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ECONOMICS OF MANAGERIAL NEGLECT IN SUPPLY CHAIN DELIVERY PERFORMANCE

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This article addresses the economic impact of improving delivery performance in a two-stage supply chain when delivery performance is evaluated with respect to a delivery window. Building on contemporary management theories that advocate variance reduction as the critical step in improving the overall performance of a system, an expected cost model is developed that financially quantifies the benefit of reducing delivery variance. The present worth of the expected costs, due to untimely delivery, that accrue over a finite time horizon provide management with input for justifying financial investment to support a continuous improvement program to reduce delivery variance. The concept of managerial neglect *is introduced and quantified as an opportunity cost of management neglecting to improve delivery performance in a timely manner.*

INTRODUCTION

In today's competitive business environment, customers require dependable on-time delivery from their suppliers. Delivery lead time is defined to be the elapsed time from the receipt of an order by the supplier to the receipt of the product ordered by the customer. Delivery lead time is composed of a series of internal (manufacturing and processing) lead times and external (distribution and transportation) lead times found at various stages of the supply chain. Early and late deliveries introduce waste in the form of excess cost into the supply chain; early deliveries contribute to excess inventory holding costs, whereas late deliveries may contribute to production stoppages costs and loss of goodwill. To protect against untimely deliveries, supply chain managers often inflate in process inventory levels and production flow buffers.

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Recent empirical research has identified delivery performance as a key management concern among supply chain practitioners (see Lockamy and McCormack (2004), Vachon and Klassen (2002), Verma and Pullman (1998)). A conceptual framework for defining delivery performance in supply chain management is found in Gunasekaran et al. (2001). Delivery performance is classified as a strategic level supply chain performance measure. Delivery reliability is viewed as a tactical level supply chain performance measure. The framework advocates that to be effective supply chain management tools, delivery performance and delivery reliability need to be measured in financial (as well as non-financial) terms.

Failure to quantify delivery performance in financial terms presents both short-term and long-term difficulties. In the short term, the buyer-supplier relationship may be negatively impacted. According to New and Sweeney (1984) a norm value of presumed performance is established by default when delivery performance is not formally measured. This norm stays constant with time and is generally higher than the organization's actual delivery performance.

It has been demonstrated that supplier evaluation systems have a positive impact on the buyer-supplier relationship, and buyer-supplier relationships ultimately have a positive impact on financial performance (Carr and Pearson, 1999). In the long term, failure to measure supplier delivery performance in financial terms may impede the capital budgeting process, which is necessary in order to support the improvement of supplier operations within a supply chain.

In this research we develop a cost-based performance metric for evaluating delivery performance and reliability to the final customer in a two-stage supply chain that is operating under a centralized management structure. Contemporary management theories advocate the reduction of variance as a key step in improving the performance of a system (see, for example, Blackhurst et al. (2004), Hopp and Spearman (1996), Lee et al. (1997), Sabri and Beamon (2000)).

In union with these prevailing theories, delivery performance is modeled as a cost-based function of the delivery variance. The financial benefit of reducing variability in delivery performance is demonstrated within the context of a continuous improvement program. We also quantify the effects of *managerial neglect*. Managerial neglect is defined as the opportunity cost of management neglecting to improve delivery performance through the reduction of delivery variability.

This article is organized as follows: First, an analytical model based on the expected costs associated with untimely delivery is developed. Next, improvement in delivery performance is modeled using a learning-based model for reducing the delivery variance. Net present value theory is used to incorporate the time value of money into the model framework to provide a guideline for the amount of investment required to improve delivery performance. Then, the economic consequence of failing to improve delivery performance through the reduction of delivery variance is studied. In the concluding section, we summarize the findings of this research and present directions for future research.

