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**SWP 1/93 THE EFFECT OF LIMITED PRODUCTION CAPACITY
ON SAFETY STOCK REQUIREMENTS FOR
PERIODIC REVIEW INVENTORY SYSTEMS**

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The Effect of Limited Production Capacity on Safety Stock
Requirements for Periodic Review Inventory Systems

by

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Introduction

Although one of the objectives of most manufacturing systems is to operate at as close to full capacity utilisation as possible, there are several disadvantages in doing so. Plossl [1] has pointed out that excess capacity is essential for flexibility if fast reaction to change is an important competitive requirement. In the Just-in Time approach to manufacturing, excess capacity is necessary in order to allow the pull system of production scheduling to operate [2]. Several authors have shown how excess capacity can reduce levels of work-in-process inventories [3, 4, 5, 6].

South and Hixson [7] have demonstrated that not only does excess capacity reduce work-in-process inventories but also the same level of customer service can be maintained with less finished goods inventory. This is because, when demand is higher than expected, more of this demand can be met from current production so that less safety stock is needed for a given service level.

Holt et al [8] have devoted considerable theoretical attention to planning rules that minimise the expected costs associated with operating with different levels of capacity. However, little is said about the practical problems of assigning numbers to the various factors included in their model.

A number of authors have addressed the aggregate planning problem, trying to develop decision rules which will minimise the sum of production and inventory costs over a given planning horizon [9,10,11]. While the methods used provide a useful theoretical insight into the factors influencing aggregate planning, their practical application appears to be limited.

For most organisations, capacity is relatively fixed in the short-term and so the problem becomes one of determining the safety stock necessary to provide the desired service level for a given production capacity.

In this paper an attempt is made to quantify the relationship between excess capacity, safety stock and service level in a periodic review inventory system. The results demonstrate that, as capacity approaches 100 per cent, substantial increases in safety stock are necessary in order to maintain customer service levels.

Part of the task of the production manager is to achieve high levels of customer service using low levels of resources while coping with unpredictable fluctuations in customer demand. The resources comprise materials in the form of raw materials and finished goods and capacity in the form of labour and capital equipment.

One way of coping with uncertain demand is to only manufacture to order. For this to be possible, the manufacturing lead time must be less than the lead time required by the customer. Also spare capacity must be available in order to ensure that all the orders can be completed within the required lead time even during periods when demand is high.

When customers require short lead times it is more usual to manufacture for stock. By holding sufficient finished goods stocks, high customer service levels can still be maintained in spite of fluctuations in customer demand and production is to some extent decoupled from these fluctuations.

When setting safety stocks for products which are manufactured internally the conventional approach assumes that production capacity is unlimited. This can lead to lower customer service levels than expected. If a periodic review system is being used then, at regular intervals, usually weekly, the stock level of each product is reviewed and a production quantity is scheduled sufficient to bring total stock up to a target level equal to safety stock + average demand during the review period. After a period of high demand, production capacity may be insufficient to enable the desired target stock to be reached by the time of the next review. Consequently, during the period until the target stock level can once more be reached there will be a higher than expected risk of a stockout. In order to maintain a given customer service level, safety stock will need to be increased to take into account the effect of limited capacity. As average demand approaches closer to production capacity, the safety stock necessary for a given stockout risk will increase. The following analysis discusses the implications of this for the simplest case where the available production capacity is being used to manufacture a single product.

Unlimited production capacity

If there is no upper limit on production capacity and the manufacturing time is negligible then the stock at the start of each review period can always be set equal to the target stock. If demand during the review period is normally distributed with mean, μ and standard deviation, σ then, for a stockout risk of p ,

$$\text{target stock} = \mu + k \sigma$$

Values of k for typical levels of stockout risk are shown below.

