Proceedings

Thirty-Third
annual meeting

Transportation Research Forum (TRF)

Halloween In New Orleans

October 31 -
November 2, 1991
New Orleans, LA

Editor:
Louis A. Le Blanc

TRANSPORTATION SELECTION AND LOGISTICS COSTS IN AN UNCERTAIN DEMAND AND LEAD TIME ENVIRONMENT

John E. Tyworth
Kant Rao
Alan J. Stenger
The Pennsylvania State University
University Park, PA 16802

Purchasing transportation to haul freight involves both strategic and tactical planning elements. The strategic elements include the choice of mode and the method of acquiring transportation services. Among other things, such choices will affect the logistics network configuration, the level and deployment of inventories, the selection of suppliers, the levels of productivity in manufacturing and distribution, and the realization of long-term customer service goals. The tactical planning elements principally focus on carrier selection and shipment size. These decisions will have an impact on factors such as the mix of intransit, cycle, and safety stocks for specific lanes, the ability to exploit volume prices and freight rates, and the quality of customer service. Thus savvy transportation buyers consider the impact of their purchasing decisions on the quality, as well as the costs, of logistics performance.

The problem is that quantifying the trade-offs related to transportation purchases becomes especially complex when both demand and lead time are uncertain. Such analyses encompass many variables with tangled relationships, as well as some challenging conceptual and technical difficulties. Not surprisingly, many transportation buyers do not even try to gather the data necessary to conduct such analyses (Chow and Poist, 1984). Instead, the trend is for companies to develop transportation quality programs in which (1) carriers are certified to meet certain standards of service quality and (2) both long- and short-term purchases are made from the "certified" carriers that offer competitive freight rates (Automotive Industry Action Group, 1989; Bardi et al., 1990).

From the modeling perspective, the prevailing conceptual framework for the tradeoff analysis problem involves a choice between two unappealing compromises: either make simplifications to obtain mathematically tractable, but imprecise, results or use complex formulations that can produce reasonably accurate results, but are difficult to solve and often intractable (Bagchi et al., 1984; Banks and Spoerer, 1987). Currently, the firm-level transportation selection models have opted for the first compromise. The commercially successful "ShipSmart" model, for example, adopted an analytic approach that works by assuming that demand is known with certainty and that unit shipping costs can be modeled accurately as a continuous function (Sheffi et al., 1988). Other models use the standard inventory theoretic approach, which assumes an uncertain demand and lead-time setting and primarily focuses on the tactical decisions related to repetitive shipments of a single item over the same lane, and a continuous review inventory system (see Tyworth, 1991a). The specific task facing these kinds of (s, T, Q) transportation selection models is to determine the transportation option (T), the shipment size (Q), and the replenishment level (s) that will minimize the expected total annual logistics costs for a desired level of customer service.

This paper presents a model that extends and refines the current state of transportation selection analysis. This model exploits the power, flexibility, and convenience of microcomputers to examine the complex formulations that (1) arise from nonlinearities in purchasing, inventory, and transportation costs, (2) produce more accurate results, but (3) thwart the development of direct mathematical solutions. In addition, this tool embraces a new approach for assessing the effects of transportation service attributes on safety stock holding costs in a stochastic setting. This approach is apropos for high demand items, which represent a high percentage of inventory assets, require relatively frequent shipments, and thus are of special interest to transportation planners.

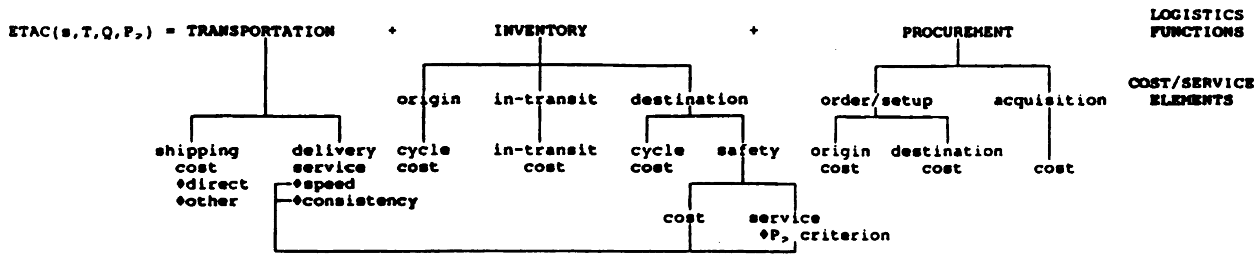
Although the new model does not consider every factor that may be relevant to a particular transportation purchase (such as a subjective assessment of a carrier's financial strength, a customer's preference for a certain carrier, and so forth), it does include an extensive list of quantifiable elements that shippers and carriers will find useful for evaluating alternative price-service offerings. In effect, the framework presented in this paper is a blueprint for a high resolution, "manager-friendly" computer model. Transportation buyers, as well as carriers, can readily adapt this framework to a spreadsheet environment for the analysis of tradeoffs among transportation, inventory, customer service, and procurement elements.