MODEL DEVELOPMENT

Delivery windows are an effective tool for modeling the expected costs associated with untimely delivery. Several researchers advocate the use of delivery windows in time-based manufacturing systems (see, for example, Jaruphongsa et al. (2004), Lee et al. (2001), Fawcett and Birou (1993), Corbett (1992)). Metrics based on delivery (order) windows capture the most important aspect of the delivery process: reliability (Johnson and Davis, 1998). Under the concept of delivery windows, the customer supplies an earliest allowable delivery date and a latest allowable delivery date. A delivery window is defined as the difference between the earliest acceptable delivery date and the latest acceptable delivery date. Within the delivery window, a delivery (X) may be classified as early, on-time, or late. Figure 1 illustrates a delivery window under a truncated normal delivery distribution with truncation points a and b. The on-time portion of the delivery window is defined by $c_2 - c_1$. Ideally, $c_2 - c_1 = 0$. However, the extent to which $c_2 - c_1 > 0$ may be measured in hours, days or weeks depending on the industrial situation.

Consider a two-stage supply chain in operation over a time horizon of length T years, where a demand requirement for a single product of D units will be met with a constant delivery lot size Q. The manufacturer (stage 1 of the supply chain), henceforth referred to as the supplier, is the sole source of delivery of the product to the final customer (buyer) at the terminating second stage of the supply chain. Let m equal the number of deliveries to be made over time horizon T. The length of a delivery cycle is equal to T/m. Delivery time periods over the planning horizon are indexed by t, $1 \leq t \leq m$. Let X represent the delivery time for Q; i.e., the elapsed time from the receipt of an order by the supplier to the receipt of the delivery lot size by the buyer. Hence, the delivery time X consists of the internal manufacturing lead time(s) of the supplier (W_1), plus the external lead time associated with transporting the lot size from supplier to the customer (W_2).

The individual lead time components of the supply chain are commonly modeled using the normal distribution and independence is assumed (see, for example, Erlebacher and Singh (1999), Tyworth and O'Neill (1997)). Let $f_{W_i}(w_i)$ represent the normally distributed lead time components

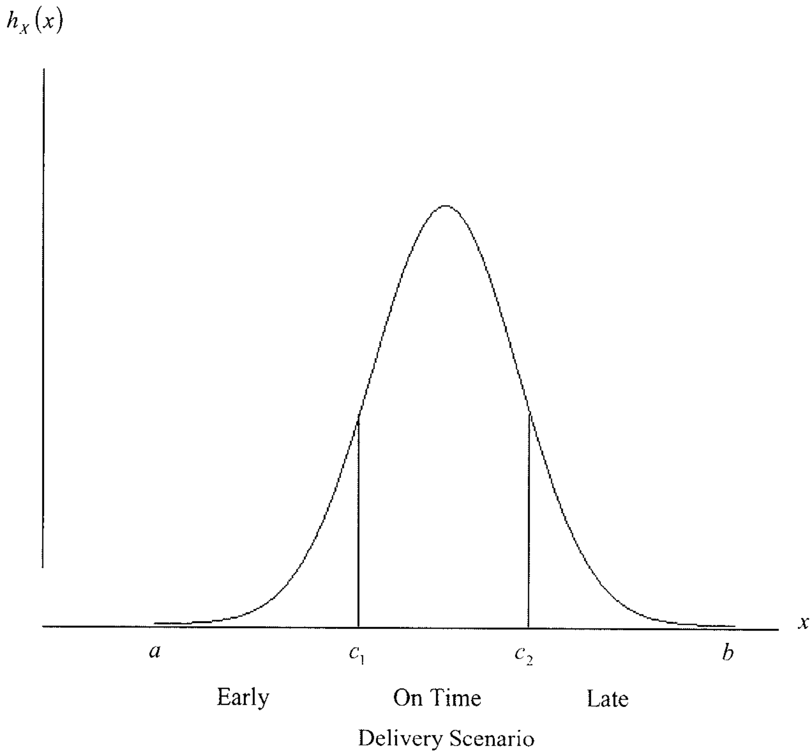

Figure 1. Illustration of delivery window for truncated normal delivery distribution. a = earliest delivery time; c_1 = beginning of on-time delivery; c_2 = end of on-time delivery; and b = latest acceptable delivery time.

