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SUPPLY PERFORMANCE OBJECTIVES FOR UPPER ECHELONS IN A MULTI-ECHELON SUPPLY SYSTEM

INVENTORY RESEARCH OFFICE

December 1981

US Army Inventory Research Office
US Army Materiel Systems Analysis Activity
800 Custom House, 2d & Chestnut Sts.
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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This paper considers what should be the proper supply performance objective for the upper echelon in a multi-echelon supply system which operates as a series of independent single echelon systems. Conclusions are reached about the proper role of unit price in setting individual item performance targets.

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PREFACE

The work described in this report was first presented at the Multi-Echelon Inventory Conference of June 1981.

TABLE OF CONTENTS

TABLES

SUPPLY PERFORMANCE OBJECTIVES FOR UPPER ECHELONS

1. Background

It is probably more the rule than the exception for a multi-echelon supply system to operate as a series of independent single echelon systems. Typically, there is no information flow between echelons other than that arising directly from the processes of requisition and supply. Quite possibly, the difficulties of centralized stock level determination for each stock point in each echelon may outweigh the benefits.

If each echelon is to operate independently, what combination of policies should be recommended to achieve minimum total system cost? In this report we explore one aspect of this question relating to proper supply performance objectives for upper echelons. Some results contrary to current military practice (as outlined in DoDI 4140.39)[8] are obtained.

2. Model

We investigate a two-echelon system with a wholesaler supporting n identical retailers. All unfilled demands are backordered. Items are assumed to be of equal importance, so all backorders are costed out equally. However, wholesale backorders are not important in themselves, but only in so far as they may contribute to the generation of retail backorders.

If such a system is managed by independent single echelon inventory systems at wholesale and retail, a typical performance objective at each echelon is to minimize the sum of holding cost and backorder cost at that echelon. Backorder cost is expressed as the product of the expected average number of backorders outstanding multiplied by a backorder cost parameter which is manipulated so that the projected backorder rate meets some management goal; i.e., use of a higher backorder cost parameter in the inventory model will result in more inventory and fewer backorders, so a simple search procedure can be employed to find that parameter which will bring the expected backorder rate just below the allowable level. Such an approach is used within the US Dept of Defense [8], with some modifications, to manage many classes of wholesale items (cf [8] or [4] and [6] for additional technical details).

Let:

S = stockage objective for an item.

$BFR(S)$ = "backorder fill rate," or percent of demands for that item which cannot be filled from stock on hand.

$BSR(S)$ = "backorder status rate," or percent of time item has one or more backorders.

B_c = backorder cost per backorder outstanding per day.

H = holding cost per dollar of inventory per day.

UP = unit price of item.

Objective: Minimize H x (Average \$ inventory for all items) + B_c x (Average daily backorders outstanding for all items)

To make the analysis simpler, we will assume that demands are Poisson and that each supplier follows an (S,S-1) policy, i.e. he orders every time he has a demand so that stock on hand plus on order always equals S.

Then, for a single echelon model, with assumptions and objective as given, it is well known (see Note 1) that S^* is the optimum S if and only if:

$$BSR(S^*) < \frac{(UP)(H)}{B_c} \leq BFR(S^*) \tag{2.1}$$

Thus, $\frac{(UP)(H)}{B_c}$ may be thought of as an "unavailability target," since not only must this expression lie between the two unavailability rate measures, but given $(UP)(H)/B_c$, optimum stock can be found as the unique stock level which gives unavailabilities surrounding this value.

Since B_c and H are constant over all items, equation (2.1) implies that target backorder rates are proportional to unit price. This inference actually holds true even if demands are not Poisson and if suppliers batch order in economic lots and underlies much of the wholesale item management within DoD, although in practice it is mitigated by various implementing considerations.

3. Research Questions

In a two echelon system, with each echelon using a single echelon optimization model, should wholesaler (upper echelon) backorder rates really be proportional to unit price? Theory, i.e. equation (2.1), tells us retailer rates should be. If the retailer (lower echelon) is using a simple policy, setting his stock level S to a fixed number of days of supply, does this change our conclusions?

Finally, what can be said about the magnitude of optimum wholesaler backorder rates relative to retailer rates?

We use the terms wholesaler (WHO) and retailer (RET) for convenience, rather than the more general terms upper echelon organization and lower echelon organization.

