The Need and Determination of Safety Stocks in a Deterministic Universe due to Lot-Sizing Problems in a Supply chain Dedicated to Customized Mass Production

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Introduction

This article demonstrates the need of a new kind of safety stock and gives the method to calculate its level. We study an elementary supply chain consisting of a production unit (the customer) configured as an assembly line that allows mass production of various products (e.g., an automotive production line) and another unit (the supplier) that produces alternate components (e.g., car engines) or optional components (e.g., sunroofs) assembled on a work station of this line and contributing to the required diversity (Anderson & Pine, 1997). In the context of our study, optional components are a particular type of alternate components.

For several weeks, the customer daily production \( n \) is predetermined by the opening duration of the line (stable on this horizon) and the line’s cycle time. The total daily demand of alternate components to order from the supplier is thus known. From there systematically follows a time-gap between orders and deliveries. This mechanism, commonly called rank-change, may be analyzed with the help of the multinomial distribution associated with these alternate components. Only a simulation approach is relevant because an analytic approach is not possible. Such an analysis allows assessing the importance of the need to form safety stocks because of lot-sizing, even though requirements are known.
sequenced according to the revolving planning logic. The ordered list of all alternate components to mount determines the order of demand of these components. For the purpose of our study, it is assumed that the requirements are daily. They are designed to fulfill the sequenced demand of alternate components. In our case, the lead-time $\lambda$ is shorter than $K$ so as to stay in a context in which the sequence of the alternate components to mount is known when the daily orders are sent.

In this context, the requirements that are submitted must be considered as firm. We will assume that their delivery was guaranteed. The impact of batch constraints on the supply chain control does not seem to be evoked in the literature. The lot-sizing influence on capacity due to scheduling is well known. The capacity is reduced by the set-up time of a reference, possibly depending on the sequence of references to produce (White & Wilson, 1977). The optimal sizes for the batches result from the minimization of a cost function that includes possession and set-up costs. The determination of the size of the batches to produce can be constrained by conditioning or by the limited storage near a workstation that mounts alternate components. Conditioning also plays a role in certain issues regarding transportation: it influences the transportation means capacity, but not the orders assessment to submit to the supplier. Therefore we will broach the effect of lot-sizing constraints on the management of the various logistical flows, assuming that deliveries match with the orders and were made on time.

This problem will be analyzed in the context of a supply of alternate components to an assembly line but the same problem occurs when the production schedule of an assembly line is constrained by the fact that a workstation assembling alternate components is supplied by sequence of pallets each pallet containing the same component. The lead-time $\lambda$ is shorter than $K$ so as to stay in a context in which the sequence of alternate components to mount is known when the daily orders are sent. The impact of batch constraints on the supply chain control does not seem to be evoked in the literature. The lot-sizing influence on capacity due to scheduling is well known. The capacity is reduced by the set-up time of a reference, possibly depending on the sequence of references to produce (White & Wilson, 1977). The optimal sizes for the batches result from the minimization of a cost function that includes possession and set-up costs. The determination of the size of the batches to produce can be constrained by conditioning or by the limited storage near a workstation that mounts alternate components. Conditioning also plays a role in certain issues regarding transportation: it influences the transportation means capacity, but not the orders assessment to submit to the supplier. Therefore we will broach the effect of lot-sizing constraints on the management of the various logistical flows, assuming that deliveries match with the orders and were made on time.

The demand of alternate components to mount at a workstation on the assembly line is expressed by the ordered list $S_i$, periodically updated. The customer orders $M$ engines every $\theta$ days and receives, with the same periodicity, a shipment of $M$ engines, ordered $\lambda$ days before ($\lambda$ being the supplier’s lead time). It is assumed that deliveries are completed on time and perfectly match the demand. Lot-sizing has two consequences:

- At the arrival of each delivery one must perform a reconstruction of the sequence of delivered references by lots of $m$ identical products, which leads to a delivery of $y = M/m$ batches.