$W_i (i = 1, 2)$. Then, the density function of delivery time X with mean μ and variance v is based on the convolution of the normally distributed lead time components, $f_X(x) = f_{W_1+W_2}$. For situations necessitating the need to truncate the normal density to prevent nonnegative delivery times or select nonsymmetrical density functions defined for only positive values of the delivery time, see Guiffrida (2005). A brief explanation of the truncation process of a more general case when an earliest delivery time (a) and latest acceptable delivery time (b) are imposed on $f_X(x)$, is as follows:

$$h_X(x) = \frac{f_X(x)}{\int_a^b f_X(x)} \qquad (1)$$

For a two-stage supply chain the expected penalty cost per delivery period for untimely delivery, Y, is

$$Y = QH \int_{a}^{c_1} (c_1 - x)h_X(x)dx + K \int_{c_2}^{b} (x - c_2)h_X(x)dx \qquad (2)$$

where

$Q =$ constant delivery lot size per cycle
$H =$ supplier's inventory holding cost per unit per time
$K =$ penalty cost per time unit late (levied by the buyer)
$a, b, c_1, c_2 =$ parameters defining the delivery window
$h_X(x) =$ density function of delivery time.

Furthermore, the following assumptions are made: (1) the coefficient of variation of X is less than 0.25 and (2) no order crossing occurs.

It is a common purchasing agreement practice to allow the buyer to charge the supplier for untimely deliveries (see, for example, Schneiderman (1996), Freehand (1991)). For example, in the automotive industry, Saturn levies fines of $500 per minute against suppliers who cause production line stoppages (Frame, 1992). Chrysler fines suppliers $32,000 per hour when an order is late (Russell and Taylor, 1998). Reductions in early deliveries reduced inventory holding costs at Hewlett-Packard by $9 million (Burt, 1989). The penalty cost in these cases is an opportunity cost due to lost production. Purchasing managers often view the production disruptions caused by delivery stockouts to be more widespread and more costly than the lost sales that stockouts cause (Dion et al., 1991). Hence, K has been defined as an opportunity cost due to lost production as described by Frame (1992) and Russell and Taylor (1998).

Evaluating (2) under the defined assumptions yields the total expected penalty cost (see Appendix A for derivation)

$$\begin{aligned} Y = QH&\left\{\sqrt{v}\phi\left(\frac{c_1-\mu}{\sqrt{v}}\right) + (c_1-\mu)\left[\Phi\left(\frac{c_1-\mu}{\sqrt{v}}\right)\right]\right\} \\ &+K\left\{\sqrt{v}\phi\left(\frac{c_2-\mu}{\sqrt{v}}\right) - (c_2-\mu)\left[1-\Phi\left(\frac{c_2-\mu}{\sqrt{v}}\right)\right]\right\} \end{aligned} \qquad (3)$$

MODELING IMPROVEMENT IN DELIVERY PERFORMANCE

Ideally, the expected penalty cost for untimely delivery should be equal to zero. This implies that, for the currently defined delivery window all deliveries are within the on-time portion of the delivery window and that waste in the form of early and late deliveries has been eliminated from the system. The present worth of the expected penalty cost stream over time horizon T provides an estimate in current dollars of costs incurred due to untimely deliveries. Initiating improvements in supply chain delivery performance requires capital investment. The present worth estimate of the expected penalty cost stream over the time horizon provides a benchmark from which management can justify the capital investment required to improve delivery performance. Thus, management should be willing to invest an amount equal to the present worth of the expected penalty cost over time horizon T in order to improve delivery performance.

When an early or late delivery occurs, management can study the delivery process and determine the assignable cause(s) for the untimely delivery. Corrective actions can be initiated, and, as a result of the learning gained from studying the delivery process, process improvements can be implemented to remove the cause(s) of untimely delivery.

Learning curve theory is widely accepted as a framework for modeling improvement in the performance of a process (see, for example, Fine (1986), Jaber and Bonney (2003)). As the cumulative number of deliveries increases, the supplier and the buyer both gain experience in managing the delivery process. The learning achieved during the management and control of the delivery function translates to a reduction of uncertainty (variance) in the delivery distribution. This experience often leads to improvements in the system as a result of:

1. the supplier gaining tighter control over process flow times
2. enhanced coordination of freight transport
3. more efficient material handling of outbound stock by the supplier and inbound stock by the buyer
4. implementation of electronic data interchange (EDI)
5. improved communications between both parties.

