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Demand management in Multi-Stage Distribution Chain

de Kok, T.; Janssen, F.B.S.L.P.

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Demand Management in multi-stage distribution chain

A.G. de Kok [1] and F.B.S.L.P. Janssen [2]

Abstract

In this paper we discuss demand management problems in a multi-stage distribution chain. We focus on distribution chains where demand processes have high variability due to a few large customer orders. We give a possible explanation, and suggest two simple procedures that help to smooth demand. It is shown that these procedures yield stock reductions of 40%-50% in practical situations. The quantitative results are based on the analysis of the underlying model related to the two procedures proposed, called large order overflow, applicable if the supplying organization executes a multi-stage distribution chain, and delivery splitting, applicable to any situation.

1. Introduction.

Since Forrester's Industrial Dynamics (1961) a lot has been published on the control of multi-stage logistics chains. The problems signalled by Forrester with respect to amplification of demand fluctuations upstream in the logistic chain have been understood widely and Material Requirements Planning (MRP), see, for example, Orlicky (1975), and Distribution Requirements Planning (DRP), for example. Martin (1990), systems are used throughout industry to eliminate this amplification as much as possible. Yet a closer look reveals that these systems typically operate within industrial and retail organizations, but seldom, if ever, across different organizations in the logistics chain. Although it is claimed by various authors, such as Martin (1990), that the tight coupling of MRP systems of end product manufacturers with DRP systems of component manufacturers should solve or at least alleviate these problems, it is still rare that such an approach is implemented.

This paper focuses on the management of the supply chain across the organization of a supplier of fast moving consumer goods and the organizations of its customers, that is, power

[1] Graduate School of Industrial Engineering and Management Science ,Eindhoven University of Technology, P.O. Box 513, Paviljoen F4, 5600 MB Eindhoven, The Netherlands

[2] Co-operation center Tilburg and Eindhoven Universities, Tilburg University, P.O. Box 90153, B929, 5000 LE Tilburg, The Netherlands

retailers, wholesalers and retailers. The study presented in the paper is motivated by one of the authors' 10-year experience at a European electronics manufacturer supplying the global market. The case material presented originates from an internal consulting project in the Consumer Electronics Division of this company. During these years a number of projects were started aimed at implementing integrated supply chain management in Europe. The major steps taken were the establishment of a European sales and marketing organization with tight control on the local sales organization, and the implementation of European Distribution Centers when appropriate, for example, for audio products manufactured in the Far-East.

One of the major problems concerning operational control of the supply chain was the so-called 'big order' issue. The company was regularly confronted with unexpected big orders for particular products. At the same time, investigations at their customers showed that their demands were relatively stable. Apparently the stable consumer demand was changed into erratic customer demand at the interface of the supplier and its customers. Based on the empirical research it was found that the major reason for the erratic behavior of the customer demand was due to large lot sizes caused by both the supplier's sales men and the customers' buyers: the sales men needed the large lot sizes of particular products in order to achieve their monthly sales budgets, while the buyers waited for discounts associated with these large lot sizes in order to maximize their sales turnover with the given purchasing budget.

In this paper we address this problem mainly from the supplier's point of view. The supplier's supply chain consists of a factory, a Regional Distribution Center (RDC), and local sales organizations with local stock. We model this supply chain as a two-echelon divergent system. To take into account the customers perspective, we make economic trade offs. The main idea is to smooth demand at the local sales organizations by offering different customer service conditions for large orders and small orders. This may be at the expense of the customer. Yet we claim that the savings made by the supplier are of such a magnitude that this provides funding for discounts to customers to stimulate the acceptance of a differentiated customer service policy. It is our belief that differentiated customer service policy, based on the capabilities of the supplier and the customers requirements, substantially reduces the total supply chain costs. This belief is based on a number of recent master's thesis projects at various industrial companies in the Netherlands, and the customer service strategy of the Consumer Electronics company defined for the European market based on their successful customer service strategy in the USA, which yielded substantial reduction in supply chain costs, while increasing market share.

A lot of research has been devoted to supply chain management in the last five years, Lee and Billington (1992, 1993). Their research is based on a methodology similar to our research: a combination of empirical research and the applications of quantitative models. Another related paper by Vastag et al. (1994) gives a general overview of the costs involved in the management of supply chains. The literature on quantitative modelling of supply chains is huge. For an excellent overview of the research in this area until 1992 we refer to Graves et al. (1993). It should be noted that the research reviewed in Graves et al. (1993) is focused on minimization of total costs, consisting of holding, ordering, and penalty costs. Other research focused on cost minimization subject to service level constraints. Papers based on the latter approach are Lagodimos (1992), Lagodimos and Anderson (1989), De Kok (1990), and De Kok and Verrijdt (1995). In this paper we also focus on cost minimization subject to service level constraints. A subject related to our work is risk pooling as described in Eppen and Schrage (1981), and Jönsson and Silver (1987). Risk pooling arises in our situation when we reroute large customer orders to the RDC to stabilize demand at the stock points of the sales organizations. The economic theory on discount policies, as discussed in Silver and Peterson (1985) and Tersine (1994), is not the subject of research in this paper. Merely we would like to draw attention to the impact of discount policies on demand variability and to give an estimate of the cost reduction caused by employing a strategy aimed at stabilizing customer demand. This cost reduction can be used to give discounts to customers that operate according to the service strategy of the supplier.

We have argued that the problem of erratic demand is caused by ordering policies, which can be considered to be non-rational from an inventory management point of view. Yet, these policies may be quite rational from the perspective of short term cost minimization or other incentives. Because we advocate a long-term perspective, we follow the line of thought advocated in the Just In Time literature (e.g. Hall (1983)), where all waste should be avoided. Apparently such non-rational policies increase the amount of stock held in the supply chains, which is counterproductive from a long-term perspective.

The paper is organized as follows. In section 2 we present a two-echelon model of the supply chain under consideration. Furthermore, we introduce the demand process, the lead time structure, and the cost structure on which the trade offs are made. In section 3 we exploit the two-echelon supply chain structure to divert large orders from local stockpoints to the RDC. We show the effect on overall supply chain costs, subject to a service level constraint. In section 4 we concentrate on a particular local stockpoint only. We discuss the effect of so-called delivery splitting (the delivery of large orders in consecutive smaller lots to the customer) on the costs of the sales organization. In section 5 we summarize our conclusions in relation to the case and discuss further research.