- The batch of $M$ delivered components has practically no chance to coincide with the batch that will be assembled; the number of missing components corresponds to the number of surplus components.

The existence of a rank-change mechanism is known in the case of the handling of a quality issue on a vehicle production line, taking effect through the removal of the vehicles to reprocess for a variable time before their reinsertion on the line (Giard, Danjou, & Boctor, 2001a, 2001b; Giard, 2003). They

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**Figure 1**

**Origin of Rank-Changes**

<table>
<thead>
<tr>
<th>Demand</th>
<th>Sequence $S_i$ of alternate components $i$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lot-sizing linked to constraints of delivery or production</td>
</tr>
<tr>
<td></td>
<td>Sequence $S_j$ of batches of alternate components $i$</td>
</tr>
<tr>
<td></td>
<td>$r_{fi}$ rank of component $i$ in sequence $S_i$</td>
</tr>
<tr>
<td></td>
<td>Rank-change of the component $i$ $\delta = r_{2i} - r_{1i}$</td>
</tr>
<tr>
<td></td>
<td>$r_{2i}$ rank of component $i$ in sequence $S_2$</td>
</tr>
</tbody>
</table>
Table 1
Distribution of the Probability by Product

<table>
<thead>
<tr>
<th>Product</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
<th>$P_8$</th>
<th>$P_9$</th>
<th>$P_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>1.7%</td>
<td>6.1%</td>
<td>2.2%</td>
<td>0.9%</td>
<td>0.9%</td>
<td>31.3%</td>
<td>13.9%</td>
<td>1.3%</td>
<td>0.9%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$p_2$</td>
<td>0.4%</td>
<td>0.9%</td>
<td>3%</td>
<td>6.5%</td>
<td>6.1%</td>
<td>3.5%</td>
<td>6.1%</td>
<td>11.3%</td>
<td>2.6%</td>
<td></td>
</tr>
</tbody>
</table>

To define the sequence $S_l$, we need to start from sequence $S_i$ and take into account the evolution of the projected stock level affected by the following demands of $S_l$. If the consideration of the demand of rank $i$ into sequence $S_l$ leads to a negative stock level, we need to avoid a stock-out with a batch delivery of the concerned reference. Two main methods can be adopted:

- Deciding to launch a batch of $m$ components when their projected stock level equals $-m$.
- Deciding to launch a batch of $m$ components as soon as their projected stock level becomes negative (then amounting $m-1$).

Following the first method, restricted to firm demands and with a focus on product $i$ that was not yet launched and whose projected stock level just turned negative, the probability that a batch of $m$ units of the same completed demands of $i$ is removed by the variable $n$. This probability can be significant and lead to a stock-out. For instance, the risk that a batch of six products, with a probability of demand $p = 0.9$% and $1000$ unaddressed requirements, should not be completed amounts to $11.3%$. In a context in which a stock-out is hardly acceptable because of high-line stoppage cost, the second lot-sizing method is necessarily privileged. Now that the concept of rank-change is defined, we shall study its function.

**Study of the rank-change function**

To understand the following results, we shall base our approach on the probability of the rank-change of a product, with a variable $\delta$ corresponding to the number of ranks that a product won or lost at delivery compared to its consumption. There is no analytic way to determine the distribution of the rank-change probability. Only an approach by simulation, using the Monte Carlo method, allows drawing relevant conclusions.

The study of a rank-change function was conducted on the basis of a vehicle assembly line on which a workstation mounts the engine selected by the final customer, who can choose among 19 engines ($P_i$) (alternate components). The engines are produced in another plant in which there is no set-up time between references on the production line. The engines are then shipped to assembling plants in packages of six identical engines. Let us assume that the distribution of production is a random source of rank-changes, and the average $\bar{\delta}$ of the rank-changes for each product.

According to Figure 1, a negative value for rank-change $\delta$ means that the recently arrived product is advanced regarding its positioning in the initial demand; in the example, product 10 is systematically in advance. A positive value means that the product arrived with delay compared to its initial positioning, as product 6 illustrates. The weighted sum of average rank-changes by probability of use $P_i$ is null.

