The Impact of "Never Run Out" Policy
Assured Supply Chain with Dual Reorder Point Expediting

by

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Submitted to the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degree of

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Abstract

Managing a big supply chain for one of the largest quick service restaurant companies, especially when the company has a policy called "Never Run Out," is very challenging. A traditional way of managing inventory requires high level of safety stock if high level of uncertainty is involved. Sources of uncertainty include variability in demand from frequent promotions or seasonal effect, variability in order lead time from using low-cost mode of transportation, or lack of information sharing. This project developed an expediting policy with dual reorder points with demand threshold and tested the policy with a Monte Carlo simulation. Previous research on two reorder points provide great foundation for this study but they lack consideration on demand variability and approaches to set up reorder points. We propose an algorithm with a demand threshold to trigger an expedited order and heuristic approaches to develop reorder points where the total cost can be minimized while service requirements are met.

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Gil Su Lee

Cambridge, MA

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1 Introduction

1.1 Never Run Out Policy

One of the largest quick service restaurant (QSR) companies (name disguised as Company X) has a very challenging policy, "Never Run Out," and we were requested to study the impact of the policy. It is a straightforward and natural policy because Company X is quality oriented and customer service focused and any stock out in their food supply means at least loss of a customer, corporate images or even further.

Company X's supply chain is big and highly decentralized. It includes over 100 suppliers, about 15 outsourced companies running 5 hubs and 44 distribution centers (DCs), other service providers in charge of planning and execution of daily operations, and over 13,000 restaurants. About 70% of their business is franchised and a long-term partnership based on trust is the norm.

Understanding Company X's governing structure that is based on decentralization and a partnership, a bigger concept encompassing the whole supply chain is necessary. Their 'policy' of "Never Run Out" is not a policy but is more of business philosophy or mission statement to ensure the service and quality throughout the company.

Therefore, we suggest that they have an effective 'policy' to manage their supply chain, specifically inventory, better rather than just building safety stock. We will discuss alternative ways of managing inventory and transportation in the following chapters starting from challenges.

1.2 Challenges in Inventory Management

Effective inventory management under the variability in demand and order lead time is challenging. It is even more so when there is no information available on timing and size of the customer orders. The inventory manager at Company X would not have any choice but to simply build 'enough' inventory if he had no demand information and is told that inventory should 'never run out.' But the question is whether building a pile of safety stock is the best way to protect the level of service.

The first challenge for the inventory manager at Company X is understanding demand uncertainty. The uncertainty in demand is amplified if there are frequent promotions, launches of new products, or seasonal fluctuations as shown in Figure 1, 2 and 3 respectively.

Figure 1 shows a demand pattern at one of Company X's typical restaurants with promotions in every 2-3 months for two products, Product A and Product B. Each vertical grid represents 16 weeks.

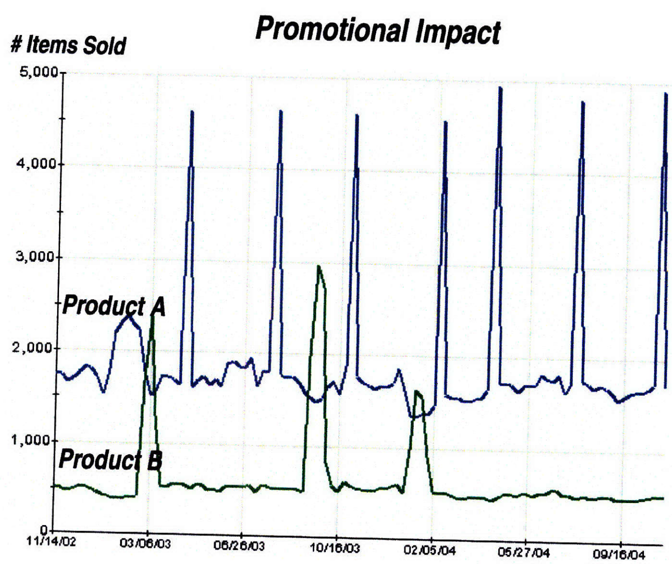

Figure 1: Demand Variability - Promotion

Figure 2 and Figure 3 also represent the demand pattern with new product launch and seasonal effect similarly. It simply shows how hard it will be to estimate the exact demand with promotions and how challenging it is for inventory managers to forecast the demand exactly.

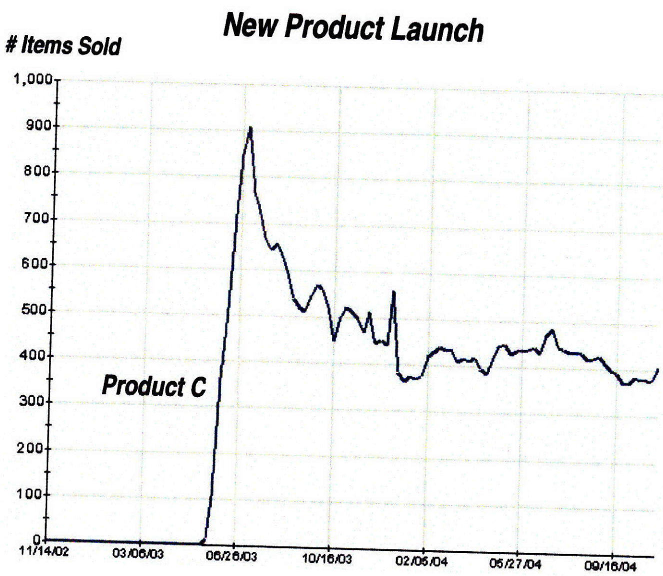

Figure 2: Demand Variability – New Product Launch

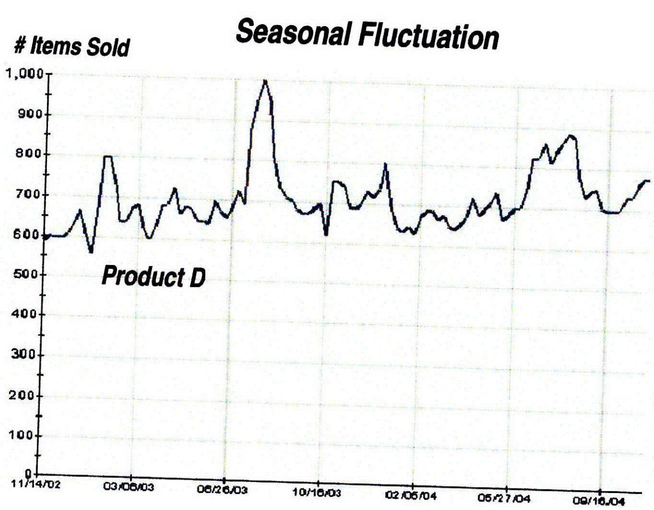

Figure 3: Demand Variability – Seasonal Fluctuation

The second challenge for an inventory manager at Company X is the lead time variability. As part of an effort to reduce cost, the Company X is using less expensive modes of transportation, such as rail, to replace current truck load (TL). However, although the rail is cheaper, in general, the lead time and the lead time variability involved with rail transportation is much greater than trucking.

The third challenge for an inventory manager at Company X is the availability of correct and timely information. Under the highly decentralized governing structure and with increasing use of less controllable transportation modes like rail, a certain limitation to acquire valid and on-time information will exist. Lacking good information for demand and shipment status, the inventory manager's choice could be limited to a high level safety stock to avoid risk of running out because it is 'safer' rather than 'better.'

The remainder of this thesis is organized as follows. Chapter 2 presents a literature review on inventory, transportation, and previous researches on expedited orders. Chapter 3 presents a two point reorder policy (s_1, s_2, Q) that the author suggests with algorithms to find effective reorder points. Chapter 4 shows simulation to test the policy in its effectiveness as a way to assure service and save cost against traditional inventory management using solely safety stock. Finally, chapter 5 summarizes the research and discusses the insights with a recommendation for future research.

2 Literature Review

In this literature review we first review some basics of inventory management and transportation to build a theory of expedited transportation with dual reorder points. A few key theses regarding expediting with two reorder points are also reviewed to help formulate the suggested policy. The key difference in expediting policy is that how demand changes are incorporated and used to trigger an expedited order and how the 'best' solution of reorder points are searched by suggested algorithms.

2.1 Inventory Review

Inventory is a way to compensate for variability in demand and supply. We have reviewed some of the basic concepts of inventory in terms of the cost impact from the variability in demand and lead times. Note how the average inventory changes with different inventory behavior models.

A lot size is the quantity to produce or purchase at one time and the average unit price is a key cost in its decision. If there is no variability in demand and lead time is instantaneous, the inventory behavior will be like the following.

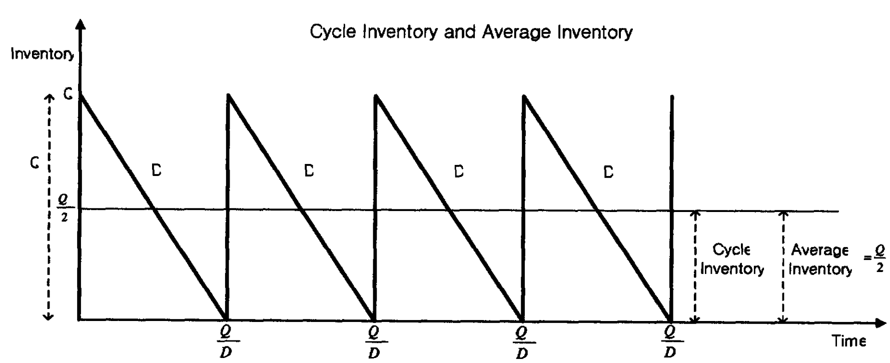

Figure 4: Cycle Inventory and Average Inventory

Cycle inventory is the average inventory in a cycle and in this case the average total inventory for this system is just the cycle inventory. It is held to take advantage of economies of scale in ordering and reduce cost, (Chopra, et al, 276). It can be noted as:

$$Cycle\ Inventory = \frac{Lot\_Size}{2} = \frac{Q}{2}$$

Equation 1: Cycle Inventory

The inventory holding and ordering costs create a trade-off at the optimum order quantity, *Q*, or Economic Order Quantity (EOQ):*

$$Q_{Opt} = EOQ = \sqrt{\frac{2AD}{vr}}$$

Equation 2: Economic Order Quantity

Where, A: Fixed ordering cost per order,

D: Demand in units per year,

v: Average unit price, and

r: Holding cost or the cost of having one unit one year.

Safety stock is carried to satisfy demand that might exceed the amount forecasted for the given lead time. Demand variability shifts inventory level up by safety stock level as in Figure 5:

$$Safety\ Stock\ (SS) = k\sigma_D$$

Equation 3: Safety Stock

Where, k: Safety factor which determines target service level CSL and

σ_D : Standard deviation of demand forecast error over lead time

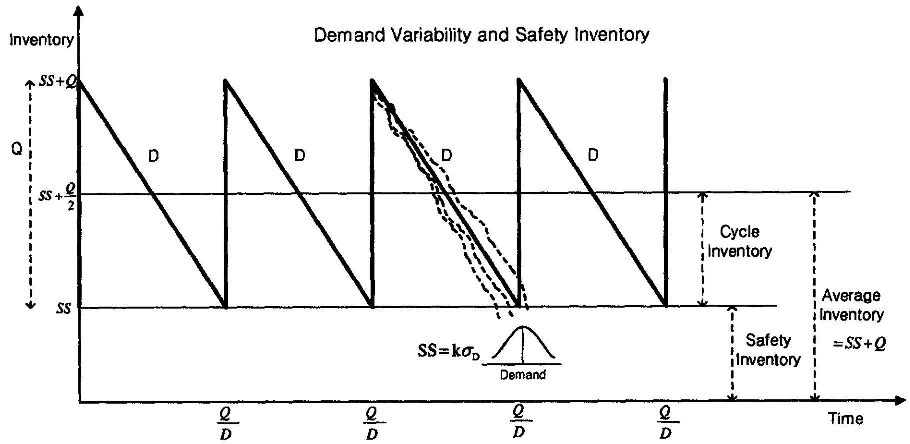

Figure 5: Demand Variability and Safety Stock

The pipeline inventory is in-transit inventory of which the order is made but not received yet and the average inventory in pipeline over year can be denoted as:

$$\text{The average inventory in pipeline over year} = (LQ)\times\left(\frac{D}{Q}\right) = LD$$

Equation 4: Average Inventory in Pipeline

Also, Inventory Position can be calculated as:

(Inventory Position) = (On-Hand) + (On Order) – (Backorders) – (Committed)

Equation 5: Inventory Position

Assuming lead time and demand are independent random variables, the expected demand over the lead time X_L is denoted as:

$$X_L = E(D_{Leadtime}) = E(L)E(D)$$

Equation 6: Demand over the Lead Time

Where, E(L): Expected lead time for an order and

E(D): Expected demand per period.

When lead time and demand are independent random variables, the standard deviation of forecast error over the lead time is calculated based on demand and lead time variability as:

$$\sigma_{Leadtime} = \sqrt{E(L)\sigma_D^2 + (E(D))^2 \sigma_L^2}$$

Equation 7: Standard Deviation of Forecast Error over the Lead Time

Where, σ_D: Standard deviation of demand per period and

σ_L: Standard deviation of forecast error over a period of L.