Stockout Risk (p)	k
0.10	1.28
0.05	1.64
0.025	1.96
0.01	2.33

The stockout risk is an estimate of the proportion of planning periods when a stockout will occur. For most organisations, a better measure of customer service is the proportion of total demand met from stock. Brown [12] has developed a method for calculating safety stock when customer service level is measured in this way. It uses the concept of partial expectation. If safety stock is a multiple k of the standard deviation of demand during the planning period, then partial expectation, $E(k)$, is the average number of units back-ordered per planning period measured in multiples of the standard deviation.

If demand during the planning period has the distribution $N(\mu, \sigma^2)$ then,

$$1-P = \frac{\sigma E(k)}{\mu}$$

where $1-P$ is back orders as a proportion of demand. For example, if production is planned weekly and the distribution of weekly demand is $N(100, 100)$ then the customer service levels for various values of k are shown below.

k	E(k)	1-P	Customer Service Level (100P)
1.28	0.047699	0.004769	99.53
1.64	0.021137	0.0021137	99.79
1.96	0.009445	0.0009445	99.91
2.33	0.003352	0.0003352	99.97

Provided that the mean and standard deviation of demand remain constant and production capacity is unlimited, then production in a given review period will equal demand during the previous review period. The production capacity required each period will therefore follow the distribution $N(\mu, \sigma^2)$. Consequently there will be a 0.99 probability that production requirements in a given period will be less than $\mu + 2.33 \sigma$. Provided production capacity equals or exceeds this figure, capacity effects will have little effect on safety stock requirements.

Production capacity equal to mean demand

This represents the limiting case when there is no excess capacity so that production in each period is constant and equal to the mean demand per period, μ . This option appears quite attractive as it gives full utilisation of capacity with finished goods stock being used to decouple production from demand fluctuations. Unfortunately it leads to unacceptable levels of stockout risk.

If starting stock is S_0 then after n periods,

$$\text{Ending stock} = S_0 + n \mu - N(n\mu, n \sigma^2)$$

The variance of the ending stock will therefore increase with n . For any given starting stock the risk of a stockout will increase over time and so it is not possible to specify any level of safety stock which will ensure a given stockout risk or service level in the long-term.

Finite excess capacity

When there is a limited amount of excess capacity, the mathematics of calculating the risk of a stockout becomes complex and so simulation has been used to determine the relationship between stockout risk and excess capacity.

In carrying out the simulation the following assumptions were made,

1. A single product is being manufactured with weekly demand $N(100,100)$.
2. Demand in successive weeks is independent.
3. At the beginning of the simulation,

Starting stock = mean weekly demand + safety stock

4. Production in week $n = \min(\text{capacity, mean weekly demand} + \text{safety stock} - \text{stock at beginning of week } n)$
5. Back ordering is permitted.

3 runs of 100,000 weeks were carried out for each simulation. Eight different production capacities were simulated for 4 levels of safety stock. For one of the simulations the limiting case was taken where production capacity is equal to average demand, 100 in this case. The results for this simulation should be interpreted with care as stockout risk and service level will never reach equilibrium. The results of the simulation runs are summarised in table 1.

Table 1
The effect of limited capacity on stockout risk

a) Stockout risk (% of weeks with stockouts)