4. Methodology

Referring back to equation (2.1), and the ensuing discussion, if optimum stock is known, but not backorder cost, there is a whole range of possible values for the "unavailability target" consistent with S^* (any value between the inequality signs). If one point were to be selected to represent this range, it would make sense to select the geometric mean of backorder status rate and backorder fill rate, labelling this the "implicit unavailability target." This was done for the upper echelon of a two echelon system.

Optimum stock levels in a two-echelon system were computed using the SIMPLE SIMON multi-echelon model [4]. Implicit unavailability targets for the wholesaler were determined. A functional relationship with unit price was then developed using regression techniques and the functional form:

$$\text{(4.1)} \qquad \text{Implicit WHO target} = (a)(UP)^b$$

If target is proportional to price, b should be close to 1; if target is independent of price, b should be close to 0, and so on.

Inputs to SIMPLE SIMON sufficient to determine the optimum levels are:

NRET = number of retailers

DEM = expected demand on a RET during a length of time equal to the ship time from WHO

STFAC = ship time from external supplier to WHO divided by ship time from WHO to RET

RET = target unavailability, i.e. (up)H/Bc where Bc applies to retail backorders

Since the RET target (Section 2) is proportional to unit price, varying RET target unavailability is equivalent to varying unit price, so the regression was actually performed on:

(4.1') $\quad$ Implicit WHO target = a (RET target)^{b}

To do the regression, common logs were taken:

(4.2) $\quad$ (Implicit target) = a + b log (RET target)

Eleven equally spaced values (along a log scale) for RET target were chosen over the range of targets of interest. Separate regressions were performed for the ranges 10% to 1%, and 1% to 0.01%.

A single echelon system was run to verify the procedure, and to iron out kinks in the methodology. In the single echelon system we know the actual target is proportional to unit price. Therefore, if our methodology is valid, when we regress the implicit target against unit price, the power should be close to 1. If it is not, then the power is simply not a valid indicator of target/unit price relationships.

Results of the single echelon run are in Table 1. They represent powers based on a range of targets from 10% to 0.0001%. Also included are the results for an alternative definition of implicit target - the simple average rather than the geometric mean. Table 1 supports the validity of the methodology. It also supports the choice of the geometric rather than the arithmetic mean since powers were closer to 1 with the geometric mean.

The standard errors of the power coefficients for the two-echelon runs are reported in Table 6. They are large enough to make some of the individual results suspect when considered in isolation. However, the entire pattern of results as discussed in Section 5 convincingly support the conclusions noted in Section 6.

The size of the standard errors is due at least in part to the fact that in the regression we are using a linear model when the relationship is not strictly linear. The powers actually increase as the unavailability targets decrease. Originally we felt that high standard errors might also be due to the discreteness of stock levels, and an effort was made to smooth out discreteness by averaging a set of points dispersed around RET demands in the range

[0.5 demand, 1.5 demand]. Both 11 and 21 points were tried, but, since standard errors were not reduced, this effort was abandoned.

5. Results

Table 2 shows the power coefficients found in varying RET targets from 1% to 10%. For example, looking at the circled value of 0.40 in the second row, last column, we see that when the number of RETs is 5; the ratio of ship times is 15; and demand on the RET during a ship time is 1; then the implicit WHO target varied with the unit price raised to the 0.4 power. Table 3 gives comparable results over a different range of RET targets.

Power coefficients are generally low, less than 0.5. An investigation was made into cases where the coefficients were high, 0.8 and above. This occurs in Table 2 for demand of 0.1 and in Table 3 for demand of 0.01. In all such cases examined (all the reported cases with NRET = 5), optimum RET stock did not vary from 1 unit. At higher demands retail stock does vary, and patterns like the following typically occur.

DECREASING UNAVAILABILITY TARGET

RET STOCK:	3	4	4	4	4	4	4	4	5	5	5
WHO STOCK	11	10	11	11	12	12	13	13	12	12	13

For targets in the range of 1% to 10%, and DEM = 0.01, RET stock was 0. These cases were not reported since when RET stock is 0, a nominal two-echelon system collapses to a single echelon system.

We have noted that when optimum RET stock did not vary, powers were high. This suggests that if RET levels are fixed, at some not necessarily optimum value, powers will also be high. This proved to be the case. DEM of 0.5, 1. and 1.5 were tried with RET stock of 1, as well as some cases with DEM and RET stock equal to 5. Power coefficients were typically above .95. Note 3 provides a rationale for this phenomenon.