Model

The purpose of the model is to estimate the expected total annual logistics costs (ETAC) for a given replenishment level (s), a transportation option (T), a replenishment size (Q), and a service criterion (P_2). The bounds on the error of the estimate of ETAC should be less than one percent.

Framework

The framework of the model appears in Figure 1. The expected total annual logistics costs [ETAC(s, T, Q, P_2)] involves key trade-offs among transportation, inventory, and procurement functions. The transportation elements include the direct costs of shipping, as well as the indirect costs that speed and consistency impose on safety stock holding costs. The inventory cost elements consist of the holding costs for cycle and safety stock located at destination and, possibly, at origin storage facilities, as well as for stock in the "pipeline." The procurement elements include the ordering/setup costs at both origin and destination and the purchase cost.



where

- s = reorder point
- T = transportation alternative
- Q = order quantity
- $P_>$ = specified fraction of annual sales satisfied

Figure 1. Framework for Expected Total Annual Cost (ETAC)

Input

Table 1 illustrates one possible arrangement of model elements with hypothetical values. As shown in Table 1, the analyst initializes the model with information that falls into four categories as follows.

Shipping. The cost of shipping will depend on the transportation option selected and the shipment size. Each option is represented by a different mix of values for the transportation cost and service elements shown in Figure 1.

The importance of transportation costs supports the use of accurate input. The actual rate structure, of course, provides the most accuracy. Fortunately, today's PCs can easily derive unit shipping costs from popular volume rate structures. The supporting computer logic is not difficult to develop, especially in a spreadsheet environment. Thus, the cost input mirrors a simplified rate table that ties rates to minimum weights. Other input may include a schedule of actual charges linked to the order size for items such as special services, loss and damage, claims administration, and packaging.

The transportation performance data comprise a table of transit times and the probability of each, which the user can develop from past history. This input is necessary to estimate the effects of transit-time performance on safety stock holding costs.

Product. The product input includes actual measurements, or estimates, of the level of annual demand, the appropriate number of periods per year, and the parameters (mean and standard deviation) of period demand. If the company has a time series forecasting system to estimate demand, the standard deviation of period forecast errors replaces the standard deviation of period demand. The step is important because such forecast systems can generate more reliable estimates that may reduce safety stock levels by as much as 15 percent (Zinn and Marmorstein, 1990).

Inventory. The inventory category requires a holding cost factor for stationary (cycle and safety) stocks, as well as for in-transit stocks. The reason for using separate factors is twofold. First, the cost of holding in-transit inventory is less than that of carrying inventory in the warehouse. Second, from a modeling standpoint, the increased resolution requires very little extra effort. Additionally, the user needs to specify an order fill (P_2) service-control criterion. This criterion is preferable to other service or shortage criteria because it will calibrate safety stock levels to achieve the same expected annual shortages for each transport option evaluated and thus holds the service effect constant (Tyworth, 1991a).

Procurement. The required procurement data consist of the ordering/setup costs per replenishment, the base price per unit, the average time for processing an order, and the unit price, which may include a schedule of discounted prices linked to minimum order sizes. This information supports several extensions of refinements to the classic model. First, the setup costs extend to the applicable fixed costs per

Table 1. Model Elements

INPUT

DEMAND		
Periods/Year	SY	250 wkdays
Annual Volume	R	25,000 units
Std. Dev. Demand	SFE	10.00 units
PRODUCT		
Items per Unit	IU	24 items
Item Weight	IW	1.5 lb
Prod. Rate/Period	p	125 units
INVENTORY		
Holding Cost–Whse	H	35%
Holding Cost–Trn	H'	20%
Order Fill	P_2	98.00%
PROCUREMENT		
Ordering Periods	T	2.00 wkday
Order Size	Q	830 units
Set-up (Des)	S_D	$25.00
Set-up (Org)	S_O	$25.00