2. Model description

To illustrate the effects of large order overflow and delivery splitting we consider a two-echelon distribution chain. The supply chain consists of a factory supplying a regional distribution center (RDC), possibly near the factory, and N local stockpoints (LSP), wherefrom customers demand is satisfied (see Figure 1). Typically, the RDC holds seasonal stocks and replenishes the local stockpoints.

In this paper we do not take into account seasonal demand processes, and therefore we ignore the seasonal stock.

The lead time from factory to RDC, denoted by L_F, represents the sum of planning lead time, production and distribution lead time between a (Far-East) factory and a (European) RDC. The transportation lead times between the RDC and the LSP's are assumed to be identical, and are denoted by L_R. We assume that all stockpoints have compound Poisson demand processes. More specifically, the customers arrive according to a Poisson process

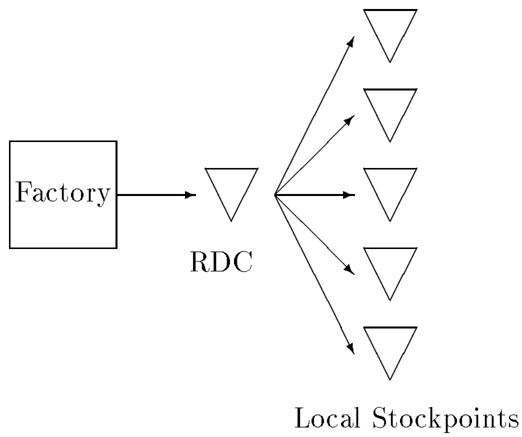

Figure 1: Supply chain with RDC and local stockpoints

with rate λ_i $(i = 1, ..., N)$. Let D denote the demand of an arbitrary customer. We assume the demands per customer are independent and identically distributed non-negative random variables with distribution function $F_D(.)$. The mean and standard deviation of the demand size D is denoted by $\mathbb{E}D$ and $\sigma(D)$ respectively. Furthermore, we denote the coefficient of variation of D by c_D, that is, $c_D = \frac{\sigma(D)}{\mathbf{E}(D)}$. The coefficient of variation is a measure for the variability of demand. Often it is assumed that if $c_D < 1$, then demand is stable and if $c_D > 1$, then demand is erratic. Note that the Poisson process assumption has been shown to hold in most practical situations with regard to customer arrival streams (for example. Tijms (1994)).

The replenishments at the RDC as well as the LSP's are controlled by (s, Q) policies, that is, when the inventory position (physical stock minus backlog plus on order) drops below the reorder point s we order a multiple of Q, such that the inventory position after ordering is between s and $s+Q$. As a service performance measure the P_2 service measure (often denoted as the fill rate) is used: the long-run fraction of demand delivered directly from shelf, see for example Silver and Peterson (1985), Tijms and Groenevelt(1984). Demands which can not be delivered directly from shelf are backordered. The aim is to minimize the costs incurred in the supply chain subject to a P_2 service level constraint.

The purpose of this paper is to analyze the cost differences of the proposed demand management policies. Therefore, we need specifications for the costs that are dependent of these policies, which are: the costs of carrying items in inventory, the ordering or setup costs, and the transportation costs. We assume that the carrying costs are proportional to the average inventory level in the distribution chain, where the costs of having one item stocked for one time unit is identical along the supply chain, and is denoted by h ($ / time unit). Assuming constant carrying cost along the supply chain is based on the fact that once a product has been completed the material value remains constant while further distributing through the supply chain. The ordering costs are fixed per replenishment (that is independent of the size of the replenishment), and are denoted by A_R at the RDC and A_L at the LSP's. We assume that transportation costs are independent of the transportation size, and are denoted by T_R at the RDC and T_L at the LSP's.This is typically the case for transportation of fast moving goods, where mostly Full (mixed) Truck Loads (FTL) are guaranteed.

3. Rerouting large orders to upstream stockpoints; large order overflow.

In general, a stockpoint in a multi-echelon distribution chain satisfies all customers that arrive at that particular stockpoint, where customers are defined as the external customers as well as replenishment orders of downstream stockpoints in the distribution chain. However, in case large order overflow is applied, customers with large demand are not satisfied by the stockpoint at which they arrive, but by an upstream stockpoint. Thus for each stockpoint a maximal customer order quantity Q_c and an alternative source τ is defined such that customers with demand larger than Q_c are satisfied by source τ. Note that the case in which large order overflow is not allowed can be identified by the situation where Q_c is equal to ∞. However, re-routing orders to another source implies in most cases increasing lead times of customers with large demand. On the other hand, the number of internal replenishments decreases. Of course it may not be easy to persuade customers to accept this new regime. It may be needed to give a discount for the customers' willingness to collaborate. How much discount can be given depends on the cost savings realized. An alternative approach to neutralize the increasing lead times is faster transportation. This also results in a trade off between the costs of fast transportation and the costs savings due to large order overflow, that is savings of holding costs.

In our numerical experiment we consider 10 local stockpoints (LSP). The lead time from factory to RDC, L_F, equals 40 days and the lead times between the RDC and the LSP's, L_R, are equal to 3 days. For sake of simplicity we assume that all stockpoints have an identical demand process, with arrival rate 1 customer each day, an expected demand ($\mathbb{E}D$) equal to 100, and the coefficient of variation c_D is equal to $\sqrt{3}$. The value for the coefficient of variation is based on an extensive analysis of about 10.000 consumer electronics products. We varied the P_2 service measure between 0.90, 0.95 and 0.99. Furthermore, we assumed that the reorder quantity Q is 10 and 5 days of demand at the RDC and the LSP's, respectively.

Given this information about the distribution chain, we determine the control policies that yield a prespecified P_2 service measure for both the RDC and the LSP's, see Appendix 1. We used a heuristic method to find the control variables. The heuristic is analogously to the approach followed by van der Heijden (1992), who analyzed divergent logistic networks with local (R, S) inventory control. The two key elements in his approach are the decomposition of the multi-echelon distribution chain into single echelon inventory models, and the calculation of the replenishment order delay due to stockouts at upstream stockpoints. Discrete event simulation is used to compute the following performance measures, which will be used to evaluate the possible benefit of large order overflow:

- X := the average cumulative stocks at the LSP's and the RDC;
- β := the actual service level averaged over the LSP's and RDC;
- N := the transportation frequency between the RDC and LSP's plus the number of diverted customers per time unit.

