-time delivery, then a bonus must be used; costs are minimized by using a bonus exclusively. This bonus can be found using equation (4) by setting $k = 1$, and $P = 0$. Since 100% on-time delivery may be very costly or impossible, firms may choose a probability that is less than 100%. If a probability that is less than 100% is selected, then the choice between penalties and bonuses is not as obvious. If equation (15) is negative then the expected relevant cost is a minimum when $B = 0$ and $P \geq 0$; P should be used exclusively. If equation (15) is positive, then the minimum occurs where $P = 0$ and $B \geq 0$; the optimal action is to use only B to achieve k. An alternative calculation to determine which incentive to select is to compute the expected cost of each incentive assuming that the other is zero. Determining whether to use $B > 0$ or $P > 0$ and then finding the necessary value of B or P using (4) or (5) to achieve the probability of on-time delivery k constitutes an optimal solution to the delivery problem.

5. Example distributions

In this section, three examples are presented. In each example, the decision between a bonus and penalty is shown. For a specific instance where all the data is known, this decision is relatively straightforward. The examples attempt to determine which incentive to use by considering only the type of distribution. General statements about exponential and uniform distributions can be made. The triangular distribution provides an example where no definitive conclusion is reached without more information. Two methods of comparing the incentives are available. The first method uses equation (13) with $P = 0$, $B \geq 0$ and $P \geq 0$, $B = 0$ to directly compare the cost of the incentive schemes. The second method uses equation (15) to determine how cost changes as P changes. In developing the examples, both methods were used. For the exponential and uniform distributions, conclusions made by direct comparison using (13) are more easily proven. For the triangular distribution, the results using (13) are more compact.

5.1. Uniformly distributed flow time

In order to determine which incentive to use, the allowance A must be specified as a function of k. Do this by setting the cumulative distribution function equal to k and solving for A. For the uniform distribution, $A = l + k(u - l)$, where (u, l) are the upper and lower bounds of the distribution. The value of A_0 is found by setting $k = \frac{\beta}{\alpha+\beta}$ in the equation for A. For the uniform distribution $A_0 = l + \frac{\beta}{\alpha+\beta}(u - l)$. When $B > 0$ and $P = 0$, equation (13) can be stated as

$$X_B(B, 0) = R + \frac{(u - l)[k(\alpha + \beta) - \beta]^2}{\alpha + \beta}. \tag{16}$$

When $B = 0$ and $P > 0$, equation (13) is

$$X_B(0, P) = R + \frac{[k(\alpha + \beta) - \beta]^2 \cdot [-2\alpha - \beta + k(\alpha + \beta)](u - l)}{2(\alpha + \beta)^2(k - 1)}. \tag{17}$$

$$X_B(0,P) - X_B(B,0) = \frac{[k(\alpha+\beta)-\beta]^3(u-l)}{2(\alpha+\beta)^2(1-k)}. \tag{18}$$

The denominator of (18) is positive when $k < 1$. If $[k(\alpha+\beta)-\beta] \geq 0$, the numerator is non-negative. If $k = \frac{\beta}{\alpha+\beta}$, then

$$[k(\alpha+\beta)-\beta] = 0. \tag{19}$$

If $k = \frac{\beta}{\alpha+\beta} + \epsilon$ where $0 < \epsilon \leq \frac{\alpha}{\alpha+\beta}$, then

$$\alpha k - (1-k)\beta = (\alpha+\beta)\epsilon. \tag{20}$$

For $\alpha > 0$, and $\beta > 0$, (20) must be positive. When $k = 1$, $\alpha k > 0$. The numerator is non-negative for relevant values of k. Therefore, the minimum cost incentive scheme is $P = 0$ and $B \geq 0$. The buyer should use (4) to select the appropriate bonus B_k.

5.2. Exponentially distributed flow time

Consider exponentially distributed flow times with parameter λ. For this distribution $A = \frac{1}{\lambda} ln(1-k)$ and $A_0 = \frac{1}{\lambda} ln(1 - \frac{\beta}{\alpha+\beta})$. Comparing $P = 0$, $B \geq 0$ and $P \geq 0$, $B = 0$ using equation (13) yields

$$X_B(0,P) - X_B(B,0) = [-\beta + k(\alpha+\beta)] \cdot \frac{\frac{-1}{\lambda} + \frac{\alpha}{(\alpha+\beta)\lambda} + \frac{k}{\lambda}}{(1-k)} - \frac{[-\beta + k(\alpha+\beta)]^2}{(\alpha+\beta)(1-k)\lambda} \tag{21}$$

Equation (21) simplifies to zero. Therefore, the cost of an incentive scheme to achieve a given probability of on-time delivery is equal using either a bonus or a penalty. The buyer can choose either type of incentive scheme. The buyer can use either the equation for B_k as stated in (4) or for P_k as stated in (5) to find the appropriate incentive to achieve the desired probability of on-time delivery.