SHIPPING OPTION T: 1

UNIT PRICE SCHEDULE

Index	Q Units Ordered	v_i Price/Unit
i	0	1
0	1	$100.00
1	100	$100.00
2	500	$100.00
3	1,000	$100.00

FREIGHT RATES

Index	WB_m Weight Break	MW_m Minimum Weight	f_m Freight Rate/cwt
m		0	1
0	1	1	$30.67
1	391	500	$24.00
2	741	1,000	$17.78
3	1,684	2,000	$14.97
4	4,028	5,000	$12.06
5	9,022	10,000	$10.88
6	10,643	20,000	$5.79
7	23,679	30,000	$4.57
8	39,737	40,000	$4.54

OTHER SHIPPING CHGS

Index	AW_n Actual Weight	CH_n Charge per cwt
n	0	1
0	1	$0.00
1	10,000	$0.50
2	50,000	$0.50

SHIPPING TIME PROBABILITIES

j	1	2	3	4	5	6	7	8	9	10
p(j)	0.000	0.000	0.000	0.200	0.650	0.100	0.030	0.000	0.000	0.020

RESULTS GIVEN Q, P_2, T

ELEMENTS			EXPECTED ANNUAL COSTS		
TRANSPORTATION			*TRANSPORTATION*		
Unit Weight	UW	36.0 lb	Direct Shipping	SC	$41,295
Actual Weight	AW	29,880 lb	Other Charges	AC	4,500
Minimum Weight	MW	30,000 lb	Total	TRN	$45,795
Billed Weight	BW	30,000 lb			
Freight Rate	f_m	$4.57 /cwt			
Other Charges	CH_n	$0.50 /cwt			
Shipping Time	ST	3.06 wkday			
PROCUREMENT			**PROCUREMENT**		
Setup Costs	A	$50.00	Setup	OR	$1,506
Orders/Year	RY	30.1	Acquisition	AC	2,500,000
Reorder Level	s	563 units	Total	PRO	$2,501,506
Unit value (Des)	UV_D	$101.83			
Unit Value (Org)	UV_O	$100.00			
INVENTORY			**INVENTORY**		
Period demand	d	100 units	Cycle Stock Org	INVO	$11,620
Lead Time Periods	LT	5.06 wkdays	Cycle Stock Des	INVD	14,790
Cycle Stock (Des)	CS_D	415 units	In-Transit Stock	INVT	6,232
Cycle Stock (Org)	CS_O	332 units	Safety Stock	SSC	2,039
In-Transit Stock	IS	306 units	Total	INV	$34,681
Safety Stock	SS	57 units			
Planned Short/Cycle	ESPRC	16.600 units			
Expected Shortage	E(S)	16.600 units			
Fraction Unfilled	FU	2.00% sales	TOTAL COST	ETAC	$2,581,982

DERIVED

REPLENISHMENT LEVEL

Q	s
550	611
570	606
590	602
610	598
630	594
650	590
670	587
690	584
710	581
730	578
750	575
770	572
790	569
810	566
830	563
850	560
870	558
890	555
910	552
930	550
950	547
970	545
990	542

order incurred at origin, say in a channel-alliance setting. Second, the price schedule permits an explicit evaluation of unit acquisition costs that may shrink over a range of replenishment sizes. Third, lead time includes both ordering time and shipping time. This last refinement is significant, because order processing activities may comprise 40 percent or more of lead time (LaLonde et al., 1988).

Mathematical Formulation

The mathematical specification of the cost elements uses a schematic approach that successively deconstructs the equations into easily understood identities. This approach facilitates the translation of the conceptual framework into a working computer model.