The expected penalty cost model (3) can be defined as a decreasing function of the delivery variance under learning as (see Appendix B for derivation)

$$Y(v,t) = QH\left[\sqrt{\frac{v(0)\,t^d}{2\pi}}\exp(-k_{11}) + (c_1-\mu)\,\Phi(z_{11})\right] + K\left\{\sqrt{\frac{v(0)\,t^d}{2\pi}}\exp(-k_{21}) - (c_2-\mu)(1-\Phi(z_{21}))\right\} \quad (4)$$

where $k_{g1} = \frac{(c_g-\mu)^2}{2v(0)(t^d)}$ and $z_{g1} = (c_g-\mu)/\left(\sqrt{v(0)(t^d)}\right)$ for $g = 1, 2$.

Financially Justifying Investment for Delivery Improvement

The present worth of the expected penalty cost provides management with a benchmark for justifying capital investment for improving supply chain delivery performance. Under continuous compounding (with nominal interest rate r), the present worth of the cost flow defined by the expected penalty cost under learning can be evaluated over the m equally spaced delivery cycles of length $i = T/m$ that define time horizon T as

$$Y_{NPV}(v, t) = \sum_{t=1}^{m} Y(v, t) \exp[-r(it)] \tag{5}$$

Numerical Illustrations
Illustrative examples that demonstrate the present worth calculations under learning-based variance reduction are presented. The parameters used are: $Q = 500$, $H = \$10$ per day, $K = \$10,000$ per day, $T = 3$ years, $m = 36$, $i = 1/12$ years, $\mu = 15$ days, $|c_1 - \mu| = 1$ day, $c_2 - \mu = 1$ day, $r = 0.3$, $\sqrt{v(0)} = 4$ days and $\theta = 0.85, 0.75$ and 0.65.

Using the parameters defined above, $Y_{NPV}(v, t)$ ranged from \$271,046 when $\theta = 0.85$ to \$136,041 when $\theta = 0.65$. Under a given learning rate, management should therefore be willing to invest an amount equivalent to these net present values in a continuous improvement program over time horizon T to improve delivery timeliness by reducing the variance of delivery.

MANAGERIAL NEGLECT IN DELIVERY PERFORMANCE IMPROVEMENT

Figure 2a illustrates the improvement in the expected penalty cost as a result of variance reduction over time horizon of length T. Let C denote the time period defining the end of the neglect period (see Figure 2b). If management delays the implementation of the continuous improvement program to reduce delivery variance until time period $C + 1$, the constant expected penalty cost, $Y(v, 0)$, is incurred during the first C delivery cycles and the declining expected penalty cost under improvement is incurred during the remaining $m - C$ delivery cycles. This scenario represents *managerial neglect,* or the opportunity cost of management not attempting to improve delivery performance during delivery cycles $1 \leq t \leq C$. During this period of delay, or 'neglect,' expected penalty costs, due to untimely delivery, continue to accrue at their maximum level. The additional cost

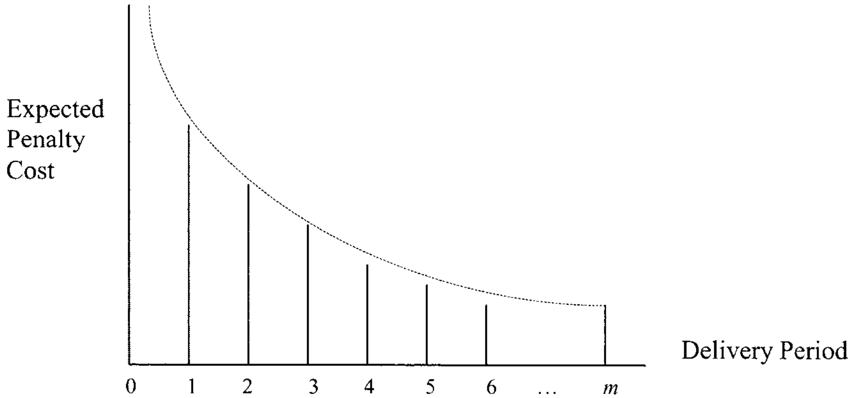

Figure 2a. Variance-based improvement in expected penalty cost.