Theoretical stockout risk					
Safety stock		12.8	16.4	19.6	23.3
Stockout risk		0.1003	0.0505	0.0250	0.0099
Stockout risks from simulation					
Cap.		Safety stock			
		12.8	16.4	19.6	23.3
500	Run 1	0.101	0.051	0.025	0.009
	Run 2	0.101	0.050	0.024	0.009
	Run 3	0.099	0.051	0.024	0.009
	Run 4	0.102	0.051	0.025	0.009
	Mean	0.101	0.051	0.024	0.009
130	Run 1	0.100	0.049	0.025	0.009
	Run 2	0.103	0.051	0.025	0.010
	Run 3	0.102	0.051	0.025	0.009
	Run 4	0.102	0.051	0.024	0.009
	Mean	0.102	0.050	0.025	0.009
125	Run 1	0.101	0.050	0.023	0.009
	Run 2	0.104	0.052	0.024	0.009
	Run 3	0.102	0.051	0.025	0.009
	Run 4	0.101	0.051	0.025	0.010
	Mean	0.102	0.051	0.024	0.009
120	Run 1	0.105	0.053	0.026	0.010
	Run 2	0.103	0.052	0.026	0.010
	Run 3	0.105	0.052	0.025	0.010
	Run 4	0.104	0.052	0.025	0.010
	Mean	0.104	0.052	0.026	0.010
115	Run 1	0.110	0.058	0.029	0.012
	Run 2	0.112	0.058	0.029	0.011
	Run 3	0.108	0.058	0.029	0.011
	Run 4	0.111	0.058	0.029	0.011
	Mean	0.110	0.058	0.029	0.011
110	Run 1	0.135	0.077	0.044	0.023
	Run 2	0.137	0.077	0.045	0.021
	Run 3	0.137	0.077	0.043	0.021
	Run 4	0.136	0.078	0.043	0.022
	Mean	0.136	0.077	0.044	0.022
105	Run 1	0.254	0.183	0.134	0.091
	Run 2	0.251	0.172	0.135	0.090
	Run 3	0.253	0.180	0.130	0.093
	Run 4	0.246	0.181	0.134	0.089
	Mean	0.251	0.179	0.133	0.091

102	Run 1	0.519	0.451	0.398	0.346
	Run 2	0.514	0.438	0.394	0.341
	Run 3	0.517	0.446	0.391	0.337
	Run 4	0.518	0.442	0.379	0.341
	Mean	0.517	0.444	0.390	0.341
101	Run 1	0.711	0.660	0.624	0.576
	Run 2	0.712	0.666	0.621	0.586
	Run 3	0.705	0.661	0.650	0.562
	Run 4	0.709	0.645	0.615	0.556
	Mean	0.709	0.658	0.628	0.570
100	Run 1	0.999	0.991	0.996	0.990
	Run 2	0.989	0.978	0.987	0.994
	Run 3	0.984	0.992	0.987	0.988
	Run 4	0.987	0.994	0.972	0.979
	Mean	0.990	0.989	0.986	0.988

b) Service level (% of orders met from stock)

Theoretical service level

Safety stock	12.8	16.4	19.6	23.3
Service level	99.53	99.79	99.91	99.97

Service levels from simulation

Cap.		Safety stock			
		12.8	16.4	19.6	23.3
500	Run 1	99.53	99.80	99.91	99.97
	Run 2	99.53	99.80	99.91	99.97
	Run 3	99.54	99.80	99.91	99.97
	Run 4	99.53	99.79	99.91	99.97
	Mean	99.53	99.80	99.91	99.97
130	Run 1	99.54	99.80	99.91	99.97
	Run 2	99.52	99.79	99.91	99.97
	Run 3	99.53	99.80	99.91	99.97
	Run 4	99.53	99.80	99.91	99.97
	Mean	99.53	99.80	99.91	99.97
125	Run 1	99.54	99.80	99.92	99.97
	Run 2	99.52	99.79	99.91	99.97
	Run 3	99.52	99.79	99.91	99.97
	Run 4	99.53	99.79	99.91	99.97
	Mean	99.53	99.79	99.91	99.97
120	Run 1	99.51	99.79	99.91	99.97
	Run 2	99.52	99.79	99.90	99.97
	Run 3	99.51	99.79	99.91	99.97
	Run 4	99.52	99.79	99.91	99.97
	Mean	99.52	99.79	99.91	99.97