5.3. Triangular flow time distribution

Consider a triangular distribution with parameters (a, b, c) indicating the lower bound, the mode, and the upper bound of the distribution respectively. For simplicity, the allowance is assumed to exceed the mode, $A \geq b$. In other words, the most likely flow time to occur results in on-time delivery. For this distribution,

$$A = c - \sqrt{(1-k)(c-b)(c-a)} \tag{22}$$

and

$$A_0 = c - \sqrt{\frac{\alpha(a-c)(b-c)}{\alpha+\beta}}. \tag{23}$$

The probability density function is

$$g(F) = \frac{2(c-f)}{(c-a)(c-b)}. \tag{24}$$

The difference between the expected cost of using a bonus and a penalty is

$$\begin{aligned} X_B(0,P) - X_B(B,0) = \\ \left[\frac{\alpha(a-c)(b-c)}{\alpha+\beta}^{\frac{3}{2}} - [(c-a)(c-b)(1-k)]^{\frac{3}{2}}\right] \frac{\alpha k - (1-k)\beta}{3(c-a)(c-b)(1-k)} - \\ \frac{(c-a)(c-b)(\alpha k - (1-k)\beta)^2}{2(\alpha+\beta)\sqrt{(c-a)(c-b)(1-k)}}. \end{aligned} \tag{25}$$

When $k = \frac{\beta}{\alpha+\beta}$, $X_B(0,P) - X_B(B,0) = 0$. When $k > \frac{\beta}{\alpha+\beta}$, determining the sign of (25) is more difficult. In order for a penalty to be preferred, equation (25) must be negative. This would require that β be much larger than α. However, as β gets larger so does $\frac{\beta}{\alpha+\beta}$, the minimum reasonable value for k. Because of this relationship among the variables, no instances of negative values of (25) were found in numerical examples using different ratios of α and β. This suggests that the use of a bonus *may* be preferred to a penalty. For a specific instance, the optimal incentive can be determined using equation (25) to select the type of incentive and using equations (4) or (5) to determine the value of that incentive.

In summary, the determination of which incentive to use is considered in three examples. The actual determination of the value of the incentive is not presented explicitly. In order to actually determine the type and value of incentive to use, the buyer must know the supplier's holding cost, shortage cost, and flow time distribution. The model presented here assumes the buyer has this knowledge. If this assumption holds, the model gives managers a tool for selecting an approximately correct incentive scheme. The model may not be exactly correct because the supplier may not respond optimally to the incentives offered. The supplier may also choose to reduce the variance of flow time resulting in deliveries that are more timely than expected. Assuming that the buyer knows the supplier's costs is not uncommon in related research ([22,23] for instance). Determining how to cope with asymmetric information would be a worthwhile topic for further research.

6. Conclusions

Since as many as half of JIT contracts involve incentives, it is appropriate to consider how these incentives should be selected. Two types of incentives are considered here: a fixed-value, all-or-nothing incentive that is called a bonus and a per-time-period incentive that is called a penalty. Equations that can be used to calculate the value of the bonus or penalty required to achieve a given probability of on-time delivery are presented. An equation describing the indifference point between using a bonus and a penalty is also provided. The ability to determine which type of incentive results in the least cost and the value of that type of incentive constitute the optimal method of achieving a given probability of on-time delivery.

The result of this research is that under stylized conditions of JIT purchasing, the optimal method is that either a fixed-value, all-or-nothing bonus or a per-time-period penalty should be used but not a combination of of the two. Three flow time distributions are presented as examples of determining which type of incentive to use. Given that combinations are not optimal, the determination can be made by directly comparing the costs of using only a bonus with that of using only a penalty. Another method of determining which incentive to use is by finding the slope of the expected cost of achieving a given probability of on-time delivery. For uniformly distributed flow times, a bonus is shown to be preferred to a penalty. For exponentially distributed flow times, the buyer is indifferent to the type of incentive scheme used. Either a bonus or a penalty selected to achieve a specific probability of on-time delivery will result in the same cost. When the flow time distribution is triangular, with the allowance greater than the mode, no definitive conclusion was shown. However, of the specific instances of triangular distributions that were considered, all resulted in the bonus being selected. An example where a penalty is strictly preferred would be of interest. Finding such an example is a matter for future research.