The safety stock in Equation 3 is thus denoted with demand and lead time variability as:

$$Safety\ stock = k\sigma_{Leadtime} = k\sqrt{E(L)\sigma_D^2 + (E(D))^2 \sigma_L^2}$$

Equation 8: Safety stock with Demand and Lead Time Variability

The reorder point is the sum of safety stock and demand over the lead time, X_L. From Equation 8, the formula for reorder point, $s = X_L + k\sigma_{Leadtime}$, can be denoted as:

$$s = X_L + k\sqrt{E(L)\sigma_D^2 + (E(D))^2 \sigma_L^2}$$

Equation 9: Reorder Point with Variability in Demand and Lead Time

2.2 *Service Measurement*

A cycle service level (*CSL*) is the probability of not stocking out in a replenishment cycle or the probability of having less demand than reorder point during the order lead time *(X_L)*. It can be denoted as the following (Chopra et. al. p322):

$$CSL = P[X_L \le s] = NORMDIST(ROP, D_L, \sigma_L, 1) = NORMSDIST(k) \; (In\ Excel)$$

Equation 10: Cycle Service Level

Expected shortage per replenishment cycle *(ESC)* is the average units of demand that are not satisfied from inventory in stock per replenishment cycle and is used to calculate fill rate *(FR)* (Chopra et. al. p324). When *ss=safety stock*, it is denoted as:

$$ESC = \int_{x=ROP}^{\infty} (x - ROP) f(x) dx = -ss\left[1 - F_S\left(\frac{ss}{\sigma_L}\right)\right] + \sigma_L f_S\left(\frac{ss}{\sigma_L}\right)$$

$$= -ss[1 - NORMDIST(ss/\sigma_L, 0,1,1)] + \sigma_L NORMDIST(ss/\sigma_L, 0,1,0) \; (In\ Excel)$$

Equation 11: Expected Shortage per replenishment Cycle (ESC)

Product fill rate *(FR)* is the fraction of product demand that is satisfied from product in inventory or the probability that product demand is supplied from available inventory. It should be measured over specified amount of demand rather than time (Chopra et. al. p320). Given a lot size of *Q*, the fraction of demand lots is thus *ESC/Q* and the product fill rate *FR* becomes:

$$FR = 1 - ESC/Q = (Q - ESC)/Q$$

Equation 12: Fill Rate

In reviewing the performance of a supply chain, the throughput is an important factor. We discuss the role of inventory in terms of throughput as per Little's Law when inventory is represented by *I*, flow time by *T*, and throughput by *D* as below (Chopra et. al. p67):

$$I = DT$$

Equation 13: Little's Law

When the average flow rate equals to demand or sales, the average flow time can be denoted in terms of cycle inventory as below:

$$Average\ Flow\ Time = \frac{average - inventory}{average - flow - rate} = \frac{cycle - inventory}{demand} = \frac{Q}{2D}$$

Equation 14: Average Flow Time

2.3 *Transportation Review*

In order to study expedited transportation we identified different modes of transportation and the utilization by weight and value. Below Table 1 shows the shipments by mode and weight in million tons and Table 2 shows the value in billion dollars.

As shown in Table 1 and Table 2, truck is by far the biggest mode of transportation. Rail, however, is not such a common mode of transportation although it handles weight shipments. The transportation modes can be denoted by the speed, reliability, cost, and weight. In general, speedy service is more reliable with less variability in lead time but is more expensive.

Table 1: Transportation Facts: Shipments by Mode and Weight (Mil. tons)

	2002				2035			
	Total	Domestic	Exports[3]	Imports[3]	Total	Domestic	Exports[3]	Imports[3]
Total	(P) 19,326	17,670	(P) 524	(P) 1,133	(P) 37,178	33,668	(P) 1,105	(P) 2,404
Truck	11,539	11,336	106	97	22,814	22,231	262	320
Rail	1,879	1,769	32	78	3,525	3,292	57	176
Water	701	595	62	44	1,041	874	114	54
Air, air & truck	(P) 10	3	(P) 3	(P) 4	(P) 27	10	(P) 7	(P) 10
Intermodal[1]	1,292	196	317	780	2,598	334	660	1,604
Pipeline & unknown[2]	3,905	3,772	4	130	7,172	6,926	5	240

Source: U.S. DOT, Federal Highway Administration, Office of Freight Management and Operations, Freight Analysis Framework, 2006.

Table 2: Transportation Facts: Shipments by Mode and Value ($Bil)

	2002				2035			
	Total	Domestic	Exports[3]	Imports[3]	Total	Domestic	Exports[3]	Imports[3]
Total	(P) 13,120	11,083	(P) 735	(P) 1,302	(P) 38,399	29,592	(P) 2,623	(P) 6,184
Truck	8,856	8,447	201	208	23,767	21,655	806	1,306
Rail	382	288	26	68	702	483	63	156
Water	103	76	13	13	151	103	31	18
Air, air & truck	(P) 663	162	(P) 226	(P) 275	(P) 2,455	721	(P) 778	(P) 955
Intermodal[1]	1,967	983	268	716	8,966	4,315	943	3,708
Pipeline and unknown[2]	1,149	1,127	1	22	2,357	2,315	1	41

Source: U.S. DOT, Federal Highway Administration, Office of Freight Management and Operations, Freight Analysis Framework, 2006.

2.4 *Expedited Orders*

2.4.1 Allen and D'Esopo Model

Allen and D'Esopo (1967) suggested an ordering policy for stock items when delivery can be expedited. The approach considered a continuous review policy with a reorder point X and order quantity Q and proposed a secondary reorder point, E, for an expedited order. When the stock on hand is reduced to the level E, then an outstanding order is expedited for amount Q and the order is received in a lead time of R, an expedited lead time, which is less than the standard order lead time L. They assumed the lead time R and L as constant but the effective lead time as becoming a random variable distributed over the interval *(R, L)* such that,

$E[LT] = \alpha R + (1-\alpha)L$ where α =probability an order is expedited.

One of key assumptions in their research was that if the demand over the lead time is significantly smaller than Q, the inventory on hand is almost certainly restored to a level greater than reorder point for standard order X when an order is received. They referred to this type of policy as an *(X, Q, E)* policy and the familiar formulas with fixed lead time need to be revised as below.

Formulas in Allen and D'Esopo Expedite Model:

Allen and D'Esopo assumed that the order can be triggered any time between *0* and *L-R* then the 'effective' lead time Z becomes a random variable distributed over the interval R to L and the time *L-R* becomes the last time point at which an expediting decision can be made. The formulas in Allen and D'Esopo expedite models are as below:

The expected value of Z: $E(Z) = L - \int_0^{L-R} \Pr(T < t)dt$

$$= L - \int_0^{L-R} \Pr(Y_t \geq X - E)dt$$

Equation 15: Expected Effective Lead Time to Expedite in Allen and D'Esopo Model

Where, T = the random time that inventory on hand is reduced to E and

Y_t = the number of demand occurring between zero and the time t.

The expected inventory can be denoted, where D = *Demand*:

The expected inventory: $I = X + \frac{Q}{2} - DE(Z)$

Equation 16: Expected Inventory in Allen and D'Esopo Model

In order to identify expected shortage per replenishment cycle, expected shortages of non-expedited case and expedited case are presented as S_1 and S_2 respectively as:

$$S_1 = \int_{y=0}^{K} \int_{z=X-y}^{\infty} (z + y - X)d\Pr(Y_R \leq z)d\Pr(Y_{L-R} \leq y).$$

Equation 17: Expected Shortages of Non-expedited Case (S_1)

$$S_2 = \Pr(Y_{L-R} \geq K)\int_E^{\infty} (y - E)d\Pr(Y_R \leq y)$$

Equation 18: Expected Shortages of Expedited Case (S_2)

Hence, from Equation 17 and Equation 18, the expected shortage per cycle is denoted as:

$$\text{Expected Shortage per Cycle: } S = \frac{D}{Q}(S_1 + S_2)$$

Equation 19: Expected Shortage Rate in Allen and D'Esopo Model

The Total Expected Cost $C = rcI + sS + AO + A'W + c'U$

$$= rc\left\{X + \frac{Q}{2} - D\left[L - \int_0^{L-R} \Pr(Y_t \geq K)dt\right]\right\} + s\frac{D}{Q}\left[\int_{y=0}^{K}\int_{z=X-y}^{\infty}(z + y - X)d\Pr(Y_R \leq z)d\Pr(Y_{L-R} \leq y\right.$$

$$\left. + \Pr(Y_{L-R} \geq K)\int_E^{\infty}(y - E)d\Pr(Y_R \leq y)\right] + \left(\frac{D}{Q}\right)[A + A'\Pr(Y_{L-R} \geq K)] + c'D\Pr(Y_{L-R} \geq K)]$$

Equation 20: Total Expected Cost in Allen and D'Esopo Model

Where, c *= the unit cost of the item,*

r *= the holding cost rate,*

s *= the unit shortage rate,*

A *= the order cost,*

A' *= the expedited order cost, and*

c' *= the increment to item unit cost for expediting*

Allen and D'Esopo provided a good foundation on expediting orders with an expedited reorder point. They hypothesized that whenever the inventory level drops to the expediting level, an outstanding order will be expedited and delivered after a short period. The main interest in their study was that the lead time effectively becomes a random variable.

In the following literature review by Chiang (2002), we consider the effectiveness of expediting with total cost by setting a fourth parameter of threshold time.

2.4.2 Chiang's Model

Chiang (2002) presented a continuous-review single-facility single-item two ordering policies when expediting is allowed. Chiang suggested two approaches: a Modified Allen and D'Esopo Model and Heuristic Policy. The former is a modified version of Allen and D'Esopo model with the fourth parameter called the threshold time. The latter is with the consideration of detailed segments of lead time: the manufacturing period M and the delivery period N.

The biggest difference in modified and 'original' Allan and D'Esopo model is that in the original model, the expedited order is triggered whenever the inventory level drops to the expediting level E and whenever the expedited order is 'effective' but in Chiang's modified model (Chiang's Model), the threshold time τ defines whether the expedited order is now 'cost-effective' by discouraging unnecessary or less helpful expedited orders with a threshold time, or the last time point when an expediting decision will be made. That is, after this time point, even if the inventory level drops to the expediting level, outstanding orders are not expedited so the inventory level must drop to E at a time no later than τ. Note that $\tau < L - R$ in Chiang's model, while $\tau = L - R$ in Allen and D'Esopo model. Chiang also introduces modified formulas

Formulas in Chiang's Model:

The effective lead time denoted by Allen and D'Esops can be rewritten in similar manner. Let t be the random time that the inventory level is reduced to E, Y_t the demand between time 0 and t, and $g_t(Y_t)$ the probability density function of Y_t. $\Pr(Y_t \geq s - E)$ is the probability of expediting.

$$E(Z) = L - \int_0^{\tau} \Pr(Y_t \geq s - E)dt - (L - \tau - R)\Pr(Y_t \geq s - E)$$

Equation 21: Expected Effective Lead Time to Expedite in Chiang's Model

$$TC(\tau, s, Q, E) = \frac{AD}{Q} + (\frac{A'D}{Q} + c'D)\Pr(Y_t \geq s - E) + rc[s - DE(Z) + 0.5Q]$$

Equation 22: Total Expected Cost in Chiang's Model

Where, c = the unit cost of the item,

c' = the increment to item unit cost for expediting,

r = the holding cost rate,

s = the unit shortage rate,

A = the order cost, and

A' = the expedited order cost.

The shortage cost is excluded because it is difficult to estimate but it is convenient for management to specify desired service level. Service level, denoted by φ, is defined in terms of shortage probability. In order to derive the shortage probability per order cycle, Chiang also considered two cases: the expediting case and the no-expediting case.

$$\Pr(Y_t \geq s - E)\Pr(Y_R > E) + \int_0^{s-E} \left(\int_{s-Y_t}^{\infty} g_{L-t}(Y_{L-t})dY_{L-t} \right) g_{\tau}(Y_{\tau})dY_{\tau} \leq 1 - \varphi$$

Equation 23: Probability of Shortage per Order Cycle in Chiang's Model

From the Equation 23, as the expediting level E becomes lower (other parameters being equal), $\Pr(Y - \tau \geq s - E)$ is smaller and thus expected total cost in Equation 22 also becomes smaller, but the shortage probability tends to be larger. Hence, given τ and s, the smallest value of E that satisfies Equation 23 can be found and when E is also known, Q can be solved by the following Equation 24.

$$Q = \left\{ \frac{2D[A + A' \Pr(Y_t \geq s - E)]}{rc} \right\}^{0.5}$$

Equation 24: Expedited Order Quantity in Chiang's Model

The expected total cost per unit time is thus reduced to be function of τ and s, denoted by $TC(\tau, s)$ and the lowest-cost solution can be found by the simple search on integer value s as the following algorithm.

Chiang's Algorithm

1. Given a certain s and each possible value of τ, find the smallest E satisfying Equation 23, compute Q by Equation 24, and record the solution's cost, $TC(\tau, s)$. Determine the value of τ that yields the lowest-cost solution.
2. For a different value of orders s, repeat step 1 until the optimal solution can be decided.

Chiang also investigated the effect of service level φ as well as the ratios A'/A, c'/c and R/L on the performance of the model. As tested, Chiang suggests that the higher the service level, the more cost-effective the proposed model. The results seem intuitively reasonable because high service levels justify expediting the outstanding orders.

3 Expedited Reorder Policy *(s_1, s_2, Q)*

Currently Company X is using rail for fast moving and low cost-per-weight items such as French fries and it is expected that more items will be switched from TL to rail for cost savings. We focused on the effect of transportation mode on inventory because the low-cost mode of transportation usually involves longer lead time and greater variability in lead time which in turn increases the safety stock level. We evaluate the impact of transportation on inventory and suggest a policy under the situation where the stock out cost is regarded reasonably high.