Although the power coefficients were low, they do reflect some impact of unit price. Muckstadt [4], using an entirely different approach, concluded unit price had negligible impact when WHO average due-in was ≥ 20 (found by multiplying NRET by DEM by STFAC). This is not consistent with our results. However, Muckstadt was using METRIC as his optimum 2-echelon model. METRIC is a less accurate predecessor of SIMPLE SIMON. When we substituted METRIC for SIMPLE SIMON, power did drop markedly: for DEM of 0.1 and 1.0, over the entire target range (.01% to 10%), the highest power was .11.

Tables 4 and 5 reflect actual upper echelon implicit unavailability targets. For example, the circled value in Table 4 shows that the geometric mean of the upper echelon implicit targets was 19%, when NRET was 5, STFAC was 15, DEM = 1, and the RET target was varying between 1% and 10%. The geometric mean of the RET targets was 3%.

Clearly, then, upper echelon unavailability targets are higher than lower echelon targets. Two additional observations may also be made: unavailability targets generally increase as demand increases, and drop as STFAC increases. A theoretical rationale is derived in Note 3.

Henard [2] in 1964 had reached the conclusion that lower echelon performance was insensitive to upper echelon performance. He used simulation to reach this conclusion, and dealt with a five echelon system using actual Army policies to develop stock levels for intermediate echelons.

In a recent article Rosenbaum [7] also examined service level relationships in a two echelon system. In her problem demand rates were large and normally distributed and the retailers used EOQ's, although these typically represented only about five days of supply. Rosenbaum's major effort was in developing a heuristic for finding (approximately) optimum upper and lower echelon stockage levels. However, she provided two graphs of particular interest to us. In one graph, optimum wholesale service level was found for 3 values of retail target unavailabilities (all other inputs fixed); in the other graph, optimum wholesale service level was found for 3 values of retailer order and ship time (all other inputs fixed). Her results were consistent with our conclusions.

Interestingly, Rosenbaum observed that it was better to drop wholesaler performance from the optimum than to raise it. Does this mean that if the power b in equation (4.1) should optimally be b^*, it is better to use $b^* - k$ than $b^* + k$ for positive constants k? We examined her case when target unavailability to the customer was .05 and her case when it was .01. In the first case, the answer is yes, and in the second that it does not matter.

6. Conclusions:

In a two echelon system, upper echelon targeted supply performance should show some sensitivity to unit price, but not be so sensitive as it could be if the upper echelon were viewed in isolation. If a single echelon model is rur at the upper echelon, then in safety level calculations the square root or some higher root of unit price is a more appropriate input than unit price. While the work reported here was based on such assumptions as Poisson demand and (S,S-1) ordering policies, and did not include higher demand items, we would expect the conclusions to be generally applicable, so long as the primary function of the upper echelon is to support the lower echelon and not directly support users. Rosenbaum's paper now supports this speculation.

We were implicitly assuming that the lower echelon knew what performance to expect from the upper echelon; i.e., the results were based on optimum stock levels which were found under conditions of perfect information exchange. If information exchange is imperfect, one might expect this to further support an upper echelon policy which either attempted equal performance for all items, or performance which varied in a known way as a function of variables known to the lower echelon. Unit price is known, but upper echelon demand is not known to the lower echelon.

We assumed the lower echelon was using an optimum policy. If the lower echelon is following a fixed stockage policy in which stock does not depend on unit price, then we have found that upper echelon targets should be highly sensitive to unit price. Constraints on stockage (e.g. lower and upper bounds on reorder points) may make apparently sophisticated lower echelon policy in fact insensitive to price.

In a two-echelon system, upper echelon performance targets should not be as ambitious as lower echelon targets. The relationship depends on such factors as relative resupply times to the two echelons, and item demand rates, but is insensitive to the number of retailers supported.

Note 1: Proof of Optimality Conditions and Backorder Rate Relationship

Backorder Rate Relationship

Let $H_t(S)$ be net on hand at time t, given a stockage objective of S. Net on-hand is on-hand minus backorders. Then:

(1) $$H_t(S-K) = H_t(S) - K \qquad \text{for all } K$$

Equation (1) follows from the fact that net on hand at t is the sum of the initial stockage objective plus total procurements which have been received in [o,t] minus total demands in [o,t]. However, demands and procurements are independent of the stockage objective; i.e. a procurement is made whenever a demand is received. (Even if the policy were to order Q at a time, procurements would depend on when Q demands accumulate, and not on the stockage objective).