Note that the service at the RDC is also incorporated in β, because diverted customers will be served by the RDC. In the simulation experiment we sampled 20 runs of 50.000 time units (corresponding to 500.000 customers each run). For each of the performance measures, defined as above, the average value and the corresponding 95% confidence interval over the 20 runs are tabulated in Appendix 2. Moreover we used a mixture of Erlang distributions to sample the demand size (see Tijms(1994) pp. 358).

In Figure 2 we show the average cumulative stock needed to guarantee a target customer service level of 90%, 95% and 99% for various values of Q_c. Figure 3 illustrates the relative stock savings $((X(\infty) - X(Q_c))/X(\infty) \times 100\%)$.

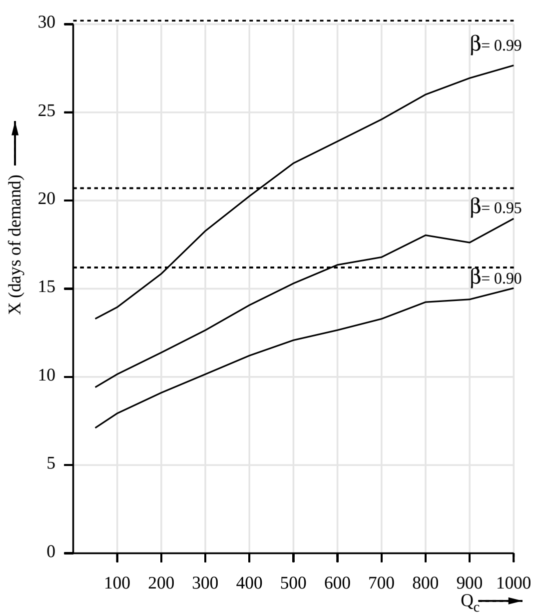

Figure 2: Average cumulative stock needed with large order overflow.

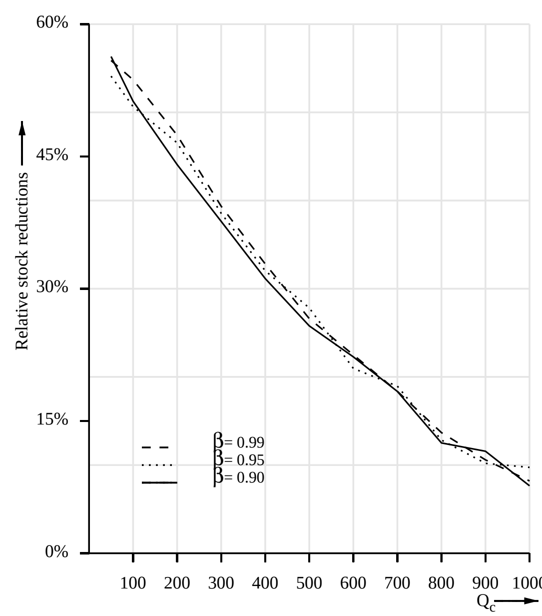

Figure 3: Relative stock reduction with large order overflow.

The average cumulative stock needed, in the distribution chain which is not controlled by large order overflow, to guarantee a prespecified P_2 service level of 90%, 95% and 99% is about 16, 21 and 30 days demand respectively (horizontallines in figure 2). We notice that by diverting large orders to the RDC if demands are larger than 3 times the average customer order size the cumulative stock needed to guarantee a service level of 90%, 95% and 99% equals 9,11 and 16 days of demand respectively. By taking Q_c equal to the average customer order size we apparently discriminate between small and large orders leading to relative cumulative stock savings of about 50%.

The analysis reveals another important point. Without large order overflow we need very high stocks to maintain a 99% service level, as is usually proposed as a standard in the Operations Management literature. In practice we find such high stocks unacceptable from an economic point of view. Thus one accepts a lower service level or one applies procedures such as large order overflow or delivery splitting, which is discussed in the next section. Such procedures (and others) are applied on an ad hoc basis, especially in situations where stock-outs are likely to occur in the near future. However, this usually comes as a surprise to the customer. We advocate the routine use of such procedures, where customers know the conditions, and target stock levels are set taking into account the benefits of the differentiated procedures. Notice, that the stock needed in case $\beta = 0.99$ and $Q_c = 200$ equals the stock needed when $\beta = 0.90$ and $Q_c = \infty$, i.e. in case customers with demands larger than 2 times the average demand are diverted to the RDC, a service of 99% can be realized with stock required to guarantee a service of 90% in case large order overflow is not applied.

It is clear that large order overflow decreases the average stock on hand enormously. Moreover, the number of internal deliveries due to replenishment orders of downstream stockpoints decrease. In fact the total amount shipped between the RDC and LSP's decreases with an amount which equals the total amount shipped from the RDC directly to the customers. Notice that the number of shipments to customers remain the same. It is clear that for riguorous treatment of the model we need to incorporate the safety stock at the customers. As motivated before we assume that the consequences for the customers are neutralized by discounts for customers accepting this new regime of large order overflow.

In order to make the proper trade offs we now introduce the Differential Total Relevant Costs (DTRC) which is defined as the difference between the total relevant costs in the situations with or without large order overflow. In the DTRC we need to incorporate the transportation cost between the RDC and LSP's and between the RDC and external customers, the holding costs and the possible extra ordering costs. Hence, the situation is considered that the customers which are diverted have extra ordering costs $A_R - A_L$ and extra transportation costs T_R. Then recall the definition of X and N which are obviously functions of Q_c. Then $DTRC(Q_c) = h(X(\infty) - X(Q_c)) + A(N(\infty) - N(Q_c))$, where h denotes the stock keeping costs per time unit and $A := A_R - A_L + T_R$.

The profitability then depends on the transportation-holding cost ratio TH, where TH=$\frac{A}{h}$. It is clear that for large TH-ratios large order overflow is not profitable, whereas for small TH-ratios the opposite holds. In figure 4 we illustrate the DTRC for $\beta = 0.99$ where we varied the TH-ratio. The indifference curves give good insight in profitability of large order overflow.