3.1 Dual Reorder Point Expediting

Both Allen and D'Esopo (1967) and Chiang (2002) assume that the demand is stable and the standard and expedited lead times are deterministic. In our model, however, we assume that the demand and the lead times are stochastic. This approach is practical and readily applicable for Company X because the uncertainty in demand and supply might result in stock outs and lead inventory managers to build high safety stock under the 'Never Run Out' inventory policy. As reviewed previously, if the supply chain of a company is agile enough to readily sense changes in demand or lead time and can prevent from stock out, the company could reduce the inventory level and become leaner.

We propose a continuous review policy for an expedited order that is triggered by a pre-defined reorder point with the consideration of demand variability. We also propose approaches to find reorder points that generate less total cost than traditional inventory policy solely with safety stock. We will discuss about the dual reorder point inventory management algorithm through the following chapters.

3.2 *Algorithm to Trigger an Expedited Order*

Allen and D'Esopo (1967) suggest an expedited order at any 'effective' lead time without further conditions. Chiang (2002) suggests an expedited order by setting a lead time threshold for a 'cost-effective' expediting. Our model suggests an expedited reorder point with a demand threshold. That is, when the inventory level drops to or below an expedited reorder point, s_2, the model tests if a stock out is expected with recent a demand trend D'.

The test condition for a stock out is derived from a triangular relationship in Figure 6 as:

$$\frac{s_1}{D'} = t_{SO} < L_S$$

Where, s_1 *: standard reorder point,*

L_S *: Expected lead time for a standard order:* $L_S = E(L_S)$,

D' *: Average demand since last standard order, and*

t_{SO} *: Expected time to stock out since last standard order.*

The algorithm also tests if an expedited order arrives earlier than the next available standard order to evaluate the risk and takes a preemptive action to assure service in cost-effective manner. The second test condition for effectiveness of expediting is derived as:

$$E(L_E) < E(L_S) - E(t_0) \text{ or } L_E < L_S - t_0$$

Where, L_E *: Expected lead time for an expedited order:* $L_E = E(L_E)$ *and*

t_0 *: Time since last standard order.*

Therefore, the algorithm to trigger an expedited order can be summarized as:

Algorithm to trigger an expedited order.

1. If inventory level < s_2, then go to the next step. If not, do not expedite an order.
2. If a stock out is expected, then go to the next step. If not, do not expedite an order.

   (Test if $\frac{s_1}{D'} = t_{SO} < L_S$)
3. If expedited order arrives earlier than the next standard order, expedited an order.

   If not, do not expedite an order. (Test if $L_E < L_S - t_0$)
4. Go to step 1.

Figure 6 shows inventory behavior with dual reorder points.

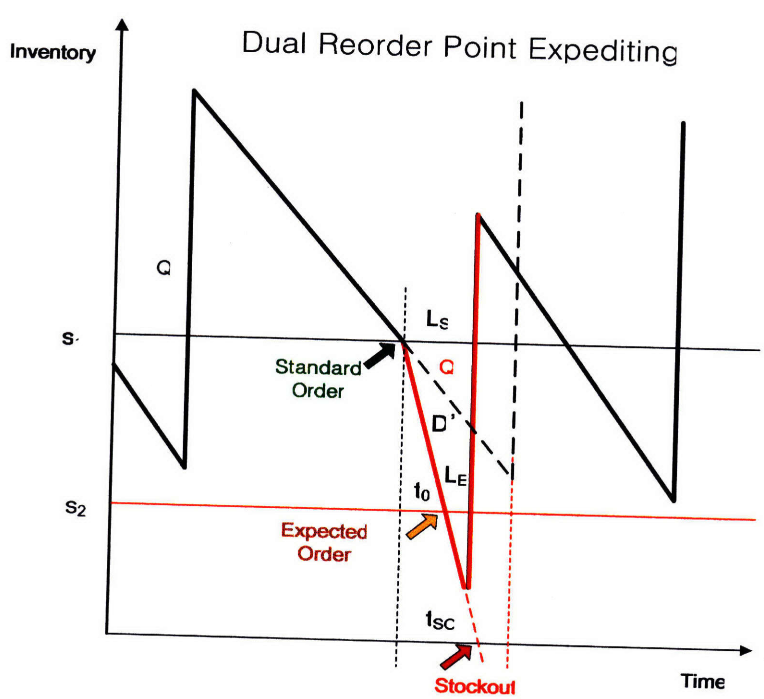

Figure 6: Dual Reorder Point Expediting Policy

3.3 *Reorder Points and Demand Threshold*

The standard reorder point in Equation 9 is adopted for s_1 and the same safety factor k is introduced in Equation 9, $s = X_L + k\sqrt{E(L)\sigma_D^2 + (E(D))^2\sigma_L^2}$. It determines service level (*CSL*) and is same as $F^{-1}(CSL)$ or, *in Excel, NORMSINV(CSL),* assuming that demand follows a Normal distribution. The same safety factor k is also used to formulate expedited reorder point s_2 so the search algorithm can shift (s_1, s_2) up and down at the same time. The demand parameter δ is introduced to make changes only for s_2.

Therefore, the standard reorder point, s_1, is determined by adopting Equation 9:

$$\text{Standard Reorder Point } s_1 = X_{L:S} + k\sqrt{E(L_S)\sigma_{D:S}^2 + (E(D_S))^2\sigma_{L:S}^2}$$

Equation 25: Standard Reorder Point

Where, $X_{L:S}$ *: Demand over lead time Ls or standard order lead time*

$E(L_S)$ *: Expected lead time for standard order*

$\sigma_{D:S}$ *: Standard deviation of demand for standard order*

$E(D_S)$ *: Expected demand for standard order*

$\sigma_{L:S}$ *: Standard deviation of lead time for standard order*

The expedited reorder point, s_2, is driven by a geometric relationship from Figure 6 so it is linked with the standard reorder point s_1 and the demand variability is reflected as below:

$$\text{Expedite Reorder Point } s_2 = s_1 - D'(L_S - L_E)$$

$$= X_{L:S} + k\sqrt{E(L_S)\sigma_{D:S}^2 + (E(D_S))^2\sigma_{L:S}^2} - D'(L_S - L_E)$$

Equation 26: Expedite Reorder Point

Where, L_E*: Expected lead time for an expedited order:* $L_E = E(L_E)$.

The expedite reorder point s_2 can be driven by the geometric relationship in the Figure 6 from where two equations can be inferred as the following:

i) $L_E < L_S - t_0$: expedite feasibility condition

ii) $\frac{s_1 - s_2}{D'} = t_0$: time since the last standard order

By combining the conditions i) and ii) the expedite condition can be formulated as below:

iii) $L_E < L_S - \frac{s_1 - s_2}{D'}$ or $s_2 > s_1 - D'(L_S - L_E)$

This equation can be rewritten with the equation for standard reorder point as following

iv) $s_2 > X_{L:S} + k\sqrt{E(L_S)\sigma_{D:S}^2 + (E(D_S))^2 \sigma_{L:S}^2} - D'(L_S - L_E)$

From Equation 26, the expedited reorder point s_2 is identified as a function of D' or the average demand since last standard order. Because demand is a random variable, D' also becomes a random variable and we cannot determine a fixed expedited reorder point s_2 so it can be used constantly. Hence, we propose a new variable reflecting the uniqueness of the channel so that an expedited reorder point is related with the demand variability.

We call it a demand threshold and the coefficient of variation *(CV)* of demand is incorporated in a way that the bigger the variability in demand, the higher the expedited reorder point s_2 so that the algorithm triggers more expedited orders to protect service. To satisfy this condition, Equation 26 requires *CV* to be a denominator.

Secondly, a new parameter δ is proposed as an inverse form of CV so that $D^{'}$ is not extremely different from the average demand *E(D)*. That is, the demand threshold $\frac{\delta}{CV}$ is formulated as a ratio against the average demand *E(D)* with no dimension. The demand variability is varies because each DC runs independent operations and the demand parameter δ can reflect these unique characteristics for each channel. It is set up in a way that the bigger the δ, the lower the s_2, thus reducing expedited transportation cost by expediting less frequently.

Throughout our research, it is identified that the *CV* of demand in Company X's supply chain falls in the range of *[0.1, 1.0]* in most of the cases, so δ will also take similar range *[0.1, 1.0]*. In our simulation example introduced chapter 5, we took the range of δ as *[0.2, 1.1]* and most of the reorder points were covered with this range.

$$\text{Demand threshold: } D^{'} = \frac{\delta}{CV_{Demand}} \times E(D)$$

Equation 27: Demand Variation Threshold

Where, δ *= Demand parameter with the value range of [0.1, 1.5]*

$CV_{Demand} = \frac{\sigma_D}{E(D)}$ *: Coefficient of Variation of demand, and*

E(D) *: Average demand per period.*

We can rewrite the equation with demand parameter as below.

$$s_2 = s_1 - D^{'}(L_S - L_E) = s_1 - \frac{\delta}{CV_{Demand}} \times E(D) \times (L_S - L_E)$$

Equation 28: Modified Reorder Point with Demand Parameter

An expedited order will be triggered when there is a sudden demand change or an unexpected delay in transportation since the standard order at level s_1. The demand parameter is designed to reflect this variability unique to the supply channel.

Also note that although the safety factor k is adopted in Equation 25 and Equation 26, it cannot be used to determine a service level *(CSL)* in dual reorder point system because the system does not count on safety stock to maintain service in the same way as in traditional inventory management system. However, by adopting the same value of k for reorder points s_1 and s_2, the search algorithm in the next chapter becomes simple. In other words, k shift (s_1, s_2) up and down at the same time and the demand parameter δ reduces only s_2, spanning solution spaces for (s_1, s_2) quickly.

3.4 Approaches to Find Effective Reorder Points

Although Chiang (2002) suggests a tabular approach to compare the total cost with different reorder points, the algorithm to find expedited reorder points was not available. We therefore propose a heuristic approach to find the best solution or a set of reorder points with a minimum total cost that might offer cost savings as well as assure target service level of 100%.

The reorder points are denoted as *(standard reorder point, expedited reorder point)* or (s_1, s_2) as in Figure 6. One simple approach to find it is to test for all possible combinations of (s_1, s_2) by running two loops with incremental steps of s_1 and s_2 as suggested below.

Steps to find (s_1, s_2): Simple Approach.

1. Determine range and steps for s_1 and s_2 for simulation run
2. Set s_1 as the minimum, set s_2 as the minimum
3. Run dual reorder point simulation to calculate total cost with (s_1, s_2)
4. Increase s_2 by a small step and go back to step 3 until s_2 reaches to range max
5. Increase s_1 by a small step and go back to step 3 until s_1 reaches to range max
6. Determine a set of (s_1, s_2) that minimizes the total cost

However, the Simple Approach has two big challenges that first of all, it takes tremendous time to test all combinations of reorder points and secondly it still does not guarantee an 'optimal' solution because the total cost function is not a convex function. The reorder points are channel or product dependant, so it is not practically recommendable if dual reorder points for all key products at all DC have to be setup for Company X that has a big supply chain as discussed earlier.

Therefore, we propose a new and simpler approach to find the best set of reorder points, (s_1, s_2), using the safety factor k and a demand parameter δ. As explained earlier, by running two loops of k and δ, where k shifts (s_1, s_2) up and down together and δ changes only s_2, the approach tests most of (s_1, s_2) more effectively as below.

Steps to find (s_1, s_2): Proposed Approach.

1. Determine ranges for k and δ for simulation run (e.g. $0.8 < k < 4.0$, $0.2 < \delta < 1.1$)
2. Set k as the minimum, set δ as the minimum
3. Calculate standard reorder point s_1 from the Equation 25 with k

4. Calculate expedited reorder point s_2 from the Equation 26 and δ
5. Run dual reorder point simulation to calculate total cost with (s_1, s_2)
6. Increase δ by a small step (0.05) and go back to step 4 until δ reaches to range max
7. Increase k by a small step (0.5) and go back to step 3 until k reaches to range max
8. Determine a set of (s_1, s_2) that minimizes the total cost

Because a closed-form expression is not available, demand parameter δ that determines demand threshold needs to be discretized as suggested by Chiang (2002). We used simulation to find δ that generates the minimum total cost and used this value to further find an expedited reorder point.

4 Simulation

In order to test the expedited ordering policy and measure the transportation impact on inventory, we built an inventory model in Excel simulating one year of DC activities including receiving customer orders, fulfilling customer orders, ordering truck load to a supplier, order replenishment by a full truck, inventory review, monitoring service level, etc. The inventory model is based on continuous review *(s, Q)* policy because the item we selected is a medium to fast speed product that is being monitored every day and the order quantity is fixed to a full truck amount.

We also built an Excel Macro program for this Monte Carlo random number simulation so that different parameters can be considered and multiple runs can be performed easily. Each run represents 1 year and one simulation typically replicates 100 runs with same parameters and the average is being recorded on result worksheet. The detail of the model is explained below.

4.1 Simulation Modeling

The simulation model generates three random variables: demand, standard order lead time and expedited order lead time. The demand and lead times follow a Normal distribution. Based on our observations and interviews, the customer order fulfillment is done every day, so we assumed daily demand.

Once demand is generated, the model looks at the current inventory on-hand level and reduces inventory level by fulfilling the order. But a back order is not considered because we believe that a shortage of any food item at a quick service restaurant is a loss of a customer and the company doesn't allow a stock out. As a result of the daily inventory review, if the inventory position falls below the standard reorder point, s_1, a standard order for amount Q is placed to a supplier by rail. Then, the model generates a lead time for standard transportation and calculates the expected arrival date. This date is used when calculating order receiving from the supplier.