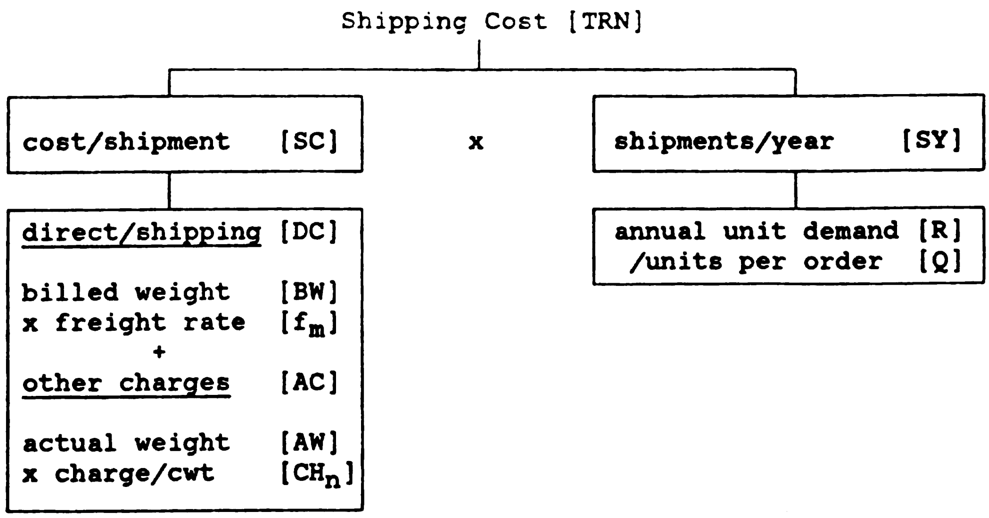
Transportation. Figure 2a outlines the transportation cost equations. Unfortunately, the mechanics of inserting the correct variable values in these equations are not as simple as the arithmetic involved. To compute the linehaul charges, one first has to determine the billing weight as either the actual weight or the minimum weight and then apply the directly corresponding rate level. Of course, the proper weight to use depends on the "weight break" of the applicable weight group. In a similar fashion, the calculation of other shipping charges simply requires identifying the charge per unit of weight that corresponds to the shipment weight. The presumption is that these charges apply only to the actual weight of the shipment.

These steps can be automated easily on a computer. Using a spreadsheet, for example, the developer only has to create simple formulas for the weight break and then use table look-up functions that key on the formula values.

Inventory. As previously indicated, holding costs may include the cycle stock held at the origin in addition to the in-transit stock, and the cycle and safety stock held at the destination. The level of origin cycle stock is a function of the replenishment size (Q) and the rates of production and consumption. As shown in Figures 3a and 3c, this level is equivalent to the destination cycle stock (Q/2) adjusted to reflect the different number of periods it takes to produce and to consume Q units (see, for example, Larson, 1988). The price schedule, which reflects any quantity discounts, will determine the appropriate unit value of this stock.

The level of in-transit stock depends on the speed of transportation option (T) and the rate of consumption or period demand (d) (see Figure 3b). If appropriate, the unit value may reflect unit shipping costs besides the unit purchase price.

The stock held at destination consists of both cycle and safety stock (see Figure 3c). The cycle stock is simply the average order size (Q/2). The level of safety stock, however, depends on the replenishment level (s), the speed and consistency of transport option (T), and the replenishment size (Q). Thus, the determination of safety stock is a conceptually and technically difficult task. Indeed, few models have tried to consider T and Q simultaneously.

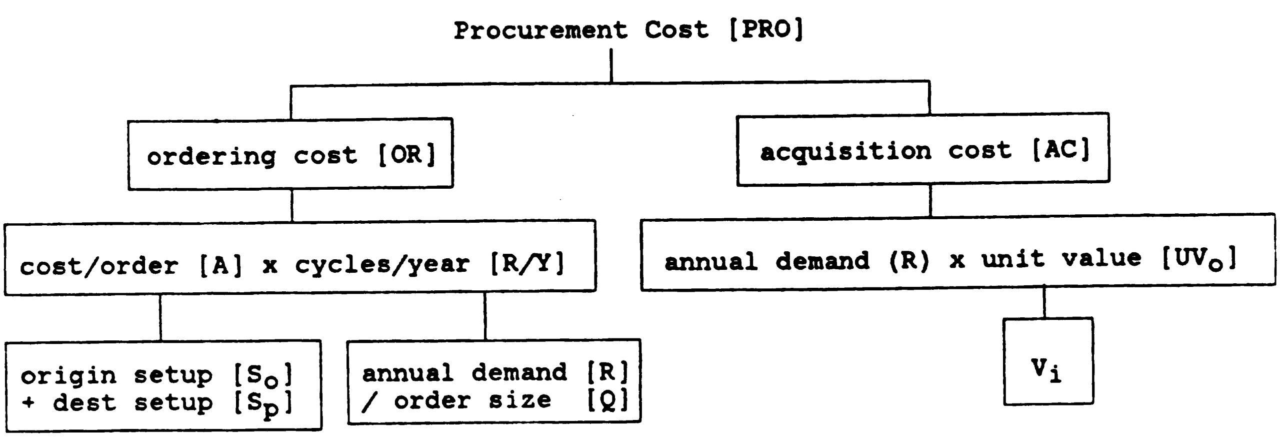


$$TRN = SC \times SY \quad (1)$$
$$= (DC+AC) \times R/Q \quad (2)$$
$$= (BW \times f_m) + (AW \times CH_n) \times R/Q \quad (3)$$