The rank-change curves of the products are not identical: the

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mathematical expectation of the rank-change of products varies in the same way as their probability of use (Figure 2), whereas the standard deviations of product rank-change vary in an inverse order of their use probability (Figure 3). Therefore, those products in low demand are delivered somewhat ahead of schedule, whereas the delivery of products in high demand is quite delayed.

The rank-change function of a product $i$ depends on both the number $I$ of products ($I > 1,...,I$) and on the distribution of probabilities $p_i$. Figure 4 details the occurrences of rank-change for a product with low demand, and Figure 5 shows a product with the highest demand; each is outlined with different scales. In the case of a product with low demand, the rank-change is essentially negative, with widely spread negative values (up until 1,000 won ranks, even 2,000 at certain points) and a very heterogeneous occurrence of values: when there is a peak for a small amount of lost ranks, then the occurrence of rank-changes decreases as the number of won ranks increases. In the case of a product with high demand, rank-changes are positive, but the number of lost ranks remains quite low (approximately no more than 75). The occurrence of rank-changes is symmetrical to an approximate value of 40 lost ranks, with no high difference between the occurrences.

Lot-sizing creates rank-changes, which in turn can create stock-outs. The customer must thus form safety stocks (at the vehicle assembling plant) to avoid lot-sizing on supply.

**Need of a Safety Stock to Counter the Side Effects of Rank-Changes Induced by Lot-Sizing**

We shall first explain the need of a safety stock to face the lot-sizing in table 2.

Table 2

<table>
<thead>
<tr>
<th>Product</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
<th>$P_8$</th>
<th>$P_9$</th>
<th>$P_{10}$</th>
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</thead>
<tbody>
<tr>
<td>$p_i$</td>
<td>0.7%</td>
<td>6.1%</td>
<td>2.2%</td>
<td>0.9%</td>
<td>0.9%</td>
<td>31.3%</td>
<td>13.9%</td>
<td>1.3%</td>
<td>0.9%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$p_i$</td>
<td>134</td>
<td>36.8</td>
<td>103</td>
<td>257</td>
<td>258</td>
<td>9.13</td>
<td>16.75</td>
<td>178.1</td>
<td>259</td>
<td>585.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product</th>
<th>$P_{11}$</th>
<th>$P_{12}$</th>
<th>$P_{13}$</th>
<th>$P_{14}$</th>
<th>$P_{15}$</th>
<th>$P_{16}$</th>
<th>$P_{17}$</th>
<th>$P_{18}$</th>
<th>$P_{19}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_i$</td>
<td>0.4%</td>
<td>0.9%</td>
<td>3%</td>
<td>6.5%</td>
<td>6.1%</td>
<td>3.5%</td>
<td>6.1%</td>
<td>11.3%</td>
<td>2.6%</td>
</tr>
<tr>
<td></td>
<td>-586</td>
<td>-229</td>
<td>-36.5</td>
<td>8.95</td>
<td>7.52</td>
<td>-24.64</td>
<td>6.40</td>
<td>25.20</td>
<td>-48.2</td>
</tr>
<tr>
<td>$p_i$</td>
<td>588</td>
<td>256</td>
<td>76.3</td>
<td>34.6</td>
<td>36.1</td>
<td>65.44</td>
<td>36.80</td>
<td>20.18</td>
<td>87.62</td>
</tr>
</tbody>
</table>

Figure 2

Evolution of the mathematical expectation of rank-change of products according to their probabilities $p_i$.

Figure 3

Evolution of the standard variation of rank-change of products according to their probabilities $p_i$.
Every simulation was performed on a demand of 6 billion products in order to empirically obtain safety stocks $SS_i$ with an insignificant stock-out probability. At the beginning of the simulation, the amount of available products was set to a value $W$. The first delivery is made immediately before the first product is taken. This first delivery corresponds to the $\theta$ first products of sequence $S_i$ and the first withdrawn product corresponds to the first product of sequence $S_i$. Each safety stock level is calculated as the difference between $W$ and the lowest inventory level during the simulation because $W$ must be high enough to avoid an empty stock.