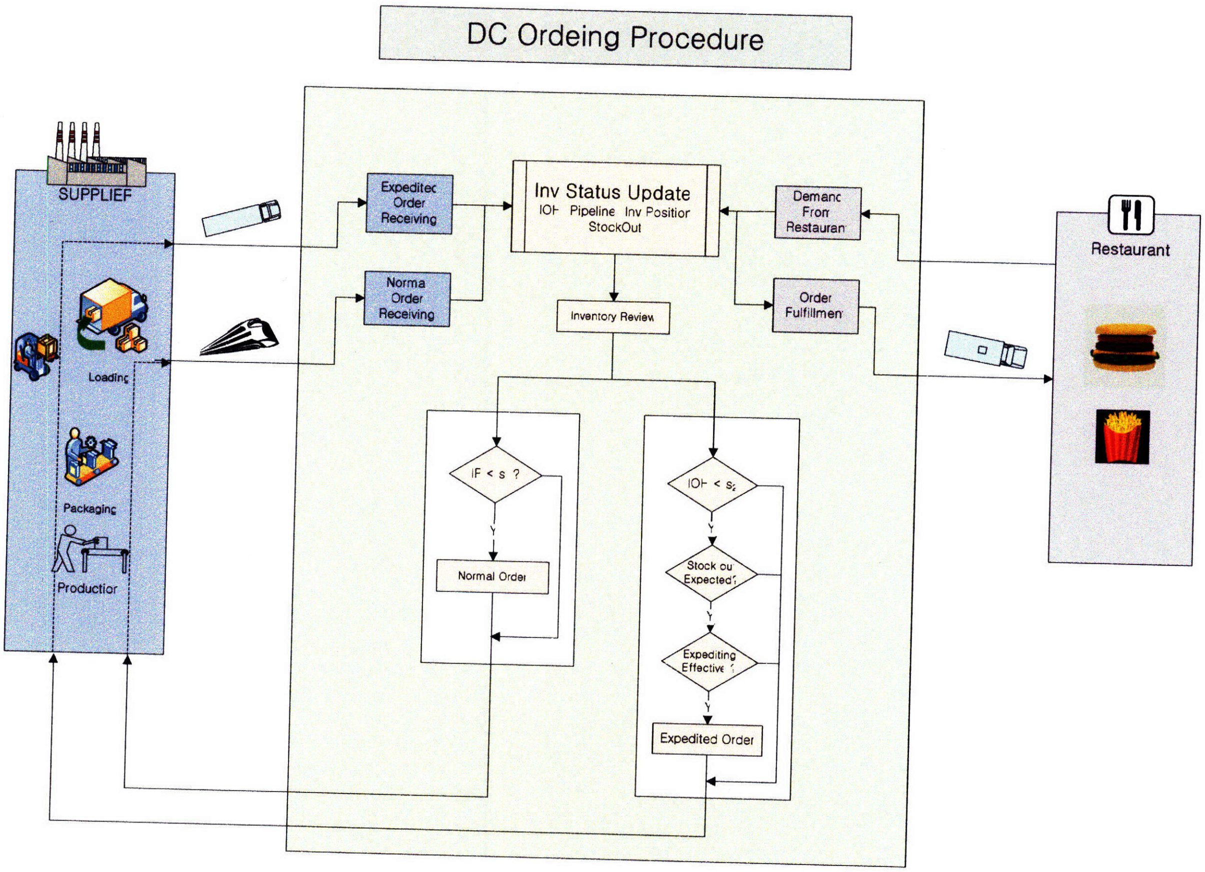

Figure 7: DC Ordering Procedure

When inventory level drops to or below expedited reorder point, s_2, the simulation model tests if a stock out will happen with the current trend of demand. To answer this, the model keeps track of demand information since last replenishment, calculates the time left until stock out and compares this time with the time for the earliest available replenishment. Secondly, it checks if expedited order can be earlier than the next available replenishment. If these three conditions are all met, an expedited order will be placed for amount of Q. We assumed that the quantity for an expedited order is the same as that for a standard order because the container for TL and rail is the same in the case of Company X. A random number for lead time of expedite order is generated and the arrival date is calculated in the same manner as a standard order.

4.1.1 Simulation Inputs

Input consists of two types of parameters: hard conditions and soft conditions. Hard conditions are necessary for the simulation runs and if any of these hard conditions are changed, the simulation needs to be re-run. However, soft conditions, such as cost assumptions, are necessary to analyze the simulation results to find best s_1 and s_2 after all simulation runs are completed, so a sensitivity analysis can be done without re-running the simulation.

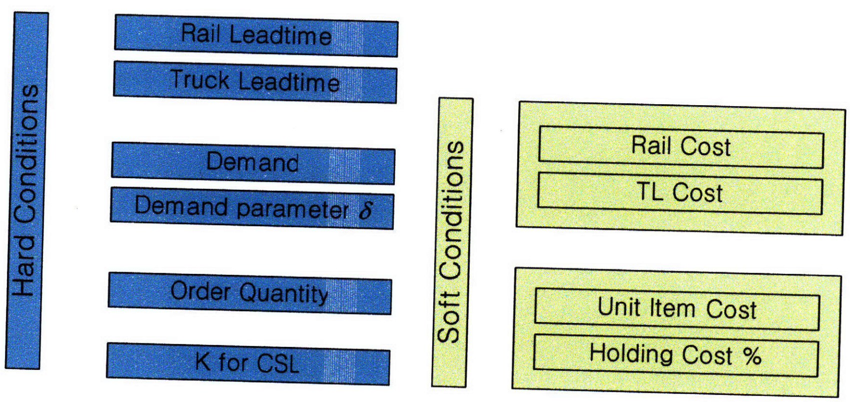

Figure 8: Simulation Input - Hard Conditions vs. Soft Conditions

Hence, if a sensitivity analysis is necessary with varying hard conditions, simulation model needs to be modified to run loops with the varying conditions. A sensitivity analysis with varying soft conditions is much easier and painless.

We have selected a supplier that is located in Oklahoma City, OK and 5 DCs that are located in different geographical zones. The distance from the supplier to each DC is shown in Table 3. We assumed that all 5 DCs are running 365-day operations for inbound and outbound shipment handling and dedicated personnel is assigned for reviewing the inventory and making orders through EDI system.

Table 3: Simulation Input – Location and Mileage of 5 DCs

DC Name	Mileage	Pick Location City	Pick Location State	Drop Location City	Drop Location State
DC-A	531	Oklahoma City	OK	Lebanon	IL
DC-B	633	Oklahoma City	OK	Port Allen	LA
DC-C	1664	Oklahoma City	OK	Stockton	CA
DC-D	1928	Oklahoma City	OK	Portland	OR
DC-E	2011	Oklahoma City	OK	Sumner	WA

The demand for each DC is provided as shown in the Table 4. Although the average demand from the restaurant was available, the standard deviation of demand was not available, so we estimated a 30% coefficient of variation. Note that the unit cost and ordering quantity are slightly different for each DC.

Table 4: Simulation Input – Demand, Unit Item Cost, Order Quantity

DC Name	Unit Item Cost	Demand (Year)	Daily Demand Average	Daily Demand Stdev	Order Q	# Order per Year	Order Interval (Days)
DC-A	$31.61	59,211	162.2	48.7	1080	55	6.7
DC-B	$32.89	275,044	753.5	226.1	1134	243	1.5
DC-C	$34.11	120,104	329.1	98.7	1078	111	3.3
DC-D	$31.61	41,896	114.8	34.4	1080	39	9.4
DC-E	$31.61	54,594	149.6	44.9	1080	51	7.2

The lead time for standard mode of transportation, rail, was not easily available but was assumed. The coefficient of variation of lead time was assumed to be 40%. The Order Cycle

Time (OCT) is defined as the time that manufacturer requires to prepare for the order or the time between an order was placed and the product is ready for pick up. The transportation lead time is then the time between when a truck picks up the freight and arrives at a DC.

Table 5: Simulation Input – Standard Transportation Lead Times

DC Name	Mileage	Trans. Cost (Rail)	Order Cycle Time Average	Order Cycle Time Stdev	Trans. Leadtime Average	Trans. Leadtime Stdev	Total Leadtime Average	Total Leadtime Stdev	CV
DC-A	531	$429	6.88	1.64	15.00	6.00	21.88	6.22	0.28
DC-B	633	$638	6.74	4.65	18.00	7.20	24.74	8.57	0.35
DC-C	1664	$1,313	6.55	1.74	21.00	8.40	27.55	8.58	0.31
DC-D	1928	$1,589	7.30	2.00	23.00	9.20	30.30	9.41	0.31
DC-E	2011	$1,701	6.73	1.47	25.00	10.00	31.73	10.11	0.32

The lead time information for truck was available from the company's ERP system for the year 2007. It is remarkable that trucking lead time is much shorter than that of rail, so expedited transportation can reduce time on road.

Table 6: Simulation Input – Expedited Transportation Lead Times

DC Name	Mileage	Trans. Cost (Truck load)	Order Cycle Time Average	Order Cycle Time Stdev	Trans. Leadtime Average	Trans. Leadtime Stdev	Total Leadtime Average (Days)	Total Leadtime Stdev (Days)	CV
DC-A	531	$857	6.88	1.64	1.15	0.66	8.02	1.81	0.23
DC-B	633	$1,276	6.74	4.65	1.05	0.80	7.79	1.75	0.22
DC-C	1664	$2,625	6.55	1.74	3.17	1.03	9.72	1.76	0.18
DC-D	1928	$3,178	7.30	2.00	3.56	0.82	10.86	1.70	0.16
DC-E	2011	$3,402	6.73	1.47	3.62	0.60	10.35	1.48	0.14

The transportation cost for rail was not available because the rail activity is not common yet at Company X. We assumed initially that it is 40% of truck. This assumption can be tested later with sensitivity analysis.

The transportation cost was provided by the Company's database for the year 2007 and we analyzed the truck transportation cost per mileage. As shown in the above graph, the transportation cost shows linearity with the mileage and an equation is available for more general situation or for planning purpose.

$$\text{TruckCost}(\$) = Max[500, 352.8 + 1.605(Mile)]$$

Equation 29: Truck Cost per Mile Equation (Approx.)

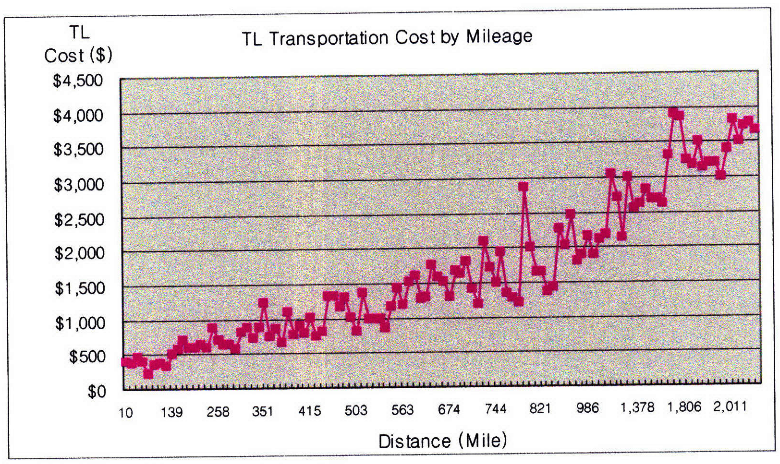

Figure 9: Transportation Cost by Mileage

Regression analysis confirms high R^2 (0.92). *P-value* is small enough to accept linearity.

Table 7: Regression Analysis for Transportation Cost

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9597
R Square	0.9210
Adjusted R Square	0.9202
Standard Error	283.8759
Observations	110

	Coefficients	Standard Erroı	t Stat	P-value	Lower 95%
Intercept	352.8265	45.638	7.731	5.92E-12	262.3632
MileageOfAvg	1.6052	0.045	35.478	2.4E-61	1.515495

Also, with the linear function we identified, we developed a standard TL rate table per mileage shown in Table 8. This can be used as an input for simulation with general assumptions on mileage or when Company X determines network plans.

Table 8: Standard TL Rates by Mileage

Standard TL Transportation Cost

	Coefficients
Intercept	352.83
Mileage	1.61

Mileage	300	600	900	1,000	1,200	1,500	1,800	2,100	2,400
Transportation Cost	$834	$1,316	$1,797	$1,958	$2,279	$2,761	$3,242	$3,724	$4,205

4.1.2 Simulation Outputs

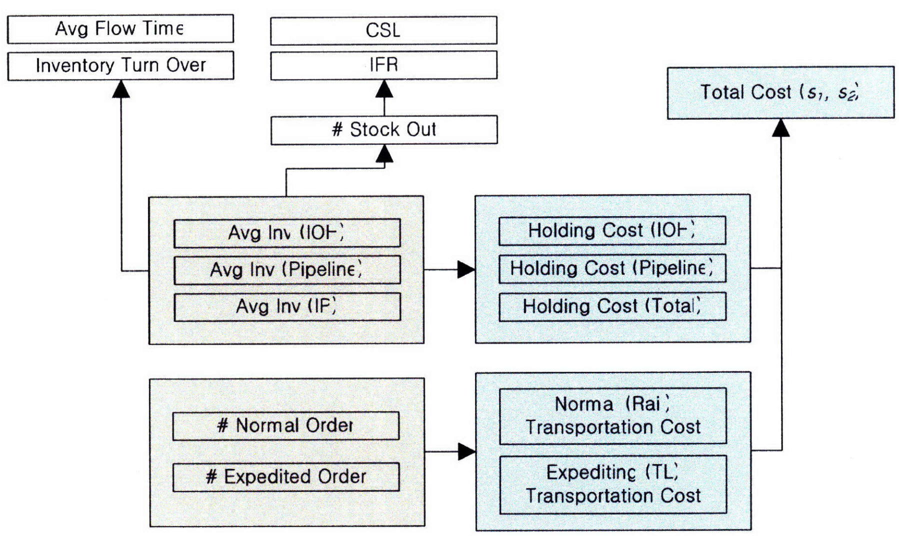

Figure 10: Simulation Outputs

The output of simulation is information on inventory levels, orders and services. Average inventory level is matched with holding cost information (unit item cost, holding cost %) to generate holding costs. Order related output is matched with unit transportation cost (rail and TL cost) to generate total transportation cost. These two costs are added to the total cost.