incurred as a result of managerial neglect, N, is equal to

$$N = C\{Y(v,0)\} - \sum_{t=m-C+1}^{m} Y(v,t) \tag{6}$$

The present worth of managerial neglect can be modeled by taking the difference of the expected cost stream over time horizon T when $C \geq 1$

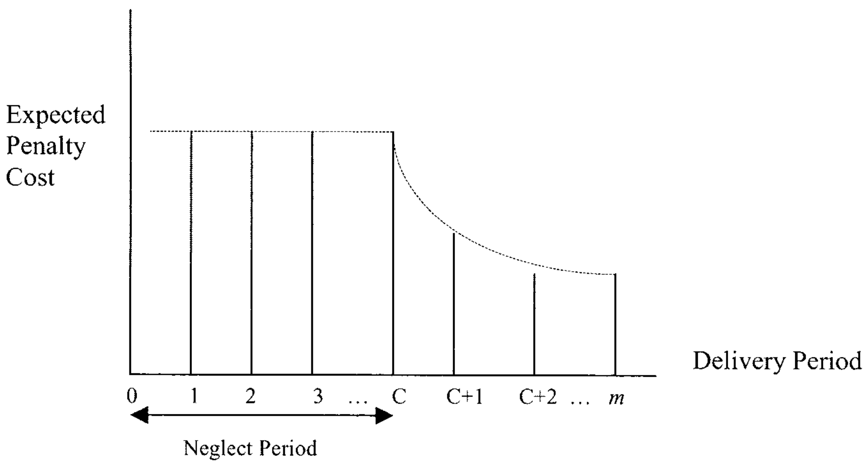

Figure 2b. Managerial neglect of variance-based improvement.

(managerial neglect) and $C = 0$ (no managerial neglect). This yields

$$\begin{aligned} N_{npv} = \{ & Y(v,0)e^{-ri} + Y(v,0)e^{-2ri} + \cdots + Y(v,0)e^{-Cri} \\ & + Y(v,1)e^{-(C+1)ri} + \cdots + Y(v,m-C)e^{-mri}\} \\ & - \{Y(v,1)e^{-ri} + Y(v,2)e^{-2ri} + \cdots + Y(v,m)e^{-mri}\} \end{aligned} \quad (7)$$

The present worth of the first C terms in (7) represents an equal cost series and remaining terms in the neglect and non-neglect cost streams can be written in summation form. Thus, (7) reduces to

$$\begin{aligned} N_{npv} = & Y(v,0)\left[\frac{1-e^{-Cri}}{e^{ri}-1}\right] + \sum_{t=C+1}^{m} Y(v,t-C)e^{-t(ri)} \\ & - \sum_{t=1}^{m} Y(v,t)e^{-t(ri)} \end{aligned} \quad (8)$$

The present worth of managerial neglect under variance reduction can be evaluated using Equation (8) as defined above.

Numerical Illustrations

The following illustrative example demonstrates the calculation of the opportunity cost of managerial neglect when the neglect period equals $C =$ 6, 12 and 18 delivery cycles.

The parameters used are: $Q = 500$, $H = \$10$ per day, $K = \$10{,}000$ per day, $T = 3$ years, $m = 36$, $i = 1/12$ years, $\mu = 15$ days, $|c_1 - \mu| = 1$ day, $c_2 - \mu = 1$ day, $r = 0.3$, $\sqrt{v(0)} = 4$ days and $\theta = 0.85$, 0.75 and 0.65. Results are presented in Table 1.