In a deterministic universe, safety stocks depend on the rank-changes and on the lead time $\theta$. The rank-changes depend in turn on the range $I$ of products and on their probabilities $p_i$. We will evaluate the safety stock level by a simulatory approach of the steady state. We shall study the impact of various factors on the safety stock in a context of a lot-sizing caused by transportation constraints. First of all, we shall analyze the impact of probabilities on the safety stock. On the basis of the data in Table 1, we obtain by those simulations the following safety stock amounts (Table 3).

The safety stock of products varies in the same way as their probabilities (Figure 6), which was not obvious a priori. In this industrial example, an approximately linear relation can be noticed ($\rho^2 = 0.983 ; SS = 0.95889 p + 3.008$). Afterward, we shall study the impact of the dispersal of probabilities on the safety stock level, this time on average. The various products can have equal probabilities: this is a case of equal probabilities of demand. They can also be extremely different; all situations are possible. We thus proceeded to new simulations, replacing the observed probabilities by distribution $p_i = p_i x_k - 1 + b$ with a constraint of $\sum_i p_i = 1$. We shall outline various

It is important to accurately gauge so that every rank-change does not systematically create an interruption of supply and, consequently, the creation of a safety stock: the supplier’s deliveries concern $\gamma$ delivered batches with a lead time $\theta$. Thus it is not sequence $S_i$ that determines interruptions of supply but the constitution of a group of delivered products, while changes in this group are still possible without bearing any consequence.

In this type of case, it is not possible to obtain analytical results from the rank-change function of a reference on the basis of the multinomial distribution. Only a simulation can be performed. This procedure allows highlighting tendencies of the impact of certain factors, as every set of hypothesis is likely to modify the relative impact of the considered factors.

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possible curves, descending and of exponential nature. We state that $b = 0.005$; it is a limit corresponding to the lowest probability for a product. $k$ is the factor for controlled decrease. The closer it is to $1$, the more equal probabilities of component demands are. Figure 7 illustrates the distribution of these probabilities.

The following factor of variation corresponds to the supply periodicity $\theta$. We proceeded to an analysis of its impact by repeating the same simulation with different values for $\theta$. This analysis was performed using three structures of demand, with $5$, $10$, and $19$ possible products, plus an equal probability of demand between those products (yielding the worst case for safety stock). We note that when the lead time increases, the average safety stock decreases in a fairly constant way (Figure 9).

The use of three different structures of demand allows highlighting two phenomenons. The first impression, on which we will further elaborate, is that when the variety of products increases, the average safety stock decreases, which seems logical because when the variety is lower, lot-sizing induces rank-changes of necessarily lesser importance. The second impression is that of a similarity between the variation profiles of the safety stock compared to the lead time for various values of $I$: the series of points for what various values of $I$ really look alike.

We proceed to a more in-depth analysis of the impact of variety $I$ on the average safety stock for equal distributions, as illustrated in Figure 10. The more products, the greater the average safety stock needs to be in order to counter rank-change side effects. However, this increase is not proportional to the increase of variety: the increase is strong for values of $I$ under 8 included, then slightly less pronounced for $I$ between 8 and 12, and the average safety stock closing in to an asymptote for $I$ greater than 12. This means that an increase of the variety of products has a strong impact on the average safety stock for $I \leq 12$ in our example, but beyond those values $I$, adding one or several alternate components bears no consequence on the average safety stock lever (if properly calculated).

Looking more closely at the distribution of demand in our industrial case, we notice that four products have very few orders: engines 10 and 11 have a probability of 0.4% and engines 9 and 12 of 0.9%. There are neither delay nor set-up costs related to a reference change on the production
Removing these four products makes no change on the average safety stock: it is the same whether 15 or 19 references are produced. Thus removing the offer of these four products is not advantageous to either the customer (average safety stock does not decrease) or the supplier (no reference change cost).