Another important output is service information. With the observation such as number of stock out, the simulation model calculates service levels. Also, with inventory related information, the simulation model identifies supply chain performances such as Average Flow Time and Inventory Turn Over.

4.1.3 Simulation Model & Mechanism

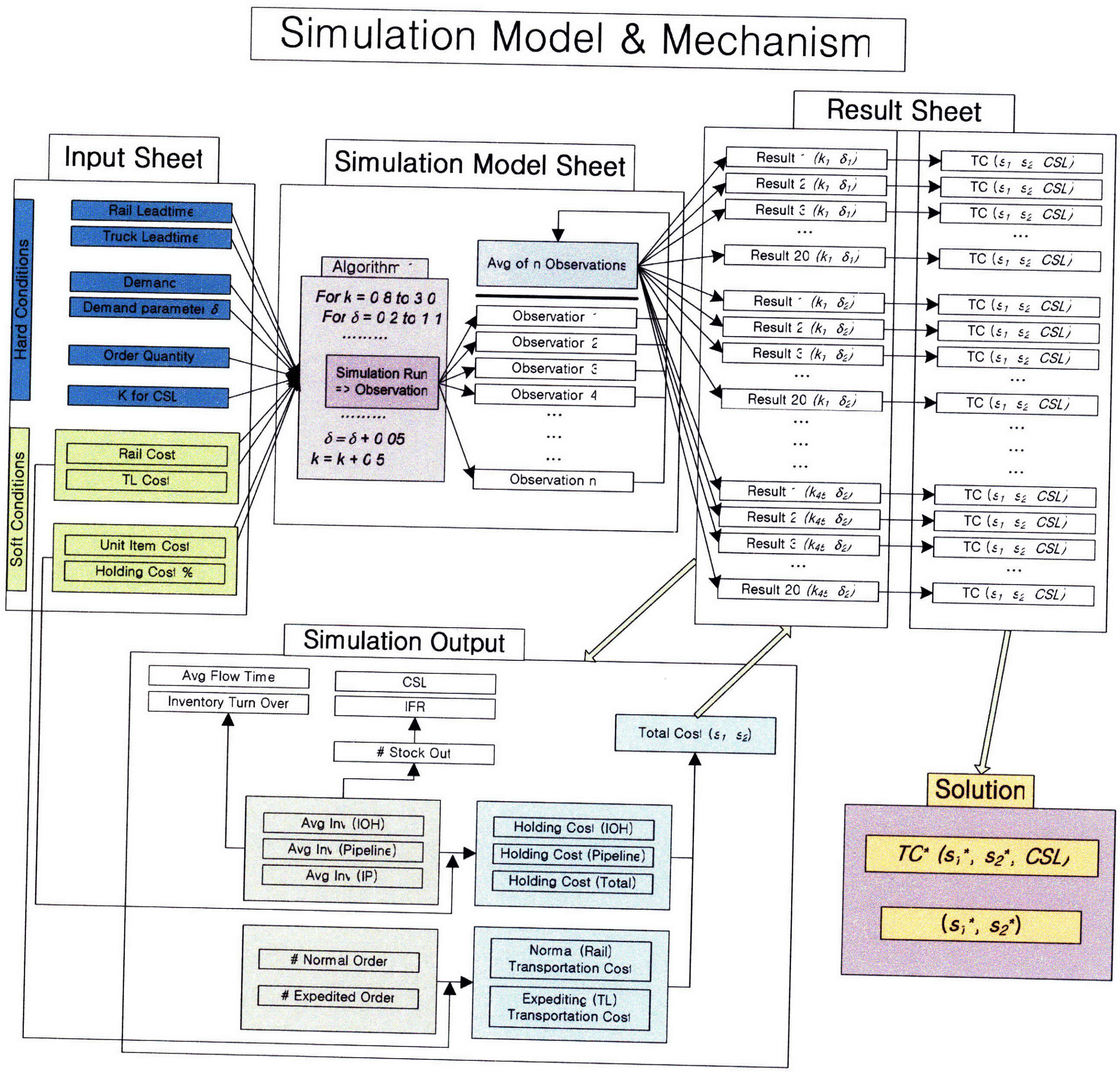

Figure 11: Simulation Model and Mechanism

The inventory model is built to simulate one year of DC activities under *(s, Q)* inventory policy, starting from January 1st and ending December 31st. There is one month of initialize period at the beginning of the simulation so the transactions in the time period are not counted.

With Proposed Approach or Algorithm 1, the simulation model tests each set of parameter (k, δ) by running the simulation n times for each case. Typically 100 times or 100 years of DC activities are generated for one result. Output of each simulation run is temporarily recorded in Simulation Model Sheet and the average of n simulation runs (n years) is copied and pasted to result ranges in Result Sheet before making any changes in parameters (k, δ), so each row in Result Sheet has a complete result for n simulation for one set of conditions. Simple Approach works the same manner with varying (s_1, s_2) rather than (k, δ) in Proposed Approach.

After all simulation runs are completed, the result is analyzed to find conditions with the least total costs. The non-expedited scenario is based on calculation because all relevant formulas are present. *CSL* is the most important factor when comparing the results. Because the company wants to be "Never Run Out" a case with *CSL = 100.000%* is considered or we could relax this target service level. By comparing the total cost from simulation result and non-expedited case under the same *CSL* level, we can find cases where expedited simulation generated less total cost.

When analyzing the results of simulation, or determining the 'best' reorder points (s_1, s_2), there are many alternatives generating similar total costs, so a close look at other activities or costs is recommended to find 'suitable best solution' for each DC.

4.1.4 Simulation Model Fit Test

After building the simulation model, we validated it by comparing the simulation result with calculated performances for DC A as in below table and concluded that the simulation model works well. For this purpose we ran the simulation 300 times and averaged the performance. The simulation generated a result with *CSL = 100.000%* and it is compared with when calculated performances when *CSL = 100.000%*.

As shown in Table 9, we confirmed that the simulation generates expected level of performances with less than 5% error range.

Table 9: Simulation Model Fit Test Result

	k	CSL	Holding Cost	Trans Cost	Total Cost
Simulated	4.45	100.000%	$54,101	$17,908	$72,008
Calclated	4.45	100.000%	$55,978	$18,804	$74,782
Diff			3.4%	4.8%	3.7%

4.2 *Simulation Results*

Simulation was used to test (s_1, s_2, Q) policy with expedited transportation are reviewed to check whether it can assures service, how appropriate (s_1, s_2) can be found and whether the policy also has cost advantage as well.

4.2.1 *Assuring Service through Expediting*

Let k be the safety factor determining *CSL* and safety stock level. The suggested algorithm uses the same k to find an expedited reorder point using coefficient of variation of demand and demand factor δ, so we can compare the *CSL* by the level of k. Figure 12 shows that expedited transportation improved the service level close to 100%. In this case δ is fixed as 0.45 and if δ is smaller, *CSL* will hit 100.000% with faster manner.

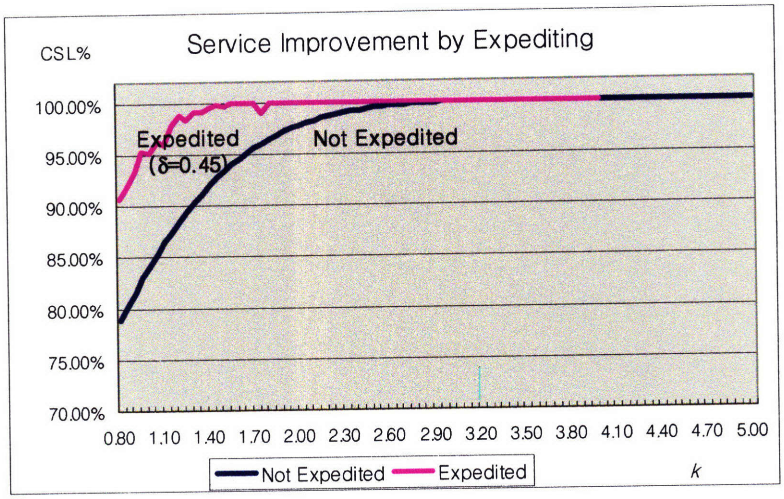

Figure 12: Result of Assuring Service through Expediting

Table 10 shows the number of expected stock outs and costs per year for two different scenarios by k when δ =0.45. The expedited transportation shows superior performance in reducing stock outs and assuring the service.

Table 10: Simulation Result – Service Assurance (δ =0.45)

k	No-Expedited					Expedited				
	# Stock Out	CSL	Inventory Cost	Transp Costs	Total Costs	# Stock Out	CSL	Inventory Cost	Transp Costs	Total Costs
0.8	11.6	78.81%	$32,108	$18,804	$50,912	4.8	90.69%	$31,979	$27,919	$59,898
1.0	8.7	84.13%	$33,416	$18,804	$52,220	2.6	95.08%	$33,232	$28,125	$61,357
1.2	6.3	88.49%	$34,724	$18,804	$53,528	0.6	98.81%	$34,572	$28,408	$62,980
1.4	4.4	91.92%	$36,032	$18,804	$54,836	0.3	99.42%	$35,850	$28,176	$64,026
1.6	3.0	94.52%	$37,340	$18,804	$56,144	0.1	99.85%	$37,108	$28,056	$65,165
1.8	2.0	96.41%	$38,648	$18,804	$57,452	0.0	99.96%	$37,707	$27,928	$65,635
2.0	1.2	97.72%	$39,956	$18,804	$58,760	0.0	100.00%	$39,628	$27,550	$67,178
2.2	0.8	98.61%	$41,264	$18,804	$60,068	0.0	100.00%	$40,969	$27,593	$68,563
2.4	0.4	99.18%	$42,572	$18,804	$61,376	0.0	100.00%	$42,132	$27,353	$69,485
2.6	0.3	99.53%	$43,880	$18,804	$62,684	0.0	100.00%	$43,425	$27,250	$70,676
2.8	0.1	99.74%	$45,188	$18,804	$63,992	0.0	100.00%	$44,754	$27,044	$71,798
3.0	0.1	99.87%	$46,496	$18,804	$65,300	0.0	100.00%	$46,086	$26,941	$73,027
3.2	0.0	99.93%	$47,804	$18,804	$66,608	0.0	100.00%	$47,238	$26,547	$73,785
3.4	0.0	99.97%	$49,111	$18,804	$67,916	0.0	100.00%	$48,506	$26,247	$74,753
3.6	0.0	99.98%	$50,419	$18,804	$69,224	0.0	100.00%	$49,715	$26,007	$75,722
3.8	0.0	99.99%	$51,727	$18,804	$70,531	0.0	100.00%	$50,922	$25,664	$76,585
4.0	0.0	100.00%	$53,035	$18,804	$71,839	0.0	100.00%	$52,248	$25,698	$77,946

4.2.2 *Algorithms to Search for Feasible Solutions*

The Simple Approach introduced in chapter 3.4 is time consuming and is still an 'optimal' solution is not guaranteed because the total cost function is not a convex function. Hence, we will test with the Proposed Approach; finds reorder points effectively as explained in chapter 3.4. Table 11 shows part of simulation results by the Proposed Approach, by varying k from 0.8 to 4.0 and δ from 0.2 to 1.1 for each step of k. It is observed that the bigger the k, the higher s_1 and s_2. δ also shifts s_2 up and down: the bigger the δ, the smaller the s_2.

The total cost is influenced by the level of s_1 and s_2. That is, if the reorder points are too high, holding costs will increase due to high inventory and if they are too low, there will be high expediting cost to make 100% *CSL*. Hence, the trade-off point could exist.