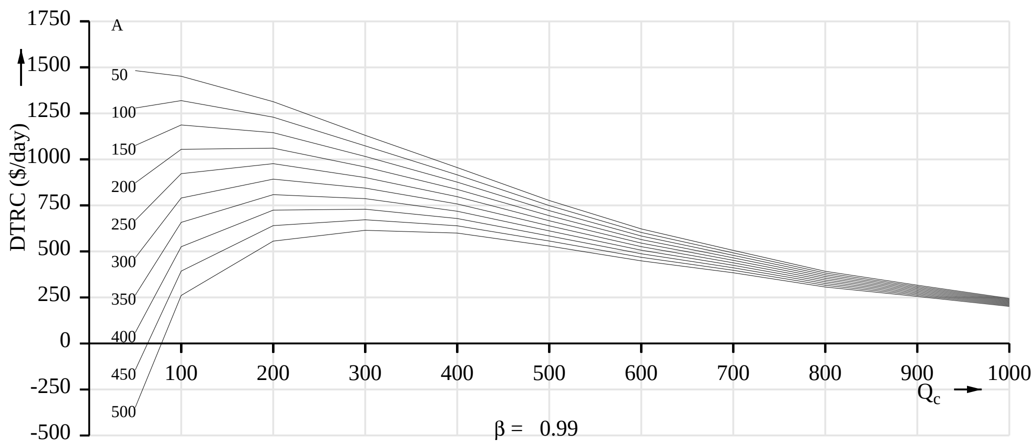

Figure 4: TRC as function of the TH-ration

For example, in case $Q_c = 300$, $A = 500$ the holding costs decrease by 1186 ($/day), where the transportation costs increase by 570, hence the overall profit is $ 615 each day. Moreover, the curves can be used as a graphical aid in determining the optimal Q_c.

4. Delivery splitting.

In this section we analyze the effect of delivery splitting on average physical stock, customer service level, and delivery frequencies. We restrict ourself to the analysis of a single local stockpoint (LSP). The large order overflow procedure aims at reducing variability of demand to be satisfied from local stockpoints. Indeed, supply chain stocks are dramatically reduced by this procedure. Yet, the customer orders are all shipped in one lot. This is likely to cause high stocks at the customers. Therefore we propose the following procedure which may induce a beneficial result for both supplier and customers. Determine a maximum shipment lot Q_s and an intershipment time T for consecutive lots of the same customer order. Then large demands will not be deliverd in one single batch, even in case the inventory level is sufficiently large. The customer receives only a limited quantity, Q_s, at a time. If the demand size is larger than Q_s, starting at the demand epoch, an amount of Q_s is delivered in a number of shipments which are T time units apart. Consequently all quantities are equal to Q_s except possibly the last. For example, when a customer arrives at time t, with demand of size D, results in the following delivery scheme for that customer:

$$\begin{cases} \text{deliver } Q_s & \text{on epoch} \quad t + jT \qquad (j = 0, ..., n-1) \\ \text{deliver } D - nQ_s & \text{on epoch} \quad t + nT \end{cases} \tag{1}$$

where $n := \max\{m \in I\!N | mQ_s \leq D\}$.

In practice, situations occur in which delivery splitting is not feasible, for example, when large orders are required immediately. However, in the situations where quantity discounts generate the large customer demand sizes, delivery splitting is especially suitable. Note, that the case in which delivery splitting in not allowed we set Q_s equal to ∞. The focus of delivery splitting is to reduce the variance in the demand process and to achieve stock reductions at the customers as a by-product, for the reduction of the inventory at the customers see Chiang and Chiang (1996).

Closely related to delivery splitting is the concept of order splitting (see, for example, Sculli and Wu (1981) and Lau and Lau (1994)). Order splitting, however, primarily aims at reducing of lead time uncertainties by splitting the replenishment orders over more than one supplier, and is therefore a lead time management strategy. Hong and Hayya (1992) give a chronological summary of the literature about order splitting. The papers about order splitting stress the trade off between the increase in delivery costs and the decrease in holding costs, which is also an important issue when delivery splitting is applied.

To quantify the effects of delivery splitting we use simulation. We specified the distribution function of the demand size $F_D(.)$ as a mixture of Erlang distributions, as in the case of large order overflow. The simulation experiments are composed of 25 runs of 100.000 time units to guarantee a 95% confidence interval of maximal 1% of the actual service level. We consider

240 cases as follows. The average customer demand size ($\mathbb{E}D$) is fixed at 50, the coefficient of variation of the customer demand size (c_D) varies as 1,2 and 4 to emphasize the high variability in demand. The average number of customer orders per day (λ) is equal to 1. The lead time of replenishment orders from the RDC to the LSP (L) varies between 10 and 20 days. The replenishment order quantity is equal to 1000 for all cases. The target customer service level is varied between 0.90 and 0.99. The intershipment time T is varied between 0.3, 0.5, 1 and 1.5 times the lead time. The maximal lot size of a shipment (Q_s) is varied between 0.5, 1, 2 and 4 times the average customer demand (see Appendix 3 for detailed specification). We used a heuristic method to find the control variables. The key elements in this heuristic are expressions for the arrival intensity of the splitted deliveries, and the first two moments of the sizes of such splitted deliveries. For a more detailed description of the heuristic see Janssen et al. (1995)). Discrete event simulation is used to compute the following performance measures:

- X:= the average physical stock at the LSP;
- β:= the actual service level at the LSP;
- N:= the delivery frequency to the customer per unit of time.

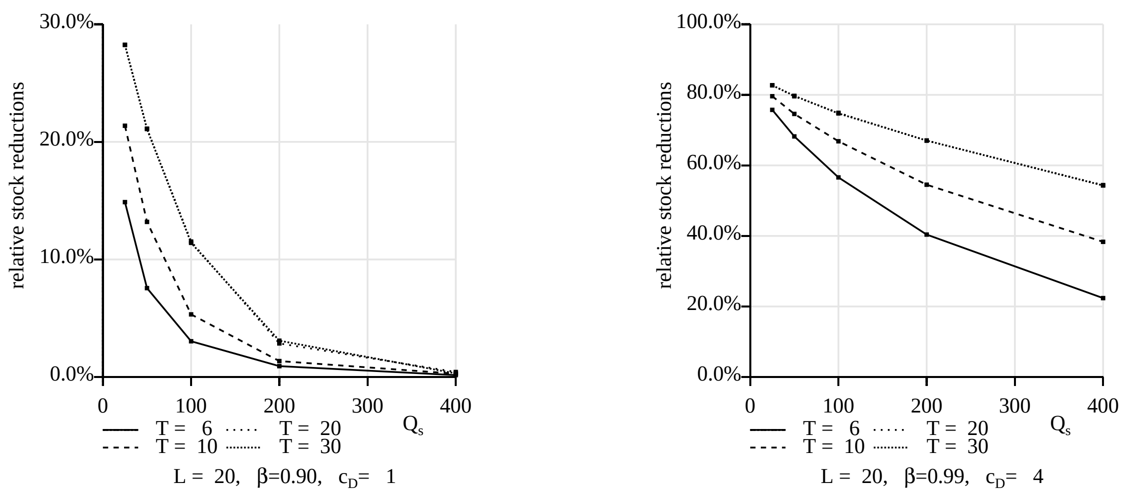

Figure 5: Stock reductions obtained by delivery splitting.