These results demonstrate that expected costs associated with delaying the implementation of an improvement program to reduce delivery variance can lead to the incurring of unnecessary costs due to untimely delivery. For the parameter values used, the present worth of managerial neglect ranged from \$63,567 for a neglect period of one-half year to \$200,999 for a neglect period of one and one-half years under a learning rate of 0.85. The worst case involves no attempt to reduce the variance of delivery over time horizon T and results in the upper bound of managerial neglect for the 0.85 learning rate of \$332,188. Similar results are demonstrated for the learning rates of 0.75 and 0.65. Figure 3 illustrates the neglect cost surface as a function

Table 1. Summary of net present value calculations

Length of the Neglect Period	Learning Rate $\theta = 0.85$		Learning Rate $\theta = 0.75$		Learning rate $\theta = 0.65$	
	NPV	NPV Neglect	NPV	NPV Neglect	NPV	NPV Neglect
No Neglect ($C = 0$) Improvement over Entire Time Horizon	$271,046		$197,452		$136,041	
1/2 Year Neglect ($C = 6$)	$334,613	$63,567	$269,386	$71,934	$214,166	$78,125
1 Year Neglect ($C = 12$)	$406,390	$135,344	$352,480	$155,028	$305,878	$169,837
$1\frac{1}{2}$ Year Neglect ($C = 18$)	$472,045	$200,999	$430,909	$233,457	$394,394	$258,353
3 Year Neglect ($C = 36$) No Improvement over Entire Time Horizon	$603,234	$332,188	$603,234	$405,782	$603,234	$467,193

of the learning rate for variance reduction and the length of the neglect period.

The values reported in Table 1 and illustrated in Figure 3 are clearly parameter dependent; however, the financial quantification of managerial neglect may serve as a useful input into the managerial decision-making process for implementing a continuous improvement program to improve delivery performance.

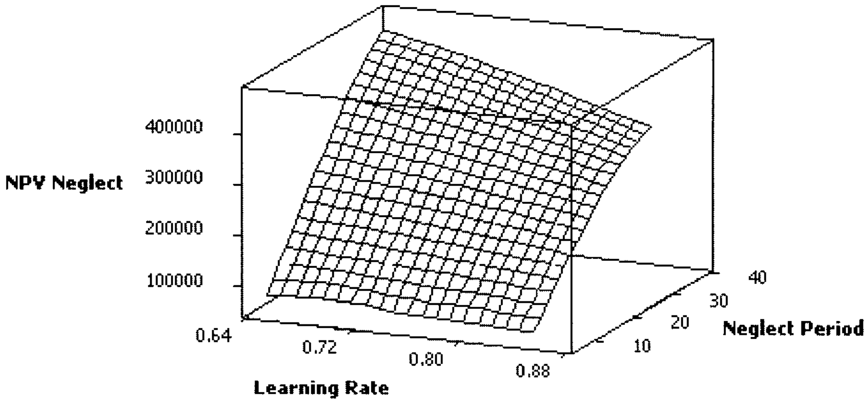

Figure 3. Neglect cost surface for illustrative example.

CONCLUSIONS

This article addressed one aspect of supply chain planning by modeling delivery performance from the contemporary perspective of reducing delivery variability. A cost-based model has been presented that financially evaluates the effects of reducing delivery variability on overall delivery performance. Using the present worth of future expected penalty costs associated with untimely delivery provided by the model, managers may utilize this information when attempting to justify the resources for investing in a continuous improvement program for supplier delivery performance.

The model was demonstrated for learning-based reduction of the delivery variance. Other functional forms for modeling variance reduction and probability densities other than the normal can be explored in a similar manner. The opportunity cost of management neglecting to improve delivery performance was introduced and illustrated for a selected set of parameters. Using the model, the detrimental financial effects of managerial neglect were demonstrated.

There are several aspects of this research that could be expanded. An optimization model could be used to determine and allocate variance reduction throughout the stage 1 component processes of the supplier subject to an investment constraint. Second, an industrial case study utilizing the model could be conducted. Third, disruptions in the learning process could be investigated. Lastly, the assumption of independence among the stages could be investigated.