Table 11: Proposed Approach – Total Costs and Reorder Points by (k, δ)

No	k	delta	s1	s2	CSL	Holding Cost-TTL	Total Trans Cost	TTL Cost (HC + $Exp)
1	0.85	0.20	4428	2930	100.000%	$33,721	$31,301	$65,021
2	0.90	0.20	4480	2982	100.000%	$34,078	$31,109	$65,187
3	0.95	0.20	4532	3034	100.000%	$34,365	$30,958	$65,322
4	0.95	0.25	4532	2659	100.000%	$33,817	$30,272	$64,089
5	0.95	0.30	4532	2284	100.000%	$33,927	$28,553	$62,481
6	1.00	0.20	4583	3085	100.000%	$34,691	$31,119	$65,810
7	1.00	0.25	4583	2711	100.000%	$34,181	$30,169	$64,350
8	1.05	0.20	4635	3137	100.000%	$34,933	$30,532	$65,466
9	1.05	0.25	4635	2762	100.000%	$34,450	$30,478	$64,928
10	1.10	0.20	4687	3189	100.000%	$35,224	$30,368	$65,592
11	1.10	0.25	4687	2814	100.000%	$34,836	$30,114	$64,950
12	1.10	0.30	4687	2440	100.000%	$34,879	$28,694	$63,573
426	4.00	0.20	7687	6189	100.000%	$52,551	$22,918	$75,470
427	4.00	0.25	7687	5814	100.000%	$52,592	$23,230	$75,822
428	4.00	0.30	7687	5439	100.000%	$52,492	$22,462	$74,954
429	4.00	0.35	7687	5065	100.000%	$52,378	$22,332	$74,710
430	4.00	0.40	7687	4690	100.000%	$52,296	$22,366	$74,662
431	4.00	0.45	7687	4316	100.000%	$52,248	$21,944	$74,192
432	4.00	0.50	7687	3941	100.000%	$51,883	$20,946	$72,829
433	4.00	0.55	7687	3567	100.000%	$51,607	$20,017	$71,623
434	4.00	0.60	7687	3192	100.000%	$51,622	$19,704	$71,326

Figure 13 demonstrates the result of simulation in Table 11 on a graph. Y-axis shows total cost and x-axis represents the column "No" in Table 11 or each combination of (k, δ) thus the total cost decreases as δ increases within the same k group, showing saw-tooth pattern with local maximum and local minimum total costs. Because our target *CSL* is 100%, we screened out non-100% *CSL* cases and identified the maximum allowable δ that generates 100% *CSL* as red circles in Figure 13, each red circle showing local minimum of total cost.

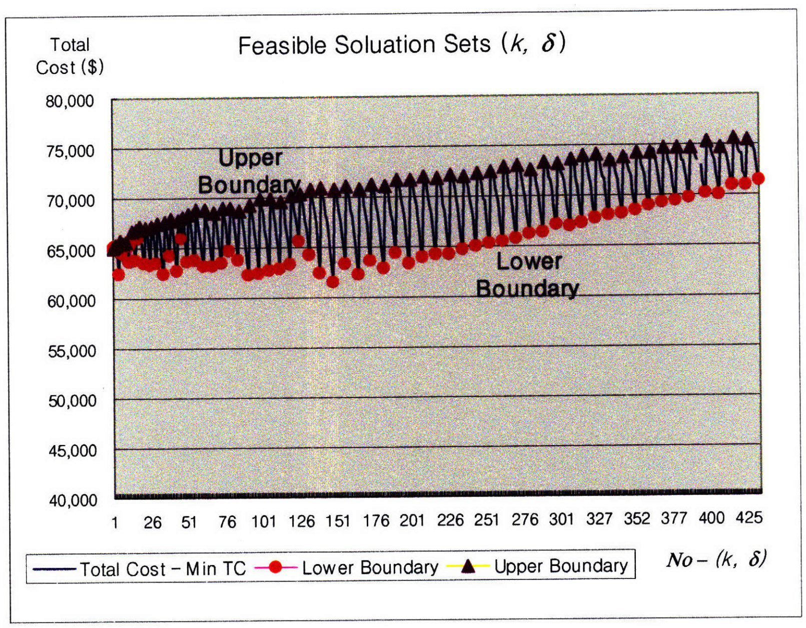

Figure 13: Feasible Solutions with Upper & Lower Boundaries

In Figure 14, 'feasible solutions' and a set of points, showing minimum total costs for each k with red circles, are mapped on axis of k and δ. We named the line a cost frontier because at these points, the total costs are minimized for each k.

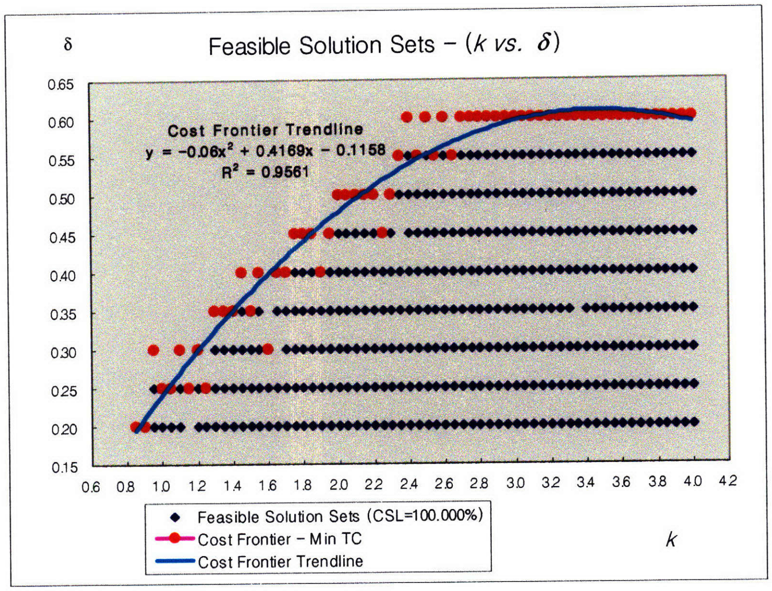

Figure 14: Feasible Solution Sets and Cost Frontier Line

4.2.3 Cost-effectiveness of Expediting

It is confirmed in the previous chapter that the *(s_1, s_2, Q)* policy certainly improves the cycle service level but whether the policy is cost effective is still a question. The simulation model basically aims at making *100% CSL* so when *k* is small, the simulation triggers frequent expedited orders to cover up low safety stock level. If expediting is effectively reduced as *k* increases, there is a chance for a trade-off between inventory holding cost and transportation cost if δ is also effectively set up.

The cost frontier found previously is matching with the lower bound as shown in below Figure 15. In order to compare the cost with non-expedited cases, the total costs for each target *CSL* are noted as separate lines. In Figure 15, we compare the total costs between expedited and non-expedited cases with the assumption that rail cost equals to *40%* of TL cost.

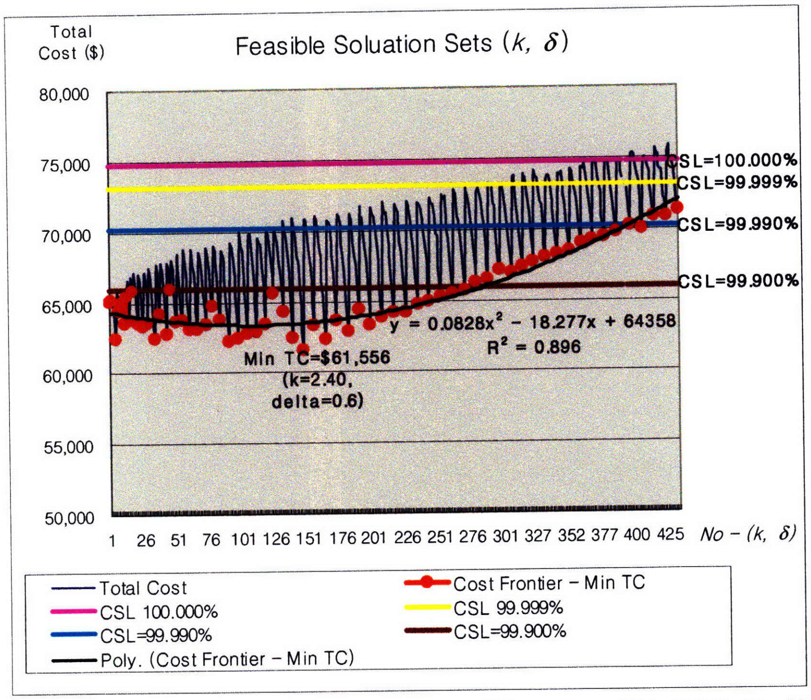

Figure 15: Cost Comparison - Expedited vs. Non-expedited (Rail=40% of TL)

The minimum total cost with expedited scenario is *$61,556*, so we can compare the savings from expedited transportation by the target *CSL* as Table 12. Note that, by the nature of the simulation model aiming for *100% CSL*, the total cost for less than *100% CSL* is not available and we compare cost with *100% CSL* case so the savings can be greater as Table 12.

Figure 15 shows the minimum total cost and it can be denoted as $TC^{*}(s_1, s_2, k, \delta) = TC^{*}(6032, 1537, 2.40, 0.6) = \$61,556$ when *CSL* is *100.000%*.

Table 12: Cost Savings by Expedited Transportation (Rail=40% of TL)

CSL	Total Cost Not	Total Cost Expedited	Saving%
100.000%	$74,782		17.7%
99.999%	$73,147		15.8%
99.990%	$70,204	$61,556	12.3%
99.900%	$65,954		6.7%
99.000%	$60,722		-1.4%

* Total cost for expedited case is available only for *100% CSL*, so saving can be greater.

In conclusion, expedited transportation could assure *100% CSL* while saving some cost. The cost frontier line can be reviewed with details of holding cost and transportation cost and the cost structure can be an important factor in determining reorder points that will be actually used.

Lastly, with the same algorithm, we found minimum total costs and solutions for all 5 DCs as shown in Table 13, cost savings from expedited reorder policy. It is confirmed that, in general, the bigger the variability in standard transportation, the bigger the savings. For example, DC-B shows the biggest savings and Table 5 confirms that it has the biggest variability in lead time *(CV=0.35)*. Also, DC-A has the smallest savings with but it has the smallest variability in lead time *(CV=0.28)* as shown in Table 5 as well.

It is very insightful that the variability determines the attractiveness of expedited policy. The variability in lead time of the standard transportation is provided but the variability in demand was not available with the research data. It is the combined variability in Equation 7 that affects the cost-effectiveness of expedited ordering policy. Although the result at Table 13 is not always straightforward only with variability in lead time, this result presents fairly good insights on the relationships between variability of the standard transportation and cost savings.

Table 13: Cost Comparison & Solutions for 5 DCs

Target CSL=99.999%	Total Cost Comparison			Solution			
	Not Expedited	Expedited	Saving%	k	δ	s_1	s_2
DC – A	$73,147	$61,556	16%	2.40	0.60	6,032	1,537
DC – B	$467,137	$318,815	32%	1.50	0.50	28,475	7,190
DC – C	$296,232	$218,865	26%	1.80	0.55	14,232	3,474
DC – D	$116,905	$93,669	20%	2.10	0.60	5,782	1,319
DC – E	$161,055	$126,083	22%	1.90	0.55	7,658	1,796

4.2.4 Simulation Result Sensitivity Analysis

The sensitivity analysis starts from a base scenario with the following assumptions for DC A: *rail cost = 40% of TL cost, TL cost=\$857, holding cost=20%, and unit item cost=\$31.61.* We achieved the minimum cost of *\$61,556* at *k=2.40* and δ *=0.60* as shown in Figure 16.

In Figure 16, the cost frontier line or the lower boundary line for expedited scenario is presented in a red line. And in order to compare the costs with non-expedited scenarios, four parallel lines with target *CSL of 100.000%, 99.999%, 99.990%* and *99.900%* are showing the total costs for non-expedited scenarios respectively on the right side.

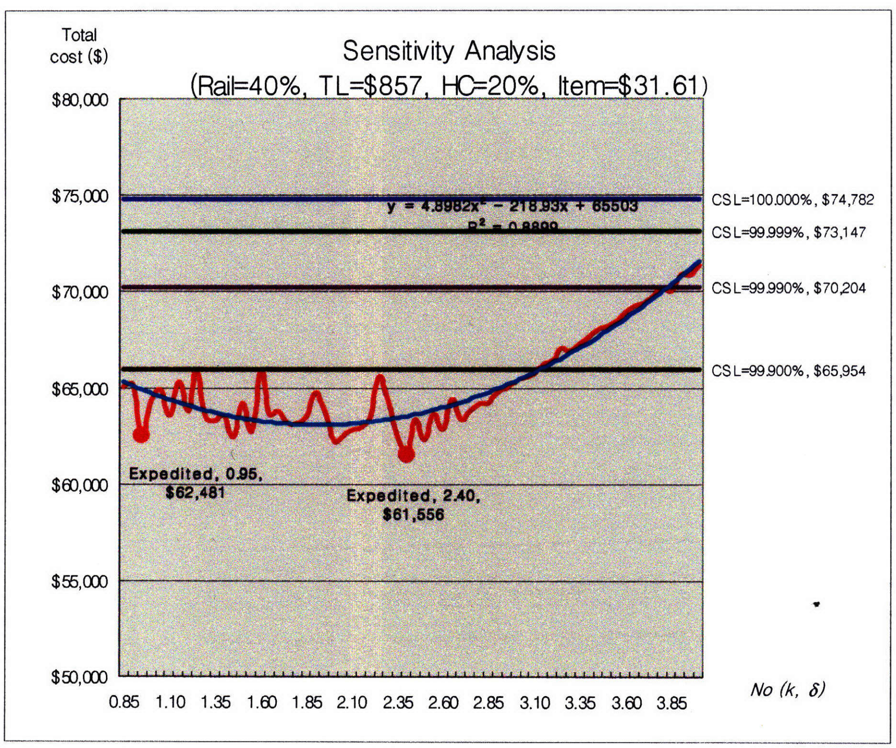

Figure 16: Sensitivity Analysis: Base Scenario

Table 14 shows a sensitivity analysis with the change in rail cost assumption from 5% to 100% of TL cost. All other conditions are not changed from the base assumption such that: *TL cost=$857, holding cost=20%, and unit item cost=$31.61*. The total costs for expedited scenario is presented on left side of the table and the total costs for non-expedited scenario are on right. The cells when expedited case generates less total cost are marked in blue and otherwise in grey.

It shows that in many cases, expedited ordering policy has the cost benefit over the non-expedited case. Note that all expedited cases are when *CSL* is 100.000% and the reorder points are also determined at where $TC^*(s_1, s_2, k, \delta)$.