In figure 5 we show the relative stock reductions obtained by delivery splitting, expressed in the percentage of the stock on hand that is needed when no delivery splitting is applied. To be more precise the figure represents the quantity $(X(\infty) - X(Q_s))/X(\infty) \times 100\%$. We conclude that for c_D relatively small ($c_D = 1$) delivery splitting does not reduce the average stock on hand much. However, for c_D large we notice the enormous stock reductions that can be obtained by delivery splitting.

On the other hand the delivery frequency increases, and thereby possibly the transportation costs. Hence, to make a trade off between applying delivery splitting or not we need to include the transportation costs, as was the case for order splitting. Because the number of customer demands remains the same we need not include the ordering costs at the LSP. We again consider the Differential Total Relevant Costs (DTRC) which is now defined as the difference between the total relevant costs in the situations using delivery splitting or not. Then $DTRC(Q_s) = h(X(\infty) - X(Q_s)) + A(N(\infty) - N(Q_s))$, where $A := T_R$. The profitability of delivery splitting depends on the ratio A/h. Figure 6 illustrates DTRC (\$/day) where h is fixed at 0.2\$/unit/day and A is varied as 15, 30, ..., 150.

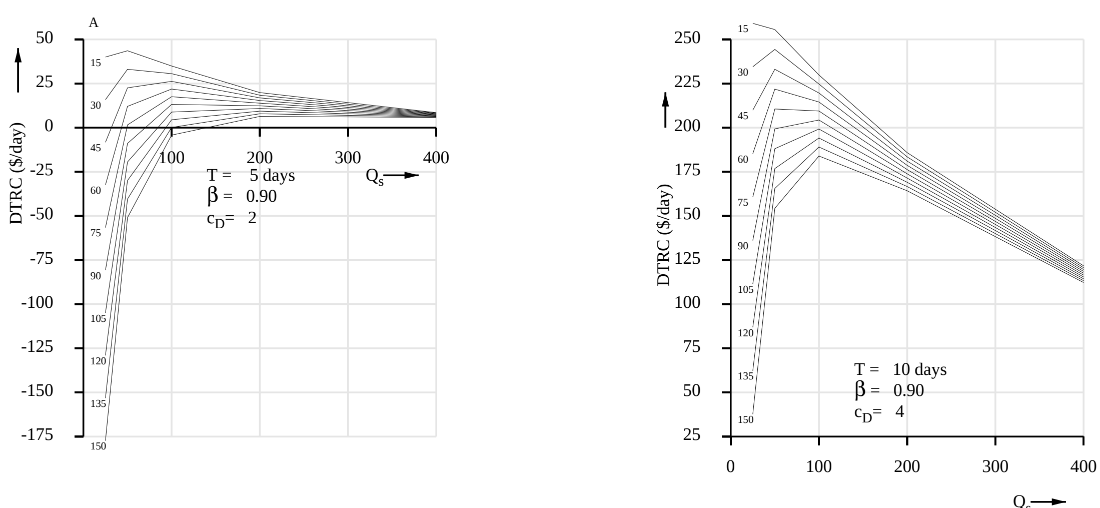

Figure 6: Differential total relative costs (\$/day.

If the ratio A/h is high, delivery splitting is not profitable at all. On the other hand when the ratio A/h is small, delivery splitting is indeed profitable. To investigate the profitability of delivery splitting for practical situations and to evaluate a number of scenarios we need a fast method to calculated $DTRC$. We refer to Janssen et al.(1995) for such a method.

So far we considered a replenishment policy which is only based on the inventory position, that is, physical inventory level plus stock on order minus backorders. However, in case delivery splitting is applied, explicit knowledge about the occurrences of future deliveries of the splitted orders is available. This knowledge could be used to improve the performance of the inventory system. To compare the effectiveness of using information about future deliveries we analyzed the same 240 cases as above. Again we used a heuristic method (Janssen et al.(1995)) to find the control parameters, whereas discrete event simulation is used to compute the performance measures (see Appendix 4). In figure 7 we present the relative stock reductions obtained by delivery splitting in case we use information about future deliveries over the stock reductions obtained by delivery splitting without using information about future deliveries. To be more precise the figure represents the quantity $(X(Q_s) - X_i(Q_s))/(X(\infty) - X(Q_s)) \times 100\%$ where X_i denotes the average stock on hand level with delivery splitting using information about future deliveries explicitly.

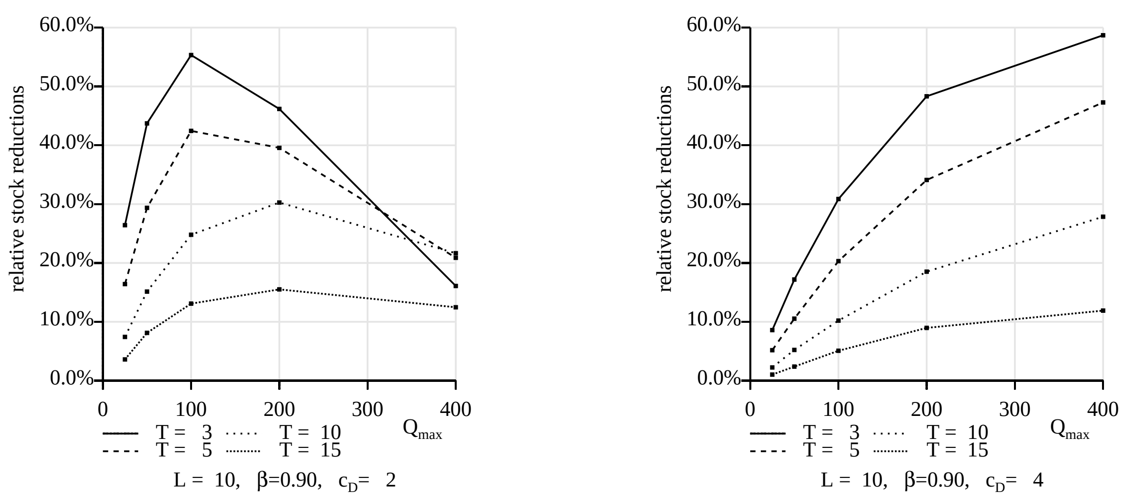

Figure 7: Additional stock reductions obtained by using information about future deliveries

It is clear that the additional stock reductions are dependent of Q_s. Actually, we conjecture that there exists a Q_s for which the additional stock reductions are maximal. The additional stock reduction increase for small Q_s because of the increasing amount known to be delivered during the lead time (the number of deliveries within the lead time remains the same but the quantity per delivery increases). Thus the information about future deliveries is used more effectively. On the other hand, for large Q_s the total amount known to be delivered during the lead time decreases, because the number of future deliveries decreases. In deciding whether to implement delivery splitting with or without using the information about future deliveries a trade off has to be made between the additional stock on hand savings and the extra cost due to a more complex replenishment strategy.