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APPENDIX A. DERIVATION OF EXPECTED PENALTY COST MODEL (EQUATION (3))

The density function of delivery time X with mean μ and variance v is based on the convolution of the normally distributed lead time components $W_i (i = 1, 2)$, $f_X(x) = f_{W_1+W_2}$. If an earliest delivery time (a) and latest acceptable delivery time (b) are imposed on $f_X(x)$, then

$$h_X(x) = \frac{f_X(x)}{\int_a^b f_X(x)} \tag{A.1}$$

and (2) is

$$Y = QH \int_a^{c_1} (c_1 - x) h_X(x) dx + K \int_{c_2}^{b} (x - c_2) h_X(x) dx \tag{A.2}$$

Examining (A.2), we observe that Y is separable in terms of the expected earliness cost and the expected lateness cost.

Expected Lateness Cost

When deliveries are distributed according to $h_X(x)$, the expected penalty cost for late delivery is

$$Y_{late} = \frac{K}{p}\int_{c_2}^{b}(x - c_2)f_X(x)dx \tag{A.3}$$

$$\text{where} \quad p = \int_{a}^{b} f_X(x)dx \tag{A.4}$$

$$\begin{aligned} Y_{late} = \frac{K}{p}\Bigg\{&\int_{c_2}^{b}\frac{x}{\sqrt{2\pi v}}\exp\left[\frac{-(x-\mu)^2}{2v}\right]dx \\ &-\int_{c_2}^{b}\frac{c_2}{\sqrt{2\pi v}}\exp\left[\frac{-(x-\mu)^2}{2v}\right]dx\Bigg\} \end{aligned} \tag{A.5}$$

Substituting $z = \frac{x-\mu}{\sqrt{v}}$, $x = \sqrt{v}z + \mu$ and $dx = \sqrt{v}dz$ into (A.5) and simplifying yields

$$\begin{aligned} Y_{late} = \frac{K}{p}\Bigg[&\sqrt{v}\int_{\frac{c_2-\mu}{\sqrt{v}}}^{\frac{b-\mu}{\sqrt{v}}}\frac{z}{\sqrt{2\pi}}\exp(-z^2/2)dz + (\mu - c_2) \\ &\times\int_{\frac{c_2-\mu}{\sqrt{v}}}^{\frac{b-\mu}{\sqrt{v}}}\frac{1}{\sqrt{2\pi}}\exp(-z^2/2)dz\Bigg] \end{aligned} \tag{A.6}$$

Introducing $\phi(\cdot)$ and $\Phi(\cdot)$ as the standard normal density (ordinate) and cumulative distribution functions, respectively, and recognizing that for the standard normal that $\int_{\omega}^{\infty} zf(z) = \phi(\omega)$, gives

$$\begin{aligned} Y_{late} = &\left[\frac{K}{\Phi\left(\frac{b-\mu}{\sqrt{v}}\right) - \Phi\left(\frac{a-\mu}{\sqrt{v}}\right)}\right] \\ &\times\left\{\sqrt{v}\left[\phi\left(\frac{c_2-\mu}{\sqrt{v}}\right) - \phi\left(\frac{b-\mu}{\sqrt{v}}\right)\right]\right. \\ &\left. -(c_2-\mu)\left[\Phi\left(\frac{b-\mu}{\sqrt{v}}\right) - \Phi\left(\frac{c_2-\mu}{\sqrt{v}}\right)\right]\right\} \end{aligned} \tag{A.7}$$

Expected Earliness Cost

Repeating the steps outlined in (A.3)–(A.7) for the expected earliness cost

$$Y_{early} = \frac{QH}{p} \int_a^{c_1} (c_1 - x) f_X(x)\, dx \tag{A.8}$$

yields

$$Y_{early} = \left[\frac{QH}{\Phi\left(\frac{b-\mu}{\sqrt{v}}\right) - \Phi\left(\frac{a-\mu}{\sqrt{v}}\right)} \right] \times \left\{ \sqrt{v} \left[\phi\left(\frac{c_1-\mu}{\sqrt{v}}\right) - \phi\left(\frac{a-\mu}{\sqrt{v}}\right) \right] - (c_1 - \mu) \left[\Phi\left(\frac{a-\mu}{\sqrt{v}}\right) - \Phi\left(\frac{c_1-\mu}{\sqrt{v}}\right) \right] \right\} \tag{A.9}$$