It shows that, as the ratio between rail vs. TL cost increases, expedited scenario becomes more attractive as the rail cost increases faster than that of TL cost which is for expedited transportation. It can be interpreted intuitively that grey cells are on top-right corner.

Table 14: Sensitivity Analysis – Rail vs. TL Ratio (%)

Rail vs. TL Cost (%)	Expedited Scenario					Non-Expedited Scenario - Total Cost by Target CSL					
	k*	delta*	s1	s2	TC*	CSL= 100.000%	CSL= 99.999%	CSL= 99.990%	CSL= 99.900%	CSL= 99.000%	CSL= 90.000%
5%	2.4	0.6	6,032	1,537	47,325	58,329	56,694	53,751	49,500	44,595	37,729
10%	2.4	0.6	6,032	1,537	49,358	60,679	59,044	56,101	51,851	46,946	40,079
15%	2.4	0.6	6,032	1,537	51,391	63,030	61,395	58,452	54,201	49,296	42,430
20%	2.4	0.6	6,032	1,537	53,424	65,380	63,745	60,802	56,552	51,647	44,780
25%	2.4	0.6	6,032	1,537	55,457	67,731	66,096	63,153	58,902	53,997	47,131
30%	2.4	0.6	6,032	1,537	57,490	70,081	68,446	65,503	61,253	56,348	49,481
35%	2.4	0.6	6,032	1,537	59,523	72,432	70,797	67,854	63,603	58,698	51,832
40%	2.4	0.6	6,032	1,537	61,556	74,782	73,147	70,204	65,954	61,049	54,182
45%	2.4	0.6	6,032	1,537	63,589	77,133	75,498	72,555	68,304	63,399	56,533
50%	0.95	0.3	4,532	2,284	65,139	79,483	77,848	74,905	70,655	65,750	58,883
55%	0.95	0.3	4,532	2,284	66,468	81,834	80,199	77,256	73,005	68,100	61,234
60%	0.95	0.3	4,532	2,284	67,797	84,184	82,549	79,607	75,356	70,451	63,584
65%	0.95	0.3	4,532	2,284	69,126	86,535	84,900	81,957	77,706	72,802	65,935
70%	0.95	0.3	4,532	2,284	70,455	88,885	87,250	84,308	80,057	75,152	68,285
75%	0.95	0.3	4,532	2,284	71,784	91,236	89,601	86,658	82,407	77,503	70,636
80%	0.95	0.3	4,532	2,284	73,113	93,586	91,951	89,009	84,758	79,853	72,986
85%	0.95	0.3	4,532	2,284	74,442	95,937	94,302	91,359	87,108	82,204	75,337
90%	0.95	0.3	4,532	2,284	75,771	98,287	96,652	93,710	89,459	84,554	77,687
95%	0.95	0.25	4,532	2,659	76,992	100,638	99,003	96,060	91,809	86,905	80,038
100%	0.95	0.25	4,532	2,659	78,165	102,988	101,354	98,411	94,160	89,255	82,388

Table 15 also shows a sensitivity analysis with TL cost change. The base scenario has TL cost as $857 and the sensitivity analysis shows the total cost with the TL cost varying from $200 to $1,500. All other assumptions are not changed but TL cost, so *the rail vs. TL cost is 40%* here as the base case assumed, *holding cost=20%, and unit item cost=$31.61.*

It shows also that in many cases, the expedited scenario has the cost benefit over the non-expedited scenario. Note that as TL cost increases, although the rail transportation cost also increases, an expedited scenario tends to become unattractive because of increased expedited transportation cost.

Table 15: Sensitivity Analysis – TL Cost ($)

TL Cost ($)	Expedited Scenario					Non-Expedited Scenario - Total Cost by Target CSL					
	k*	delta*	s1	s2	TC*	CSL= 100.000%	CSL= 99.999%	CSL= 99.990%	CSL= 99.900%	CSL= 99.000%	CSL= 90.000%
$200	0.95	0.3	4,532	2,284	39,967	59,268	57,633	54,690	50,439	45,534	38,668
$250	0.95	0.3	4,532	2,284	41,477	60,090	58,455	55,512	51,261	46,357	39,490
$300	0.95	0.3	4,532	2,284	42,987	60,912	59,277	56,335	52,084	47,179	40,312
$350	0.95	0.3	4,532	2,284	44,497	61,735	60,100	57,157	52,906	48,001	41,135
$400	0.95	0.3	4,532	2,284	46,007	62,557	60,922	57,979	53,729	48,824	41,957
$450	0.95	0.3	4,532	2,284	47,517	63,379	61,745	58,802	54,551	49,646	42,779
$500	0.95	0.3	4,532	2,284	49,027	64,202	62,567	59,624	55,373	50,469	43,602
$550	0.95	0.3	4,532	2,284	50,537	65,024	63,389	60,446	56,196	51,291	44,424
$600	0.95	0.3	4,532	2,284	52,047	65,847	64,212	61,269	57,018	52,113	45,247
$650	2.4	0.6	6,032	1,537	53,551	66,669	65,034	62,091	57,840	52,936	46,069
$700	2.4	0.6	6,032	1,537	54,501	67,491	65,856	62,914	58,663	53,758	46,891
$750	2.4	0.6	6,032	1,537	55,450	68,314	66,679	63,736	59,485	54,580	47,714
$800	2.4	0.6	6,032	1,537	56,399	69,136	67,501	64,558	60,308	55,403	48,536
$850	2.4	0.6	6,032	1,537	57,348	69,958	68,324	65,381	61,130	56,225	49,358
$900	2.4	0.6	6,032	1,537	58,298	70,781	69,146	66,203	61,952	57,048	50,181
$950	2.4	0.6	6,032	1,537	59,247	71,603	69,968	67,025	62,775	57,870	51,003
$1,000	2.4	0.6	6,032	1,537	60,196	72,426	70,791	67,848	63,597	58,692	51,826
$1,050	2.4	0.6	6,032	1,537	61,146	73,248	71,613	68,670	64,419	59,515	52,648
$1,100	2.4	0.6	6,032	1,537	62,095	74,070	72,435	69,493	65,242	60,337	53,470
$1,150	2.4	0.6	6,032	1,537	63,044	74,893	73,258	70,315	66,064	61,159	54,293
$1,200	2.4	0.6	6,032	1,537	63,994	75,715	74,080	71,137	66,887	61,982	55,115
$1,250	2.4	0.6	6,032	1,537	64,943	76,537	74,903	71,960	67,709	62,804	55,937
$1,300	2.4	0.6	6,032	1,537	65,892	77,360	75,725	72,782	68,531	63,627	56,760
$1,350	2.4	0.6	6,032	1,537	66,841	78,182	76,547	73,604	69,354	64,449	57,582
$1,400	2.4	0.6	6,032	1,537	67,791	79,005	77,370	74,427	70,176	65,271	58,405
$1,450	2.4	0.6	6,032	1,537	68,740	79,827	78,192	75,249	70,998	66,094	59,227
$1,500	2.4	0.6	6,032	1,537	69,689	80,649	79,014	76,072	71,821	66,916	60,049

Table 16 is shows the sensitivity analysis result when the cost of capital for holding cost calculation changes while all other conditions are not changed such that *rail cost = 40% of TL cost, TL cost=$857, and unit item cost=$31.61.* It shows that as the cost of capital increases, the expedited scenario becomes more cost-effective because it has lower inventory level.

Table 16: Sensitivity Analysis – Holding Cost (%)

Holding Cost (%)	Expedited Scenario					Non-Expedited Scenario - Total Cost by Target CSL					
	k*	delta*	s1	s2	TC*	CSL= 100.000%	CSL= 99.999%	CSL= 99.990%	CSL= 99.900%	CSL= 99.000%	CSL= 90.000%
1%	3.55	0.6	7,221	2,727	18,098	16,902	16,820	16,673	16,461	16,215	15,872
2%	2.85	0.6	6,497	2,003	20,361	19,701	19,537	19,243	18,818	18,328	17,641
3%	2.4	0.6	6,032	1,537	22,461	22,500	22,255	21,813	21,176	20,440	19,410
4%	2.4	0.6	6,032	1,537	24,522	25,299	24,972	24,383	23,533	22,552	21,179
5%	2.4	0.6	6,032	1,537	26,582	28,098	27,689	26,953	25,890	24,664	22,948
6%	2.4	0.6	6,032	1,537	28,643	30,897	30,406	29,523	28,248	26,777	24,717
7%	2.4	0.6	6,032	1,537	30,703	33,695	33,123	32,093	30,605	28,889	26,485
8%	2.4	0.6	6,032	1,537	32,764	36,494	35,840	34,663	32,963	31,001	28,254
9%	2.4	0.6	6,032	1,537	34,824	39,293	38,558	37,233	35,320	33,113	30,023
10%	2.4	0.6	6,032	1,537	36,885	42,092	41,275	39,803	37,678	35,225	31,792
11%	2.4	0.6	6,032	1,537	38,945	44,891	43,992	42,373	40,035	37,338	33,561
12%	2.4	0.6	6,032	1,537	41,006	47,690	46,709	44,943	42,393	39,450	35,330
13%	2.4	0.6	6,032	1,537	43,067	50,489	49,426	47,513	44,750	41,562	37,099
14%	2.4	0.6	6,032	1,537	45,127	53,288	52,143	50,083	47,108	43,674	38,868
15%	2.4	0.6	6,032	1,537	47,188	56,087	54,860	52,653	49,465	45,787	40,637
16%	2.4	0.6	6,032	1,537	49,248	58,886	57,578	55,223	51,823	47,899	42,406
17%	2.4	0.6	6,032	1,537	51,309	61,684	60,295	57,793	54,180	50,011	44,175
18%	2.4	0.6	6,032	1,537	53,369	64,483	63,012	60,363	56,538	52,123	45,943
19%	2.4	0.6	6,032	1,537	55,430	67,282	65,729	62,933	58,895	54,236	47,712
20%	2.4	0.6	6,032	1,537	57,490	70,081	68,446	65,503	61,253	56,348	49,481
21%	2.4	0.6	6,032	1,537	59,551	72,880	71,163	68,073	63,610	58,460	51,250
22%	2.4	0.6	6,032	1,537	61,611	75,679	73,881	70,643	65,968	60,572	53,019
23%	2.4	0.6	6,032	1,537	63,672	78,478	76,598	73,213	68,325	62,685	54,788
24%	2.4	0.6	6,032	1,537	65,732	81,277	79,315	75,783	70,683	64,797	56,557
25%	2.4	0.6	6,032	1,537	67,793	84,076	82,032	78,354	73,040	66,909	58,326
26%	2.4	0.6	6,032	1,537	69,853	86,875	84,749	80,924	75,397	69,021	60,095
27%	0.95	0.3	4,532	2,284	71,697	89,674	87,466	83,494	77,755	71,134	61,864
28%	0.95	0.3	4,532	2,284	73,393	92,472	90,184	86,064	80,112	73,246	63,632
29%	0.95	0.3	4,532	2,284	75,090	95,271	92,901	88,634	82,470	75,358	65,401
30%	0.95	0.3	4,532	2,284	76,786	98,070	95,618	91,204	84,827	77,470	67,170
31%	0.95	0.3	4,532	2,284	78,482	100,869	98,335	93,774	87,185	79,583	68,939
32%	0.95	0.3	4,532	2,284	80,179	103,668	101,052	96,344	89,542	81,695	70,708
33%	0.95	0.3	4,532	2,284	81,875	106,467	103,769	98,914	91,900	83,807	72,477
34%	0.95	0.3	4,532	2,284	83,572	109,266	106,487	101,484	94,257	85,919	74,246
35%	0.95	0.3	4,532	2,284	85,268	112,065	109,204	104,054	96,615	88,031	76,015
36%	0.95	0.3	4,532	2,284	86,964	114,864	111,921	106,624	98,972	90,144	77,784
37%	0.95	0.3	4,532	2,284	88,661	117,663	114,638	109,194	101,330	92,256	79,553
38%	0.95	0.3	4,532	2,284	90,357	120,461	117,355	111,764	103,687	94,368	81,322
39%	0.95	0.3	4,532	2,284	92,053	123,260	120,072	114,334	106,045	96,480	83,090
40%	0.95	0.3	4,532	2,284	93,750	126,059	122,789	116,904	108,402	98,593	84,859

Lastly, Table 17 shows the sensitivity analysis with the changes in unit item cost from $5 to $100. As unit cost also affects holding cost, the basic behavior is the same as the holding cost % or the cost of capital. That is, as the unit item cost increases, the expedited scenario becomes more attractive as it has lower inventory level.