where

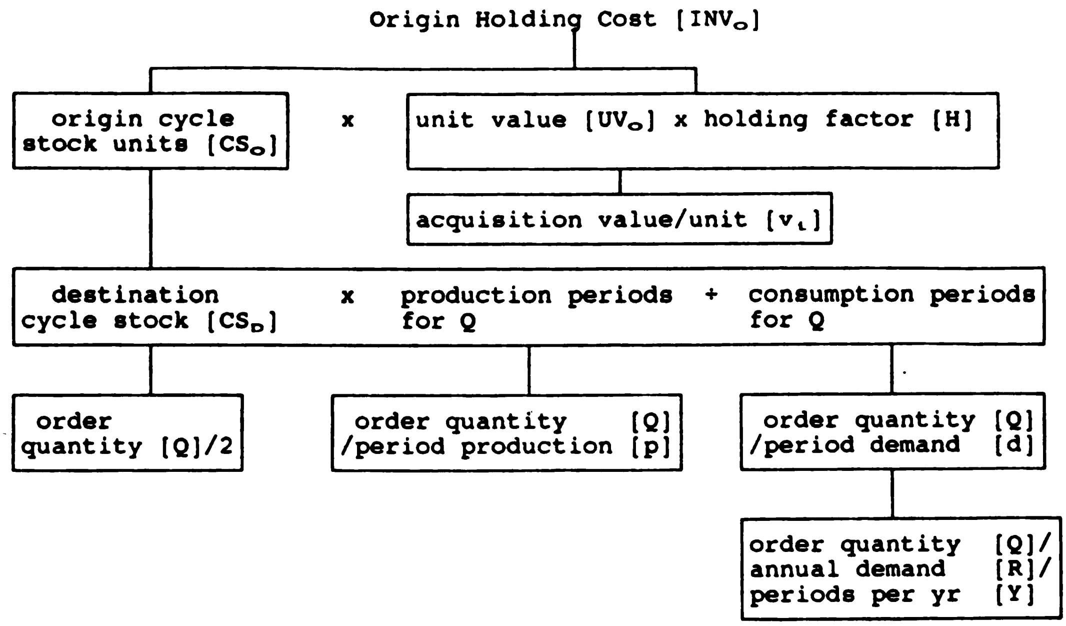
the billed weight [BW] = the actual weight = units shipped [Q] x unit weight [W], if the actual weight is less than the weight break (WB_m); else the billed weight = the minimum weight [MW_m].

Figure 2a. Transportation Cost Equations and Identities



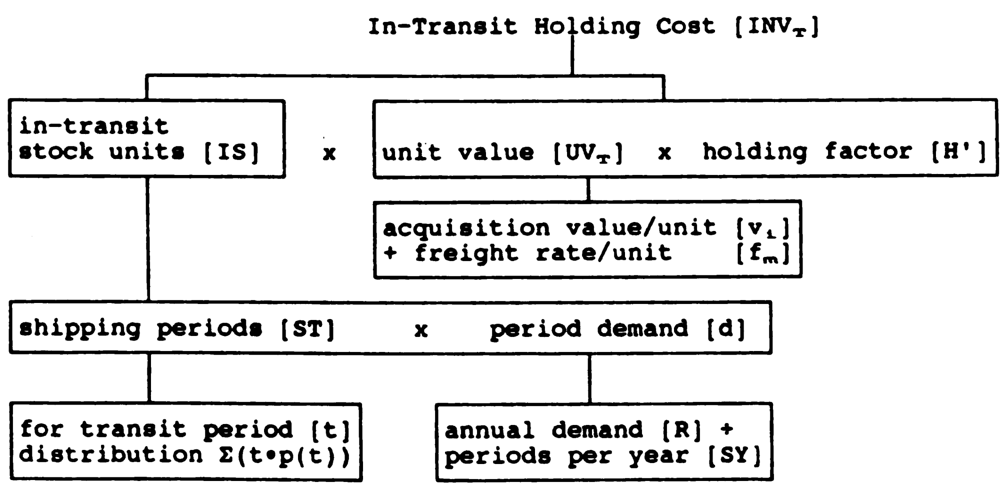
$$PRO = OR + AC \quad (4)$$
$$= A \times RY + R * UV_o \quad (5)$$
$$= S_o + S_p \times R/Q + R * V_i \quad (6)$$