Now, the backorder fill rate over some period T is

(2) $$BFR(S) = \int_o^T dt \Pr (H_t(S) \leq 0)/T$$

This reflects that a demand will be backordered if net on hand does not exceed 0 when it arrives so that demand fill rate can be related to % of time stock position is greater than 0. (Under the assumption of Poisson demand)

By definition,

(3) $$BSR(S) = \int_o^T dt \Pr (H_t(S) \leq -1)/T$$

By equation (1),

(4) $$\int_o^T dt \Pr (H_t(S) \leq -1) = \int_o^T dt \Pr (H_t(S+1) \leq 0)$$

Combining (2), (3) and (4)

(5) $$BSR(S) = BFR(S+1)$$

Optimality Condition

The reduction in average backorders if stock is increased from S to S+1 is BSR(S). Hence the change in cost is (UP)(H) - BSR(S)B_c, using the notation of

Section 2 of the report. Furthermore, BSR(S) is convex in S [1]. Hence the optimality conditions are:

(6a) $$(UP)(H) - BSR(S^*)\ B_c > 0$$

(6b) $$(UP)(H) - BSR(S^*-1)\ B_c \leq 0 \quad \text{or}$$

(6c) $$S^* = 0$$

or by algebra

(7) $$BSR(S^*) < \frac{(UP)(H)}{B_c} \leq BSR(S^*-1)$$

and by (5)

(8) $$BSR(S^*) < \frac{(UP)(H)}{B_c} \leq BFR(S^*)$$

Note 2: Upper Echelon Availability for Fixed Lower Echelon Stock

If lower echelon stock is fixed, the entire impact of increasing upper echelon backorders is to increase lower echelon backorders. We show, under the assumption that the number of units due-in to the RET is Poisson, that the change in lower echelon backorders is almost proportional to the change in upper echelon backorders. If it were exactly proportional, we could compute upper echelon stock using a single echelon model with backorder cost multiplied by the constant of proportionality. In that event target unavailability would be proportional to unit price. Instead, it is highly correlated when lower echelon stocks are fixed.

Let

D = demand on a RET during a ship time

B_U = expected upper echelon backorders at a random point in time

B_L = expected lower echelon backorders

N = number of RETs

S = RET stock level

P = expected due in to RET (RET pipeline)

$g(j;\mu)$ = Poisson probability for mean μ

$$G(j;\mu) = \sum_{x=j}^{\infty} g(x;\mu)$$

Then

$$P = D + B_U/N \quad (1)$$

$$B_L = \sum_{j=S}^{\infty} (j-S)g(j;P) \overset{*}{=} \sum_{j=S+1}^{\infty} G(j;P) \quad (2)$$

$$\frac{dB_L}{dP} = \overset{**}{\sum_{j=S}^{\infty}} g(j;P) = G(S;P) \quad (3)$$

---

[*] See Hadley & Whitin [1], Appendix 3, relationship 10.

[**] See Relationship 15.

Also, by (1)

(4) $$\frac{dP}{dB_U} = 1/N$$

So

(5) $$\frac{dB_L}{dB_U} = \frac{G(S;P)}{N}$$

But G(S;P) is lower echelon unavailability which asymptotically approaches G(S;D) as upper echelon performance improves.

Note 3: Trends in Upper Echelon Availability

We derive an estimate of upper echelon backorder cost under the assumption that the number of units due in at the RET is Poisson. We find that this backorder cost varies inversely with RET demand. We then explain why dropping the Poisson assumption results in upper echelon backorder cost varying with STFAC.

Let

D = demand on a RET during a ship time

B = upper echelon backorders

N = number of RETs

UP = unit price

S = RET stock level

P = expected due-in to RET, i.e. RET pipeline

Then

(1) $$P = D + B/N$$

Define K such that

(2) $$S = P + K \sqrt{P}$$

i.e., K is the number of standard deviations of safety level. K will depend on the RET unavailability target but we would expect it to be largely insensitive to P. We will assume it is independent of P. We will also assume that number of RET backorders is relatively insensitive to P for fixed K.

Then, the derivative of S with respect to B is:

(3) $$\frac{dS}{dB} = \left(1 + \frac{K}{2\sqrt{P}}\right)\left(\frac{1}{N}\right)$$

The derivative of total lower echelon stockage cost with respect to B is

(4) $$(UP)(N)\frac{dS}{dB} = UP\left(1 + \frac{K}{2\sqrt{P}}\right)$$

Equation (4) gives an estimate of upper echelon backorder cost. Note that it varies inversely with P, and hence with RET demand.