Table 17: Sensitivity Analysis – Unit Item Cost ($)

Unit Item Cost ($)	Expedited Scenario					Non-Expedited Scenario – Total Cost by Target CSL					
	k*	delta*	s1	s2	TC*	CSL= 100.000%	CSL= 99.999%	CSL= 99.990%	CSL= 99.900%	CSL= 99.000%	CSL= 90.000%
$5	2.4	0.6	6,032	1,537	22,798	22,958	22,699	22,233	21,561	20,785	19,699
$10	2.4	0.6	6,032	1,537	29,317	31,812	31,295	30,364	29,019	27,467	25,295
$15	2.4	0.6	6,032	1,537	35,835	40,667	39,891	38,494	36,477	34,150	30,891
$20	2.4	0.6	6,032	1,537	42,354	49,521	48,487	46,625	43,935	40,832	36,487
$25	2.4	0.6	6,032	1,537	48,873	58,376	57,083	54,755	51,393	47,514	42,083
$30	2.4	0.6	6,032	1,537	55,391	67,230	65,678	62,885	58,851	54,196	47,679
$35	2.4	0.6	6,032	1,537	61,910	76,085	74,274	71,016	66,309	60,878	53,275
$40	2.4	0.6	6,032	1,537	68,428	84,939	82,870	79,146	73,767	67,561	58,871
$45	0.95	0.3	4,532	2,284	74,194	93,794	91,466	87,277	81,225	74,243	64,467
$50	0.95	0.3	4,532	2,284	79,561	102,648	100,062	95,407	88,683	80,925	70,063
$55	0.95	0.3	4,532	2,284	84,927	111,503	108,658	103,537	96,141	87,607	75,659
$60	0.95	0.3	4,532	2,284	90,294	120,357	117,254	111,668	103,599	94,289	81,255
$65	0.95	0.3	4,532	2,284	95,660	129,211	125,850	119,798	111,057	100,972	86,852
$70	0.95	0.3	4,532	2,284	101,027	138,066	134,445	127,929	118,515	107,654	92,448
$75	0.95	0.3	4,532	2,284	106,393	146,920	143,041	136,059	125,973	114,336	98,044
$80	0.95	0.3	4,532	2,284	111,760	155,775	151,637	144,189	133,431	121,018	103,640
$85	0.95	0.3	4,532	2,284	117,126	164,629	160,233	152,320	140,889	127,700	109,236
$90	0.95	0.3	4,532	2,284	122,493	173,484	168,829	160,450	148,347	134,382	114,832
$95	0.95	0.3	4,532	2,284	127,859	182,338	177,425	168,581	155,805	141,065	120,428
$100	0.95	0.3	4,532	2,284	133,226	191,193	186,021	176,711	163,263	147,747	126,024

The tabular method presented a good insight and is convenient to compare changes in one condition, as shown in Table 14 to Table 17, but it becomes complicated even with a two conditions in a two-way table and impossible to use if there are more than two conditions to consider at the same time.

In order to make the cost comparison with changes in multiple conditions easier, we created control buttons using Excel spinner as in Figure 17. Therefore, any changes in soft conditions with control buttons make the cost lines in Figure 16 changed with values automatically so as to find meaningful break points where those lines meet. Changes can be made on one or multiple conditions at a time.

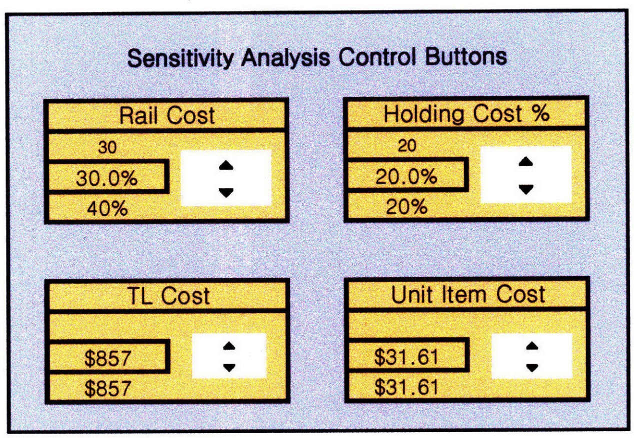

Figure 17: Sensitivity Analysis Control Buttons

First, we consider rail cost % and TL cost conditions together as in Figure 18. In most cases in our example, the expedited scenario has cost benefits, so we consider conditions that are not favorable to expedited scenario and found a breakeven point where two lines meet. At a point where *rail = 10% of TL cost* and *TL cost = $1,477*, the total cost for expedited scenario meet with a line with *99.000% CSL* for non-expedited scenario.

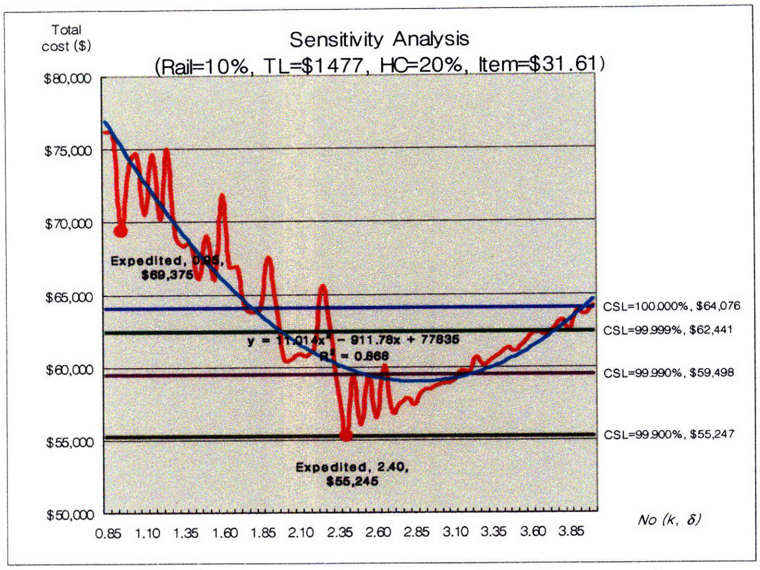

Figure 18: Sensitivity Analysis (Rail=10, TL= $1477)

It means that although TL cost solely increases due to fuel cost surge or whatever reason, the expedited scenario still has cost advantage until this point if target service level is *99.999%*. Note, however, that the expedited scenario always generates *100.000% CSL* here. The breakeven point when target *CSL* is *100.000%* is shown in Figure 19 at *rail = 1% of TL cost* and *TL cost is $3,200.* This is not practical so we can conclude that the expedited scenario always has cost advantage over non-expedited scenario with *100.000%* target *CSL.*

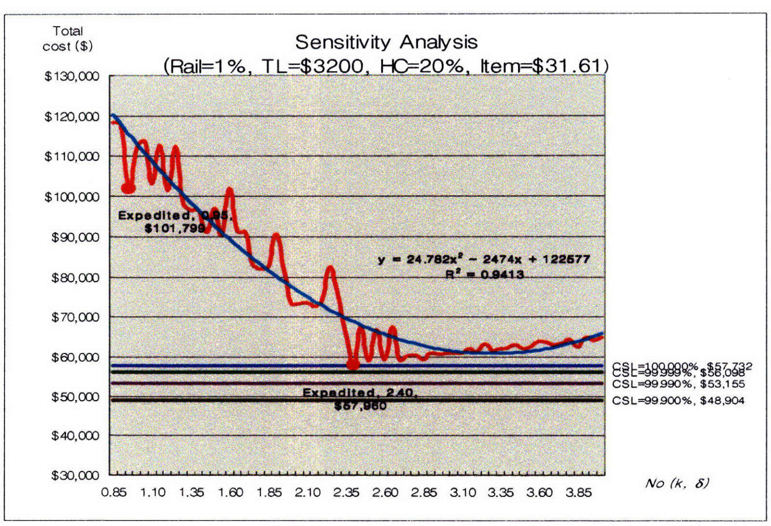

Figure 19: Sensitivity Analysis (Rail=1%, TL= $3,200)

Similarly, we test with *holding cost % (cost of capital)* and *unit item cost*. Because the behavior of these conditions are moving to the same direction, we first changed unit item cost until *$8* and found a breakeven point with *99.900% CSL* for non-expedited scenario as Figure 20.

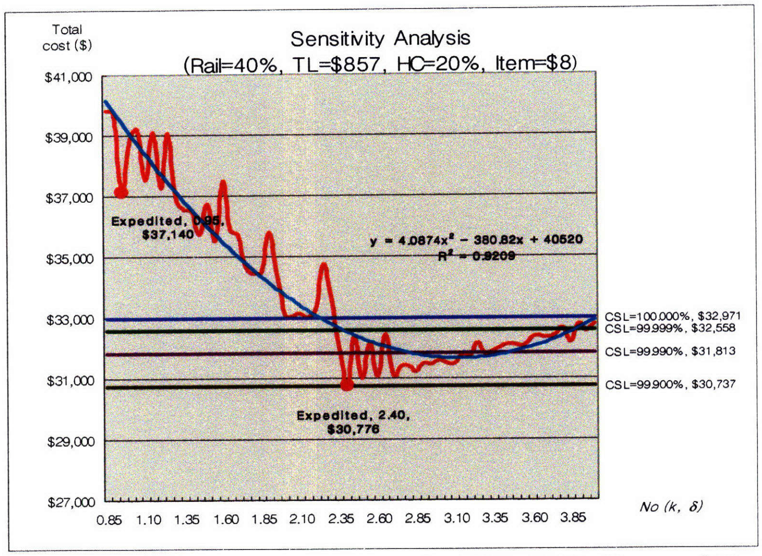

Figure 20: Sensitivity Analysis (HC=20%, Item= $8)

Then we changed the *holding cost %* condition until *8%* to find a breakeven point of *100.000% CSL* for non-expedited scenario. That is, if the *unit item cost* becomes *$8* and *cost of capital* drops to *8%*, expedited scenario loses cost advantage.

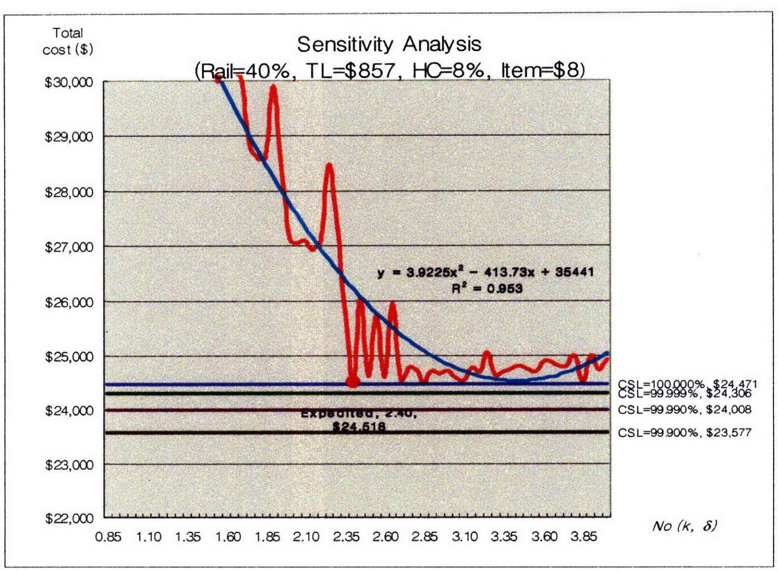

Figure 21: Sensitivity Analysis (Rail=23.5% of TL Cost)

4.3 Summary of Simulation

The simulation is designed to test the (s_1, s_2, Q) policy that is proposed by the author. The dual reorder point expedited transportation policy has been tested and confirmed that it works to assure the service as what "Never Run Out" policy asks. Also, the cost effectiveness of the policy has been tested and the conditions were discussed with sensitivity analyses.

Through sensitivity analysis using tabular method, we identified conditions where expedited reorder policy has cost advantage as well as service assurance when only one condition is changed. We also ran sensitivity analysis using a spinner for graphical interpretation on cost comparison by changing multiple conditions at the same time to identify points where expedited reorder scenario loses cost benefit. This is insightful exercise to help understand the behavior of conditions on total cost. It can be applied if any of external business environments are changed and a timely review on the appropriateness of the expedited transportation is necessary.

5 Summary

The dual reorder point expediting transportation policy was suggested and tested with a simulation. The suggested expediting policy incorporates demand variability by taking coefficient of variation and demand parameter in consideration and traces demand changes for an expedited order.

Using Monte Carlo simulation, we confirmed that expedited transportation certainly assures service. We also identified the conditions where the cost-effective solutions can exist by sensitivity analysis on four parameters. We then explored how to find a feasible set of reorder points that generate minimum total cost while assuring *100% CSL* using a suggested algorithm.

Hence, we conclude that expedited transportation can be a good alternative for traditional inventory management using safety stock in terms of service assurance and cost effectiveness as well.

5.1 Insights

A stock out is certainly the last thing for Company X, a leading quick service restaurant company that has very high standard of customer experience and quality. In that sense, their supply chain policy, "Never Run Out," is not even a policy, but rather it is a core part of management philosophy. The policy, however, could have negative impact on their business, making the people conservative or risk averse and the supply chain ineffective.

Hence, the impact of never run out policy lies not only on cost but also on every aspect of their supply chain. If the company makes it clear what the target service level is and tries to make it happen throughout the network, the whole supply chain could even more be effective while keeping or improving current resiliency.

The suggested policy could help Company X become agile by closely monitoring inventory level and demand changes and making expedited orders to recover from a stock out. That way, Company X can anticipate supply chain risks and take a preemptive action rather than waiting for a disruption. With the effort, the inventory of the company can be leaner. Only an agile company can become lean.

5.2 Recommendation to Future Research

One of the challenges with the research was the availability of appropriate data. The variability in demand and lead time was one of the most critical factors in running simulation. Some of them were not available and rail lead time was assumed with the best estimate from the industry sources, so this is the area to improve with the next-level research.

Secondly, in building the simulation model, it aims to generate *100% CSL* to create a Never Run Out business environment. However, if there is a new algorithm to shoot for target *CSL* other than *100%* by leveraging cost and service, it will provide new area of research.

Thirdly, the opportunity with alternative strategy was not explored enough, so this leaves another room to continue research.

Lastly, in implementing expedited transportation, the availability of accurate and timely information is the key to success. The demand-driven expediting and real-time order tracing can be realized with appropriate IT investment and cooperation among various supply chain partners.

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