Safety stocks are also created to counter other hazards: quality problems in a production context, variation of transportation time, or modification of the firm sequence of requirements. These are explicitly excluded from the analysis, but it is obvious that the integration of a combination of disruptions leads to a mutualization of risks. The safety stock required to face multiple disruptions is thus less than the sum of all required safety stocks if the disruptions are considered separately.

We illustrate the impact of a combination of disruptions on the safety stock with an example of rank-changes caused by lot-sizing issues at production. The analysis of this type of lot-sizing is similar to that of delivery constraints. The submitted information concerns batches between the selected unit (engine manufacturing plant) and its provider. Several technical constraints, such as limited space at the line side of a station handling big components, can lead to production scheduling in a sequence of successive batches. The difference with the previous situation (procurement) is that these batches may not concern the same product, but products sharing a common specification, such as containing the same component (in our case, the same crankcase used by several different engines).

This lot-sizing is slightly more complex. On the one hand, it implies submitting information about batches of components to deliver to the supplier. On the other hand, it leads to the creation of a second lot-sizing of the production of the designated unit, which is not homogeneous because the batch
thus created contains various products. Table 4 gives an illustration of this. We simulate the impact on the safety stock of a separate then simultaneous integration of the following:
- the rank-change related to production constraints: lot-sizing of the engines by batches of 24 identical crankcases
- quality issues: percentage of rejection after production amounting to 2% Once again, the safety stock is held by the customer (engine manufacturing plant) who has to own a safety stock of engines. The simultaneous integration of both disruptions allows decreasing the safety stock required to avoid stock-out by.

**Managerial Implications**

The supply chain is subjected to multiple risks. To avoid stock shortages, factories constitute safety stocks of the components to be assembled. When the factory can assemble on order and its supplier can produce on order, synchronous production is possible. When the differentiation of the components is made in the supplier’s plant, it is often necessary to adapt the containers to the shapes of the products to be delivered. Batch constraints due to an efficiency search of transportation then enforce to constitute safety stocks even if the problem is in a deterministic universe. Most of the time, the need and importance of these stocks are not perceived because they were created to face various risks. From a managerial point of view, the existence of this kind of stock related to batching considerations is important to understand as it involves limits to stocks reduction. In addition, it poses the problem of the localization of the differentiation: if made at the supplier plant, it may multiply the types of containers and increase the transportation costs; made at the customer plant, the transportation cost may be reduced, due to standardization of containers, but the differentiation cost may be higher at the customer plant than at the supplier’s one (due to time cycle constraints). A new trade-off has to be considered in the supply chain.

**Conclusion**

We have studied synchronization and decoupling of the control of the last two links of a supply chain dedicated to a customized mass production. Taking into account lot-sizing in a deterministic universe entails the creation of safety stocks. The explanatory factors of their importance were analyzed.

<table>
<thead>
<tr>
<th>Product</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
<th>$P_8$</th>
<th>$P_9$</th>
<th>$P_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>1.7%</td>
<td>6.1%</td>
<td>2.2%</td>
<td>0.9%</td>
<td>0.9%</td>
<td>11.4%</td>
<td>0.9%</td>
<td>0.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
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<td>6</td>
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<table>
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<th>Product</th>
<th>$P_{11}$</th>
<th>$P_{12}$</th>
<th>$P_{13}$</th>
<th>$P_{14}$</th>
<th>$P_{15}$</th>
<th>$P_{16}$</th>
<th>$P_{17}$</th>
<th>$P_{18}$</th>
<th>$P_{19}$</th>
<th>Total</th>
</tr>
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<td>0.9%</td>
<td>3%</td>
<td>6.5%</td>
<td>6.1%</td>
<td>3.5%</td>
<td>6.1%</td>
<td>11.3%</td>
<td>2.6%</td>
<td>100%</td>
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<td>6</td>
<td>12</td>
<td>6</td>
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<td></td>
</tr>
</tbody>
</table>

*Figure 10*

Average safety stock $\overline{SS}$ depending on variety $I$
References