5. Conclusions.

In this paper we discussed the problem of demand management in a multi-stage distribution chain. We argued the organizational causes for high demand variations in intermediate stages, in spite of stable end-customer demand. This effect is another example of Forrester's findings (1961), yet it differs from the usual interpretation of Forrester's conclusions, which are more related to batch sizing and information delays (see Silver and Peterson (1985)). We discussed ways of resolving the problems caused by these high variations; our discussion was based on the insight that both supplier and customer benefit from stability of the demand process at intermediate stages by stock reduction. We introduced and analyzed two simple procedures that could be applied in the order processing systems. We emphasize that the resulting procedures are customer-oriented; hence the procedures chosen are product-customer dependent. Our analysis showed the large impact of the two procedures from the point of view of the supplying stage.

We consider the two proposed procedures as powerfull tools for management to decrease variablities in demand and therefore decrease safety stocks. In that sense we deliberately used the notion of demand management, which is pro-active, as opposed to inventory management. Further research is required with respect to the implementation of the procedures and the validation of our stock savings predictions. Yet these predictions are in accordance with the savings reported by companies that implemented DRP-systems with Available-To-Promise capabilities. This constitutes another subject of further research, that is, the relation of the demand management procedures defined in this paper and the ATP-capability.

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Appendix 1 : Control parameters for the 2-echelon inventory model with large order overflow.

Q_{max}	β	0.90		0.95		0.99	
		s	Q	s	Q	s	Q
50	RDC	41593	10000	43438	10000	46893	10000
	LDC	75	57	93	57	135	57
100	RDC	41635	10000	43480	10000	46935	10000
	LDC	136	107	168	107	243	107
200	RDC	41720	10000	43565	10000	47099	10000
	LDC	234	175	290	175	425	175
300	RDC	41808	10000	43693	10000	47306	10000
	LDC	336	238	418	238	613	238
400	RDC	41937	10000	43862	10000	47554	10000
	LDC	436	296	543	296	797	296
500	RDC	42026	10000	44031	10000	47803	10000
	LDC	526	345	653	345	961	345
600	RDC	42154	10000	44159	10000	48011	10000
	LDC	603	384	750	384	1102	384
700	RDC	42241	10000	44286	10000	48178	10000
	LDC	668	415	830	415	1221	415
800	RDC	42297	10000	44371	10000	48303	10000
	LDC	722	438	897	438	1319	438
900	RDC	42371	10000	44455	10000	48427	10000
	LDC	765	455	952	455	1398	455
1000	RDC	42375	10000	44498	10000	48470	10000
	LDC	801	468	995	468	1463	468
∞	RDC	42462	10000	44586	10000	48637	10000
	LDC	892	500	1125	500	1674	500

Appendix 2 : Performance measures for the 2-echelon inventory model with large order overflow.

Q_{max}	β	0.90			0.95			0.99		
50	X	7108	[6399	, 7817]	9489	[9408	, 9570]	13295	[13225	, 13365]
	N	5.87	[5.87	, 5.88]	5.87	[5.87	, 5.88]	5.87	[5.87	, 5.88]
	β	0.9034	[0.9030	,0.9039]	0.9557	[0.9554	,0.9559]	0.9941	[0.9940	,0.9942]
100	X	7934	[7474	, 8393]	10204	[10149	, 10258]	13954	[13303	, 14606]
	N	4.43	[4.43	, 4.44]	4.43	[4.43	, 4.44]	4.44	[4.43	, 4.44]
	β	0.9039	[0.9034	,0.9044]	0.9552	[0.9549	,0.9555]	0.9935	[0.9934	,0.9936]
200	X	9103	[9018	, 9188]	11053	[10398	, 11708]	15848	[15184	, 16513]
	N	3.47	[3.47	, 3.48]	3.47	[3.47	, 3.47]	3.47	[3.47	, 3.48]
	β	0.9037	[0.9032	,0.9043]	0.9544	[0.9541	,0.9547]	0.9934	[0.9933	,0.9935]
300	X	10152	[10075	, 10228]	12705	[12644	, 12766]	18276	[18180	, 18372]
	N	2.94	[2.94	, 2.94]	2.94	[2.93	, 2.94]	2.94	[2.94	, 2.94]
	β	0.9046	[0.9041	,0.9051]	0.9545	[0.9542	,0.9548]	0.9932	[0.9931	,0.9933]
400	X	11207	[11113	, 11302]	14053	[13983	, 14123]	20248	[20184	, 20311]
	N	2.58	[2.58	, 2.58]	2.58	[2.58	, 2.58]	2.58	[2.58	, 2.59]
	β	0.9061	[0.9056	,0.9066]	0.9552	[0.9549	,0.9555]	0.9932	[0.9931	,0.9933]
500	X	12081	[12004	, 12157]	14923	[14262	, 15585]	22117	[21987	, 22247]
	N	2.34	[2.34	, 2.34]	2.34	[2.34	, 2.34]	2.34	[2.34	, 2.35]
	β	0.9076	[0.9071	,0.9081]	0.9559	[0.9557	,0.9561]	0.9933	[0.9932	,0.9934]
600	X	12652	[11995	, 13309]	16342	[16236	, 16447]	23355	[22695	, 24015]
	N	2.18	[2.18	, 2.18]	2.18	[2.18	, 2.18]	2.18	[2.18	, 2.18]
	β	0.9087	[0.9082	,0.9092]	0.9562	[0.9559	,0.9564]	0.9933	[0.9932	,0.9934]
700	X	13291	[12630	, 13952]	16757	[16055	, 17459]	24602	[23941	, 25262]
	N	2.06	[2.06	, 2.07]	2.06	[2.06	, 2.07]	2.07	[2.06	, 2.07]
	β	0.9093	[0.9089	,0.9097]	0.9523	[0.9445	,0.9601]	0.9931	[0.9931	,0.9932]
800	X	14241	[14147	, 14335]	18021	[17960	, 18082]	26012	[25923	, 26100]
	N	1.99	[1.98	, 1.99]	1.99	[1.98	, 1.99]	1.99	[1.99	, 1.99]
	β	0.9100	[0.9095	,0.9105]	0.9564	[0.9560	,0.9567]	0.9930	[0.9929	,0.9931]
900	X	14395	[13735	, 15054]	18567	[18445	, 18689]	26943	[26855	, 27031]
	N	1.93	[1.93	, 1.93]	1.93	[1.93	, 1.93]	1.93	[1.93	, 1.93]
	β	0.9098	[0.9094	,0.9103]	0.9563	[0.9560	,0.9567]	0.9928	[0.9927	,0.9929]
1000	X	15032	[14942	, 15123]	18662	[17996	, 19328]	27664	[27564	, 27764]
	N	1.89	[1.89	, 1.89]	1.89	[1.89	, 1.89]	1.89	[1.89	, 1.89]
	β	0.9101	[0.9096	,0.9107]	0.9559	[0.9556	,0.9562]	0.9926	[0.9925	,0.9927]
∞	X	16278	[16177	, 16378]	20676	[20555	, 20797]	30135	[30008	, 30262]
	N	1.80	[1.80	, 1.80]	1.80	[1.80	, 1.80]	1.80	[1.80	, 1.80]
	β	0.9048	[0.9044	,0.9052]	0.9517	[0.9514	,0.9520]	0.9900	[0.9898	,0.9901]