Figure 2b. Procurement Cost Equations and Identities



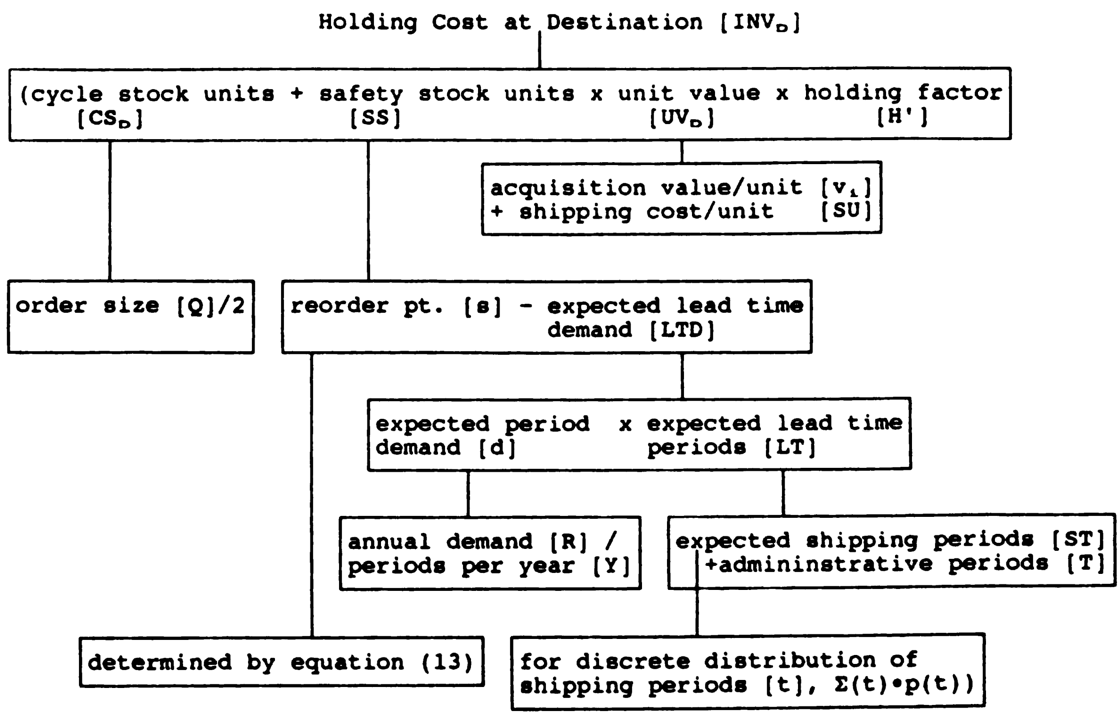
$$INV_O = CS_O \times UV_O \times H \quad (7)$$
$$= CS_D \times (Q/p)/(Q/d) \times v_i \times H \quad (8)$$
$$= Q/2 \times DD/p \times v_i \times H \quad (9)$$
$$= Q/2 \times (R/Y)/p \times v_i \times H \quad (10)$$

Figure 3a. Origin Inventory Cost Equations and Identities



$$INV_T = IS \times (UV_T) \times H' \quad (11)$$
$$= ST \times d \times (v_i + f_m) \times H' \quad (12)$$
$$= \Sigma(t \cdot p(t)) \times R/Y \times (v_i + f_m) \times H' \quad (13)$$

Figure 3b. In-Transit Inventory Cost Equations and Identities



$$INV_D = (CS_D + SS) \times (UV_D) \times H' \quad (14)$$
$$= (Q/2 + SS) \times (v_i + SU) \times H' \quad (15)$$
$$= [Q/2 + s - (d \times LT)] \times \{v_i + [(f_m + CH_n)/100 \times UW] \times H' \quad (16)$$