115	Run 1	99.46	99.75	99.89	99.96
	Run 2	99.45	99.75	99.89	99.96
	Run 3	99.47	99.75	99.89	99.96
	Run 4	99.45	99.75	99.89	99.96
	Mean	99.46	99.75	99.89	99.96
110	Run 1	99.22	99.59	99.78	99.88
	Run 2	99.21	99.59	99.77	99.90
	Run 3	99.20	99.59	99.79	99.90
	Run 4	99.23	99.59	99.79	99.90
	Mean	99.22	99.59	99.78	99.90
105	Run 1	97.36	98.14	99.65	99.09
	Run 2	97.50	98.38	98.63	99.10
	Run 3	97.47	98.18	98.70	99.06
	Run 4	97.61	98.14	98.64	99.15
	Mean	97.48	98.21	98.66	99.10
102	Run 1	86.94	88.61	89.97	91.17
	Run 2	87.73	88.87	90.40	91.21
	Run 3	87.12	89.54	90.15	91.75
	Run 4	86.76	89.30	91.21	91.95
	Mean	87.14	89.08	90.43	91.52
101	Run 1	69.29	72.72	73.04	75.71
	Run 2	69.59	71.23	71.56	75.71
	Run 3	69.13	71.12	71.98	77.24
	Run 4	68.45	72.86	73.58	76.72
	Mean	69.12	71.98	72.54	76.34
100	Run 1	8.47	5.05	3.59	0.43
	Run 2	1.48	7.88	5.52	1.31
	Run 3	7.53	2.97	7.13	3.76
	Run 4	1.96	2.23	8.33	5.59
	Mean	4.86	4.53	6.14	2.77

Figures 1 and 2 show graphically how stockout risk increases and service level falls as capacity approaches mean demand.

Figure 1: Stockout Risk and Capacity

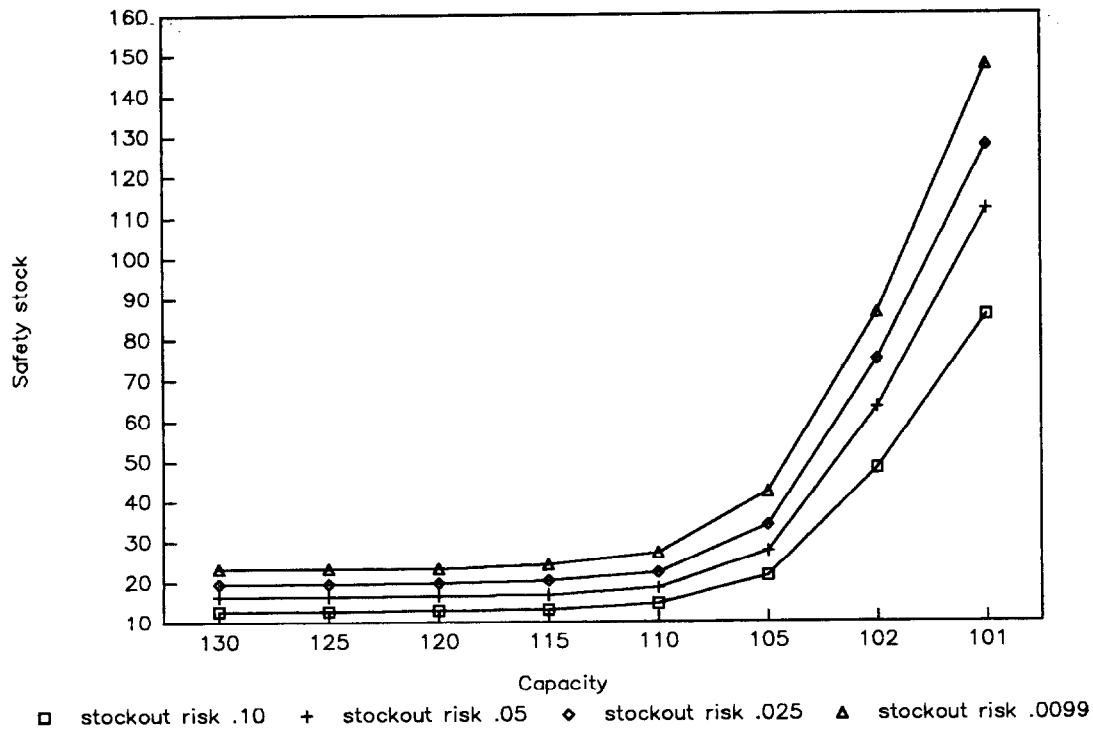
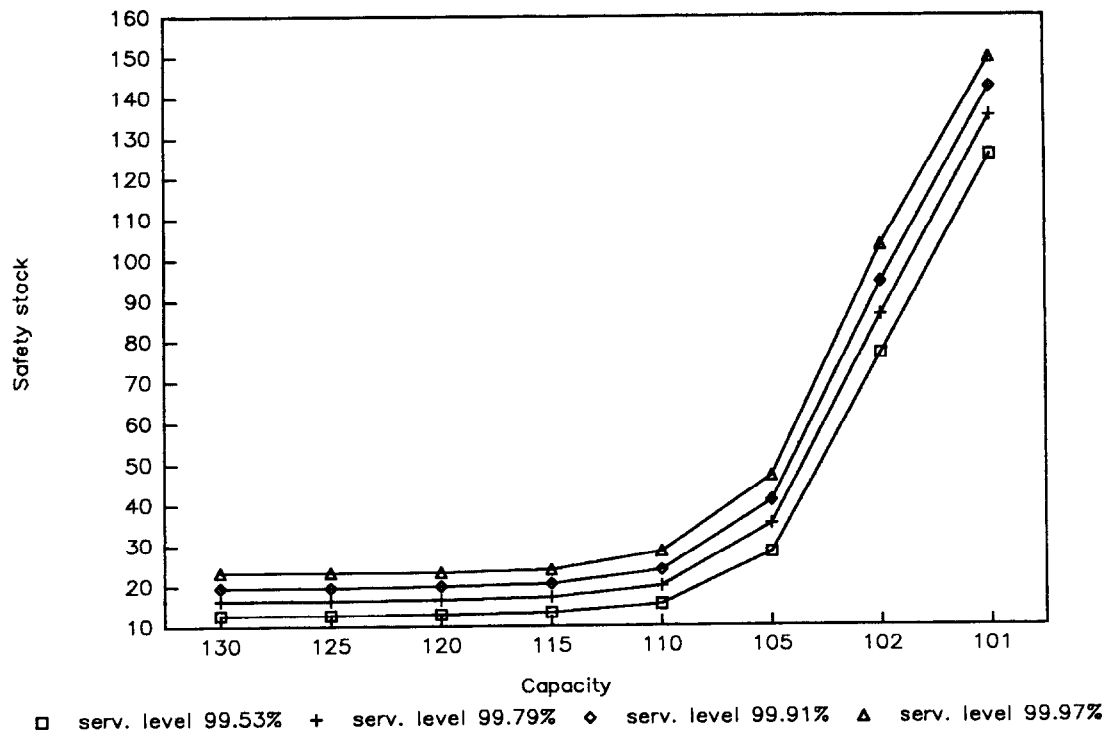