Appendix 3 : Performance measures for delivery splitting without using information about future deliveries

		L=10						L=20					
		β=0.90			β=0.99			β=0.90			β=0.99		
T	Q_s	$c_D = 1$	$c_D = 2$	$c_D = 4$	$c_D = 1$	$c_D = 2$	$c_D = 4$	$c_D = 1$	$c_D = 2$	$c_D = 4$	$c_D = 1$	$c_D = 2$	$c_D = 4$
	∞	533 1.0000 543	769 1.0000 783	1652 1.0000 1672	930 1.0000 932	1469 1.0000 1469	3442 1.0000 3433	1115 1.0000 631	1404 1.0000 928	2381 1.0000 1926	1619 1.0000 1118	2299 1.0000 1801	4534 1.0000 4039
$0.3L$	25	259 2.5400 453	142 2.6100 437	67 2.6500 424	496 2.5400 683	343 2.6100 631	226 2.6500 578	601 2.5400 485	370 2.6100 455	221 2.6500 431	897 2.5400 771	620 2.6100 698	419 2.6100 621
	50	403 1.5800 496	279 1.6900 492	132 1.7500 453	719 1.5800 804	582 1.6900 788	364 1.7500 678	873 1.5800 554	618 1.6900 540	339 1.7500 476	1269 1.5800 937	994 1.6900 906	625 1.6900 754
	100	492 1.1500 526	472 1.2800 598	285 1.3500 552	862 1.1500 887	923 1.2800 1038	680 1.3500 941	1041 1.1500 603	944 1.2800 688	583 1.3500 614	1506 1.1500 1054	1497 1.2800 1228	1058 1.2800 1079
	200	523 1.0200 538	644 1.1000 701	613 1.1600 805	918 1.0200 923	1242 1.1000 1287	1326 1.1600 1508	1102 1.0200 624	1226 1.1000 832	1051 1.1600 931	1599 1.0200 1105	1952 1.1000 1541	1878 1.1000 1743
$0.5L$	25	528 1.0000 541	723 1.0200 749	1090 1.0600 1199	928 1.0000 930	1402 1.0200 1414	2234 1.0600 2331	1112 1.0000 629	1365 1.0200 906	1680 1.0600 1393	1614 1.0000 1115	2196 1.0200 1716	3000 1.0200 2694
	50	186 2.5400 437	98 2.6100 427	49 2.6500 420	379 2.5400 623	261 2.6100 584	189 2.6500 555	458 2.5400 454	282 2.6100 436	186 2.6500 424	699 2.5400 687	484 2.6100 631	357 2.6100 589
	100	342 1.5800 476	205 1.6900 461	99 1.7500 439	616 1.5800 743	444 1.6900 694	283 1.7500 617	756 1.5800 519	481 1.6900 489	275 1.7500 451	1101 1.5800 853	778 1.6900 779	502 1.6900 671
	200	468 1.1500 516	377 1.2800 543	199 1.3500 497	818 1.1500 857	742 1.2800 900	488 1.3500 779	995 1.1500 586	780 1.2800 609	439 1.3500 531	1435 1.1500 1013	1231 1.2800 1048	791 1.2800 875
L	25	520 1.0200 536	578 1.1000 658	437 1.1600 669	912 1.0200 918	1107 1.1000 1176	952 1.1600 1177	1095 1.0200 621	1118 1.1000 771	791 1.1600 751	1587 1.0200 1097	1765 1.1000 1405	1405 1.1000 1354
	50	528 1.0000 541	706 1.0200 736	867 1.0600 1012	928 1.0000 930	1366 1.0200 1383	1792 1.0600 1928	1112 1.0000 629	1334 1.0200 886	1377 1.0600 1164	1614 1.0000 1115	2136 1.0200 1669	2441 1.0200 2215
	100	115 2.5400 424	60 2.6100 420	32 2.6500 418	267 2.5400 571	194 2.6100 550	157 2.6500 538	317 2.5400 432	207 2.6100 424	152 2.6500 420	505 2.5400 612	370 2.6100 582	301 2.6100 564
	200	261 1.5800 452	143 1.6900 440	75 1.7500 430	485 1.5800 670	330 1.6900 620	229 1.7500 580	601 1.5800 479	365 1.6900 454	230 1.7500 437	882 1.5800 750	597 1.6900 679	419 1.6900 621
$1.5L$	25	420 1.1500 497	276 1.2800 490	139 1.3500 462	735 1.1500 804	556 1.2800 764	352 1.3500 670	907 1.1500 555	605 1.2800 531	337 1.3500 480	1302 1.1500 938	953 1.2800 870	598 1.2800 734
	50	511 1.0200 532	476 1.1000 594	286 1.1600 557	894 1.0200 904	910 1.1000 1019	642 1.1600 908	1079 1.0200 614	949 1.1000 679	567 1.1600 607	1559 1.0200 1078	1481 1.1000 1200	992 1.1000 1023
	100	528 1.0000 541	665 1.0200 707	609 1.0600 799	928 1.0000 929	1272 1.0200 1301	1254 1.0600 1438	1112 1.0000 629	1266 1.0200 842	1027 1.0600 906	1614 1.0000 1115	2006 1.0200 1565	1785 1.0200 1654
	200	109 2.5400 419	56 2.6100 417	31 2.6500 417	260 2.5400 564	191 2.6100 546	155 2.6500 536	311 2.5400 426	203 2.6100 421	150 2.6500 419	498 2.5400 605	366 2.6100 577	299 2.6100 561

In each cel the top, the middle and the bottom elements denote the reorder point calculated by the method described in Janssen et al. (1995), the associated delivery frequency and the average stock position, respectively.