Now, in reality, SIMPLE SIMON models the actual distribution of P which is not Poisson. One would expect, other things being equal, that as STFAC increases, the variability of P would increase.

Let M be defined such that

(5) $\text{Std dev }(P) = (\sqrt{P})(M)$ so

(6) $S = P + K\sqrt{P}(M)$

M is the ratio of the actual standard deviation to the standard deviation which would be correct if demand were Poisson. For D = .1, two different values of N, three different values of ORG target, and three different STFAC's, M was computed using a modified version of SIMPLE SIMON. M did in fact increase with STFAC.

This suggests that the relationship between STFAC and the upper echelon unavailability target is due to the impact of STFAC on M. As a check, upper echelon implicit unavailabilities were computed based on METRIC rather than SIMPLE SIMON. METRIC assumes P is Poisson. The relationship between unavailability and demand persisted, but that between unavailability and STFAC disappeared.

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TABLE 1

POWERS FOR TARGETS VARYING FROM 10% to .0001% IN A ONE ECHELON SYSTEM

DEM	POWER FOR TARGET = GEOMETRIC MEAN	STD ERROR	POWER FOR TARGET = SIMPLE AVERAGE	STD ERROR
.1	.92	.11	.88	.10
.5	.98	.06	.94	.06
1	.98	.06	.95	.06
3	.98	.04	.97	.04
5	.94	.02	.93	.02
10	.99	.02	.98	.02
20	.98	.02	.97	.02

TABLE 2

POWERS FOR RET TARGETS VARYING FROM 1% TO 10%

	DEM = .1			DEM = 1.		
STFAC NRET	1	5	15	1	5	15
2	1.19	.08	.46	.40	.36	.48
5	.90	.82	.92	.17	.35	.40
10	.74	.93	.88	.27	.29	.39
20	.92	.86	.87	.11	.26	.34
DEM = 5						
2	.19	.32	.53			
5	.08	.29				

TABLE 3

POWERS FOR RET TARGETS VARYING FROM 1% TO .01%

DEM = .01				DEM = .1		
STFAC NRET	1	5	15	1	5	15
2	1.01	.37	.21	.08	.23	.36
5	.99	.86	.87	.13	.16	.20
10	.79	.92	.82	.05	.25	.33
20	.93	.89	.94	0.0	.05	.31
DEM = 1.				DEM = 5.		
2	.12	.33	.50	.15	.33	.47
5	.12	.17	.41	.16	.26	
10	.10	.26	.26			
20	.05	.14	.28			

TABLE 4

WHO TARGETS FOR RET TARGETS VARYING FROM 1% TO 10%

DEM = .1

NRET \ STFAC	1	5	15
2	17%	21%	11%
5	22%	14%	11%
10	25%	17%	13%
20	23%	19%	14%

DEM = 1.

NRET \ STFAC	1	5	15
2	40%	26%	18%
5	42%	27%	19%
10	44%	32%	22%
20	42%	35%	26%

DEM = 5.

NRET \ STFAC	1	5	15
2	54%	30%	19%
5	55%	36%	

TABLE 5

WHO TARGETS FOR RET TARGETS VARYING FROM 1% TO .01%

	DEM = .01			DEM = .1		
STFAC NRET	1	5	15	1	5	15
2	4.4%	5.6%	3.7%	14%	7.9%	4.0%
5	4.8%	3.2%	1.9%	11%	7.8%	4.0%
10	7.1%	3.8%	2.3%	13%	7.4%	4.2%
20	6.2%	4.0%	2.8%	13%	7.8%	5.8%
	DEM = 1.			DEM = 5.		
2	22%	8.3%	3.0%	32	10	3.4
5	25%	17%	5.2	35	15	
10	25%	14%	7.6%			
20	30%	17%	10.0			

TABLE 6

STD ERRORS FOR TABLE 2/TABLE 3

	DEM = .01			DEM = .1		
STFAC						
NRET	1	5	15	1	5	15
2	/.27	/.27	/.23	.23/.23	.23/.13	.19/.10
5	/.19	/.14	/.10	.20/.21	.10/.14	.07/.13
10	/.15	/.11	/.09	.13/.20	.07/.17	.05/.14
20	/.15	/.09	/.07	.09/.18	.05/.17	.03/.15
	DEM = 1.			DEM = 5.		
2	.14/.08	.09/.06	.06/.04	.05/.05	.04/.02	/03/.02
5	.11/.10	.08/.06	.07/.05	.06/.04	.05/.04	
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7-8