Once the buyer reduces raw material inventories to very low levels, the buyer depends heavily on the timeliness of deliveries from the supplier to allow on-going economical production. In such a scenario, managers may attempt to achieve 100% on-time delivery. This research indicates that some of these attempts may be futile. Three conditions necessary for achieving 100% on-time delivery are delineated. One hundred percent on-time delivery is only achievable if a bonus is used, the flow time distribution is finite, and the flow time distribution ends with a "step." These three conditions, particularly the last, suggest that many of the distributions that would typically be used to characterize flow time would make 100% on-time delivery unattainable. The uniform distribution is an example of a flow time distributions that meets all three conditions. This difficulty achieving 100% on-time delivery indicates some of the limitations of using incentive schemes. Even when 100% on-time delivery is not possible, the model can be useful in improving supplier delivery timeliness.

The results presented here suggest a variety of directions for further research. Changing the flow time allowance is not the preferred response to requests for JIT delivery. Further research could be conducted to determine a means of selecting incentives when the supplier can choose to reduce the variance of flow time. If the supplier reduces the variance as incentives increase, the buyer should be able to achieve the same probability of on-time delivery with less cost. Making general statements about variance reduction is difficult using the type of model presented here because the distribution of flow time must be specified. Also note that all of the results presented in this paper are for a given probability of on-time delivery. Additional research could address how to select the probability of on-time delivery that minimizes the buyer's expected cost. Relaxing the assumption of symmetrical information could lead to results that can be used when not all cost and distribution information is known to the buyer.

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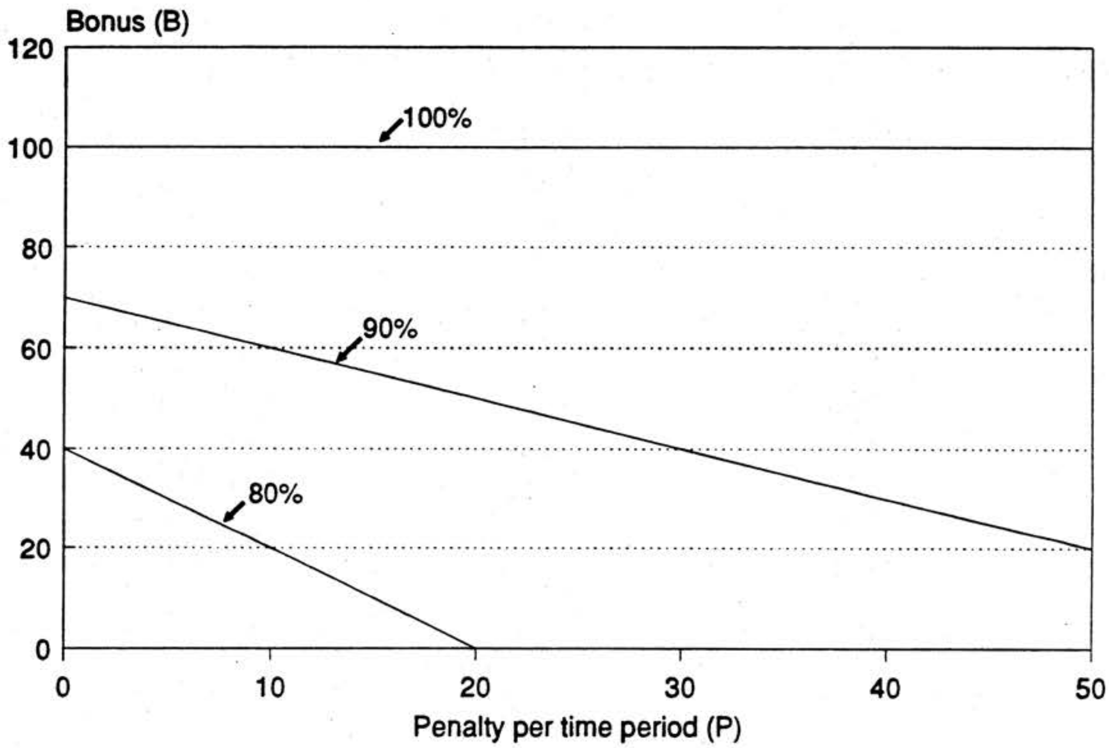

Fig. 1. Lines of equal probability of on-time delivery. The lines indicate values of equation (4) as P varies for 80%, 90% and 100% probability of on-time delivery. These lines are from uniformly distributed flow times where $u = 20$, $l = 10$, with parameter values $\alpha = 10$ and $\beta = 20$.

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