Figure 2: Customer Service Level and Capacity



Interactions between capacity and the mean and standard deviation of demand

the simulations described earlier were repeated using the same random number sequences but with different values for average weekly demand. Provided that average weekly demand and capacity were increased by the same amount, then identical results were obtained for the stockout risk and the number of back orders per planning period. in other words, these measures are a function of the number of units by which capacity exceeds average demand, not of capacity itself. this is illustrated in the table below.

safety stock	average demand	cap.excess (d)	cap. (c)	stockout risk (c-d)	back orders per period	service level
16.4	100	110	10	0.077	0.41	99.59
16.4	120	130	10	0.077	0.41	99.66
16.4	150	160	10	0.077	0.41	99.73

As customer service level is expressed as a percentage of total demand then its value will change as average demand changes.

the simulations were repeated again using the same random number sequences but this time varying the standard deviation of weekly demand. for each run the same value of k was used and excess capacity was set at the same multiple of the standard deviation. in each run the simulation gave the same stockout risk and the same value for the partial expectation, $e(k)$. this is illustrated in the table below.

k	standard devn.(s)	safety stock	excess cap.	stockout risk	back orders per period	e(k)	service level
1.64	10	16.4	10	0.077	0.41	0.041	99.59
1.64	20	32.8	20	0.077	0.82	0.041	99.18
1.64	30	49.2	30	0.077	1.23	0.041	98.77

it can therefore be concluded that stockout risk and partial expectation are both functions of the excess of capacity, (c) over average demand, (d), measured in multiples of the standard deviation of demand (s). the results of the simulation are summarised in this form in table 2. this table can be used to estimate the approximate service levels that will arise for specific combinations of safety stock, capacity, mean and standard deviation.

table 2 : the relationship between capacity and stockouts

		k							
		1.28	1.64		1.96		2.33		
c-d	stockout e(k)	stockout e(k)	stockout e(k)	stockout e(k)	stockout e(k)	stockout e(k)	stockout e(k)	stockout e(k)	
S	risk	risk	risk	risk	risk	risk	risk	risk	
40	0.10	0.047	0.051	0.020	0.024	0.009	0.009	0.003	
3.0	0.10	0.047	0.050	0.020	0.025	0.009	0.009	0.003	
2.5	0.10	0.047	0.051	0.021	0.024	0.009	0.009	0.003	
2.0	0.10	0.048	0.052	0.021	0.026	0.009	0.010	0.003	
1.5	0.11	0.054	0.058	0.025	0.029	0.011	0.011	0.004	
1.0	0.14	0.078	0.077	0.041	0.044	0.022	0.022	0.010	
0.5	0.25	0.25	0.18	0.18	0.13	0.13	0.091	0.090	
0.2	0.52	1.29	0.44	1.09	0.39	0.96	0.34	0.85	
0.1	0.71	3.09	0.68		0.62	2.75	0.57	2.37	

Safety stock necessary for a given service level

In practice it will usually be more useful to know the safety stock necessary at each capacity level to ensure a given service level. In order to establish this a series of simulation runs were carried out using the same random number sequence in each case and progressively increasing the safety stock until the stockout risk matched that for the infinite capacity case. For each level of capacity, 5 simulation runs of 1000 weeks were carried out and the results averaged. The exercise was then repeated to determine the safety stocks necessary to match the service level for the infinite capacity case. The results are summarised in Table 3.

Table 3: Safety stock for a given service level

a) Safety stock for a given stockout risk

Cap.	Stockout risk			
	0.10	0.05	0.025	0.0099
500	12.8	16.4	19.6	23.3
130	12.8	16.4	19.6	23.3
125	12.8	16.4	19.6	23.3
120	13.0	16.6	19.7	23.3
115	13.1	16.8	20.3	24.2
110	14.6	18.4	22.2	27.1
105	21.4	27.5	34.0	42.2
102	47.9	63.0	74.7	86.2
101	85.5	111.8	127.4	147.1

b) Safety stock for a given service level

Cap.	Service level			
	99.53	99.79	99.91	99.97
500	12.8	16.4	19.6	23.3
130	12.8	16.4	19.6	23.3
125	12.8	16.4	19.6	23.3
120	13.0	16.6	19.8	23.3
115	13.4	17.2	20.4	24.0
110	15.4	19.8	23.7	28.4
105	28.2	35.2	40.9	47.0
102	76.8	86.3	94.4	103.3
101	125.5	135.2	142.3	149.6

Conclusions

The results of the simulation clearly indicate that the effect of production capacity limitations is to significantly increase the amount of safety stock necessary to provide a given service level. The effect becomes noticeable when excess capacity is less than twice the standard deviation of planning period demand. In the example used in this paper, if there is excess capacity of 0.5 standard deviations over average demand then safety stock needs to be approximately double the safety stock necessary when there is no limit on capacity. It is likely that the lines which are operating at close to maximum capacity will be those making popular high volume products. These are the products for which it is important to maintain high customer service levels.

The results quoted in this paper are based on relatively short simulation runs. If the results are to be used by practitioners to set safety stocks then either the results must be based on much longer simulation runs or the results must be derived theoretically. Also it will be necessary to extend the analysis to cases where the same production capacity is used to make a range of different products.

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