Negative values for delivery times are negligible provided $\mu > 4\sqrt{v}$; hence, we set $a = \mu - 4\sqrt{v}$ and $b = \mu + 4\sqrt{v}$. This implies $\phi(\frac{a-\mu}{\sqrt{v}}) = \phi(\frac{b-\mu}{\sqrt{v}}) \cong 0$, $\Phi(\frac{a-\mu}{\sqrt{v}}) \cong 0.0$ and $\Phi(\frac{b-\mu}{\sqrt{v}}) \cong 1.0$.
Combining (A.8) and (A.9) and simplifying gives

$$Y = QH \left\{ \sqrt{v}\phi\left(\frac{c_1-\mu}{\sqrt{v}}\right) + (c_1 - \mu) \left[\Phi\left(\frac{c_1-\mu}{\sqrt{v}}\right) \right] \right\} + K \left\{ \sqrt{v}\phi\left(\frac{c_2-\mu}{\sqrt{v}}\right) - (c_2 - \mu) \left[1 - \Phi\left(\frac{c_2-\mu}{\sqrt{v}}\right) \right] \right\} \tag{A.10}$$

APPENDIX B. DERIVATION OF EXPECTED PENALTY COST FOR LEARNING BASED VARIANCE REDUCTION

The expected penalty cost can be expressed as a function of the delivery period variance, $v(t)$, as

$$Y(v,t) = QH \left[\sqrt{v(t)}\phi\left(\frac{c_1-\mu}{\sqrt{v(t)}}\right) + (c_1 - \mu)\, \Phi\left(\frac{c_1-\mu}{\sqrt{v(t)}}\right) \right] + K \left\{ \sqrt{v(t)}\phi\left(\frac{c_2-\mu}{\sqrt{v(t)}}\right) - (c_2 - \mu) \left[1 - \Phi\left(\frac{c_2-\mu}{\sqrt{v(t)}}\right) \right] \right\} \tag{B.1}$$

Under the widely adopted log-linear learning curve model (Yelle, 1979), the delivery variance is defined to be

$$v(t) = v(0)(t^d) \tag{B.2}$$

where

$v(0) =$ initial variance of the delivery distribution $f_X(x)$
$t =$ cumulative delivery number($t = 1, 2, \ldots, m$)
$v(t) =$ variance of $f_X(x)$ for t^{th} delivery
$d = (\ln \theta)/(\ln 2)$
$\theta =$ learning rate $(0.5 < \theta < 1)$.

Improvement delivery variance as defined in (B.2) takes the functional form where $v'(t) < 0$ and $v''(t) > 0$. This form implies that when improvements in delivery timeliness are implemented the variance will decrease at a diminishing rate. This functional form has intuitive appeal since it generally becomes harder to gain additional, incremental process improvements once such enhancements have already been made. This form has been widely adopted in several process improvement studies (see Tubino and Suri (2000), Choi (1994), Gerchak and Parlar (1991)).

Substituting (B.2) into (B.1) and simplifying yields (5). Two key steps of the derivation are

$$\text{Term 1 (for } g = 1, 2):\sqrt{v(t)}\phi\left(\frac{c_g - \mu}{\sqrt{v(t)}}\right) = \sqrt{\frac{v(0)(t^d)}{2\pi}}\left\{\exp\left[\frac{-(c_g - \mu)^2}{2v(0)(t^d)}\right]\right\} \tag{B.3}$$

and,

$$\text{Term 2 (for } g = 1, 2):\Phi\left(\frac{c_g - \mu}{\sqrt{v(t)}}\right) = \int_{-\infty}^{(c_g-\mu)/\sqrt{v(0)(t^d)}} \phi(x)dx = \Phi\left[\{c_g - \mu\}\Big/\sqrt{v(0)(t^d)}\right] \tag{B.4}$$

BIOGRAPHICAL SKETCHES

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