Appendix 4 : Performance measures for delivery splitting using information about future deliveries

		L=10						L=20					
		β=0.90			β=0.99			β=0.90			β=0.99		
T	Q_s	$c_D = 1$	$c_D = 2$	$c_D = 4$	$c_D = 1$	$c_D = 2$	$c_D = 4$	$c_D = 1$	$c_D = 2$	$c_D = 4$	$c_D = 1$	$c_D = 2$	$c_D = 4$
	∞	533 1.0000 543	769 1.0000 783	1652 1.0000 1672	930 1.0000 932	1469 1.0000 1469	3442 1.0000 3433	1115 1.0000 631	1404 1.0000 928	2381 1.0000 1926	1619 1.0000 1118	2299 1.0000 1801	4534 1.0000 4039
$0.3L$	25	477 2.5400 486	500 2.6100 508	513 2.6400 522	766 2.5400 766	812 2.6100 813	835 2.6400 836	1025 2.5400 537	1056 2.6100 569	1072 2.6500 582	1389 2.5400 889	1448 2.6100 950	1480 2.6100 980
	50	504 1.5800 514	571 1.7000 580	621 1.7400 631	846 1.5800 846	981 1.7000 980	1067 1.7500 1065	1069 1.5800 583	1156 1.7000 668	1218 1.7500 728	1498 1.5800 998	1670 1.6900 1171	1780 1.6900 1284
	100	519 1.1600 531	653 1.2900 663	806 1.3500 813	897 1.1600 897	1180 1.2800 1180	1447 1.3500 1448	1096 1.1600 611	1268 1.2800 785	1450 1.3500 966	1570 1.1600 1071	1916 1.2800 1417	2250 1.2800 1753
	200	527 1.0200 538	712 1.1000 726	1075 1.1600 1088	922 1.0200 923	1340 1.0900 1341	2012 1.1600 2013	1109 1.0200 625	1349 1.1000 868	1766 1.1600 1286	1606 1.0200 1107	2117 1.1000 1616	2905 1.1000 2408
$0.5L$	25	528 1.0000 541	737 1.0200 752	1360 1.0600 1376	928 1.0000 929	1423 1.0200 1426	2691 1.0600 2691	1112 1.0000 630	1390 1.0200 914	2091 1.0700 1612	1614 1.0000 1115	2231 1.0200 1734	3634 1.0200 3135
	50	449 2.5400 457	454 2.6100 462	456 2.6400 466	697 2.5400 697	709 2.6100 709	714 2.6400 716	984 2.5400 496	991 2.6100 502	994 2.6400 508	1297 2.5400 798	1314 2.6100 815	1322 2.6100 823
	100	481 1.5800 491	502 1.7000 512	514 1.7500 524	788 1.5800 788	836 1.6900 836	861 1.7400 865	1035 1.5800 547	1065 1.7000 578	1082 1.7500 592	1422 1.5800 923	1488 1.6900 989	1521 1.6900 1026
	200	510 1.1600 521	576 1.2900 586	622 1.3500 633	871 1.1600 872	1012 1.2900 1011	1103 1.3500 1102	1081 1.1600 597	1171 1.2800 687	1232 1.3400 752	1535 1.1600 1036	1721 1.2900 1219	1840 1.2900 1339
L	25	525 1.0200 538	662 1.1000 676	804 1.1600 818	919 1.0200 919	1220 1.1000 1221	1490 1.1600 1489	1106 1.0200 622	1288 1.1000 805	1466 1.1600 985	1599 1.0200 1100	1980 1.1000 1482	2328 1.1000 1837
	50	528 1.0000 541	724 1.0200 739	1072 1.0600 1087	928 1.0000 929	1391 1.0200 1392	2054 1.0700 2052	1112 1.0000 629	1373 1.0200 892	1785 1.0700 1312	1614 1.0000 1115	2183 1.0200 1687	2991 1.0200 2491
	100	422 2.5400 430	422 2.6100 429	422 2.6300 433	623 2.5400 623	623 2.6100 624	623 2.6400 623	942 2.5400 452	942 2.6100 452	942 2.6400 453	1195 2.5400 695	1196 2.6100 698	1196 2.6100 698
	200	446 1.5800 456	447 1.6900 457	448 1.7500 459	704 1.5800 705	708 1.7000 708	710 1.7500 710	985 1.5800 497	987 1.6900 500	987 1.7500 502	1312 1.5800 812	1316 1.7000 814	1319 1.7000 824
$1.5L$	25	483 1.1600 494	494 1.2800 505	499 1.3400 512	810 1.1600 810	839 1.2800 840	851 1.3500 851	1044 1.1600 558	1061 1.2800 574	1068 1.3500 583	1457 1.1600 958	1498 1.2800 1000	1514 1.2800 1014
	50	517 1.0200 529	572 1.1000 585	596 1.1600 608	899 1.0200 899	1033 1.1000 1034	1091 1.1600 1092	1096 1.0200 612	1175 1.1000 692	1211 1.1600 728	1577 1.0200 1078	1756 1.1000 1256	1834 1.1000 1331
	100	528 1.0000 541	670 1.0200 686	768 1.0700 784	928 1.0000 928	1266 1.0200 1266	1487 1.0600 1487	1112 1.0000 628	1309 1.0200 828	1441 1.0600 964	1613 1.0000 1114	2055 1.0200 1556	2340 1.0200 1841
	200	422 2.5400 430	422 2.6100 429	422 2.6400 431	623 2.5400 623	623 2.6100 624	623 2.6500 622	942 2.5400 452	942 2.6100 453	942 2.6400 455	1195 2.5400 696	1196 2.6000 699	1196 2.6000 699

In each cel the top, the middle and the bottom elements denote the reorder point calculated by the method described in Janssen et al. (1995), the associated delivery frequency and the average stock position, respectively.