__where s is determined so:__

$$\Sigma\, G_u(k_j) \bullet \sigma j \bullet p(j) = \text{expected short per replenishment cycle [ESPRC]} \quad (17)$$

and

j = lead time period

$$k_j = u(s) = (s - \mu j)/\sigma_j) = (s - j \bullet d)/(\sqrt{j} \bullet \sigma_{rm}) \quad (18)$$

$G_u(k_j)$ = partial expectation estimated by Brown's [1967] rational approximation method

$$ESPRC = (1-P_2) \bullet Q \quad (19)$$

P_2 = specified fraction of annual sales not lost

Figure 3c. Destination Inventory Cost Equations and Identities

The approach to determine safety stock follows Tyworth's paradigm shift (1991c). This paradigm is appropriate if period demands, or period demand forecast errors, follow a normal distribution. Studies indicate that this assumption is warranted for high demand items having a period demand often or more units (Archibald and Silver, 1974; Bagchi et al., 1984; Hax and Candea, 1984). This approach will produce accurate results for any discrete empirical distribution of transit times, including discrete approximations of continuous distributions. Further, unlike the classic procedures, this approach does not require any assumptions about the shape of lead time demand. Thus the analyst does not face the choice of (1) positing a lead time demand distribution that can be evaluated easily, (2) trying to model a compound distribution and hoping the results are analytically tractable, or (3) resorting to simulation methods.

The steps needed to determine safety stock are as follows:

1. Given the desired order fill rate (P_2) and the replenishment size (Q), calculate the expected units short per replenishment cycle (ESPRC) as ($1-P_2$) multiplied by Q.

2. Compute ESPRC using an alternative expression that is a composite rational function of the replenishment level *s* and the replenishment size Q (see Figure 6). The problem is to determine the value of *s* that yields an expected shortage equal to the result derived in the first step, or equivalently, the value of *s* that yields the order fill rate (P_2). Determining *s* involves finding the roots (zeroes) of a polynomial function of degree four, a task that encompasses nonlinear solution procedures, such as the reduced gradient method (see, for example, Ostrowski, 1960; Ralston, 1965).

These two steps are repeated for a range of Q values to produce expected shortage (s, Q) tables for each transportation option. Although this is a complex process, inexpensive PC software makes its implementation relatively easy. In fact, a prototype spreadsheet model, which calls on a commercially available optimization routine and follows a few macro commands, completed this process quickly and efficiently (see Table 1).

Thus given Q, the replenishment level *s* is found in the shortage table to determine safety stock, which is the difference between *s* and the expected lead time demand. The unit value of this stock, like the value for in-transit stock, may include the unit shipping cost to the unit price.

Procurement. The formulation of procurement costs follows the standard pattern with two exceptions (see Figure 2b). First, setup/ ordering cost elements at the origin may be included. Second, unit price discounts are permitted. Although a discount price structure will produce the same acquisition cost for each alternative, it affects the order size. This effect is important, because the order size can influence the carrier selection when carriers have distinct volume discount rate structures.

Solution Procedure

The solution procedure requires three steps. In the first step, it is necessary to construct the expected shortage tables for each transportation option. As previously indicated, these tables list the replenishment level (s) needed to achieve the pre-specified order fill level (P_2) over a range of replenishment sizes (Q). The second step involves the explicit enumeration of the ETAC (s, P_2) of each transport option over a range of Q values. In the third step, one compares the ETAC curves to identify the lowest cost option.

Like its predecessors, this model has solution procedures that require computer support for practical application. The spreadsheet, which has become a staple in the business community, provides an excellent medium for such applications (see, for example, Tyworth and Grenoble, 1991; Tyworth, 1991b).

Conclusions and Recommendations

The model presented in this paper reaches a high-level resolution by extending, refining, and integrating elements of current transportation selection models and by using a new "numerical engine" to evaluate the effects of transportation performance on safety stock holding costs. The model, moreover, translates fairly easily into a manager-friendly spreadsheet program.

In practice, the field implementation of this model may simply retain the basic form presented in this paper, or it may become more elaborate. Developers can add new cost elements terms to the ETAC equation, say, for inspection costs. In addition, developers could change the model into a decision support system tool by constructing links to corporate databases so that the models procedures could be applied easily to many lanes and products.

One potential avenue of future research is to investigate an extension of this model to the multiproduct and multiperiod setting in which products are ordered and fulfilled jointly. Another avenue is to explore extensions of the model to the order splitting and multiple supplier settings.

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