A LOGISTICS FRAMEWORK FOR COORDINATING SUPPLY CHAINS ON UNSTABLE MARKETS

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In this paper we discuss the difficulties of customized mass production in case of high manufacturing setup costs and unstable markets, where due to high service level requirements and demand volatility the risk of remaining obsolete inventory is significant. We propose a two-level logistics framework for coordinating supply channels in such production networks and methods for medium-term lot sizing decisions considering uncertainty.

1. INTRODUCTION

Growing customer expectations and *mass customization* induce large complexity and uncertainty in the consumer markets. Such markets are typically served by *supply networks* where demand is met by a focal manufacturer who operates in a network, together with suppliers of components, sub-assemblies and packaging materials. The common goal of each network partner is to provide high service level towards the customers of end-products, while, at the same time, keeping production and logistics costs as low as possible. However, these requirements are conflicting: high service level can only be guaranteed by *inventories* (of components, packaging materials, end-products). Furthermore, in mass production technology lower costs can be achieved with larger lot sizes, which involve, again, higher product and component inventories as well as increased work-in-process. On the other hand, markets of customized mass products are volatile. If the demand unexpectedly ceases for a product, then accumulated inventories become *obsolete* and cause significant losses. Most difficult is the situation with non-standardizable components (e.g., packaging materials of customized products): due to an unexpected change or cancellation of demand the product may *run out*, leaving obsolete inventories behind.

We are interested in *coordinating* production of supply networks. The particular motivation of this work comes from a large-scale national industry-academy R&D project aimed at realizing real-time, cooperative enterprises. The actual network has to meet ever-changing, hardly predictable, complex demand on a market of customized mass products. A further challenge is that all network partners are *autonomous*, and those in the supplier's role take typically part in other network relations as well.

For solving the network coordination problem, we suggest a generic *logistics framework* that links the planning and control functions of the manufacturer and its suppliers. The aim of this framework is to facilitate the exchange of information that is essential to minimize overall costs in the chain while guaranteeing high service level. In particular, it provides channels for exchanging, matching and adjusting both medium- and short-term demand of the manufacturer and corresponding production and delivery plans of the suppliers.

An integral part of supply chain management is to decide whether and how much to produce from particular products and components at a given moment. This is essentially a *lot sizing problem* (LSP) that is well studied in the literature. The most widespread standard models are the Economic Order Quantity (EOQ) and the Wagner-Whitin methods. However, while these models are easy to solve, realistic variants of LSPs are usually NP-hard problems (Brahimi, 2006). Stochastic inventory policies can handle *uncertainty* in case of demand volatility (such as the (*s,S*) policy) and one-period uncertain demand (*newsvendor* model) (Hopp, 1996), but the unforeseeable termination of the demand is still missing. Recently, there was also proposed a distinction between the two types of uncertainty (Grabot, 2005). However, in this model uncertainties are attached to orders and not to product. Furthermore, for handling uncertainties, a fuzzy logic approach is taken.

According to our experience, the run-out of products is an exogenous property of the market that must be taken into account when making supply decisions. In our previous work, we have identified two types of demand uncertainty: (1) quantity fluctuation and (2) the run-out (Váncza, 2006). While the former one can be handled with traditional approaches (safety stocks, time fences, rolling horizon planning), the latter should be included in the lot sizing model. Hence, after presenting outlines of a coordination platform, we give novel methods for lot sizing that concern all main cost factors, including the cost of expected obsolete inventories. Furthermore, we also present results of comparative simulation experiments run on historic data sets.

2. COORDINATION FRAMEWORK

Planning tasks of enterprises are usually categorized according to their horizons into three levels: long term, medium term and short term (Fleischmann, 2003). Consequently, a supply coordination model should cover all of these levels. The purchasing of raw materials can be planned relatively easily in the long term exploiting economies of scale, forasmuch the bulk of them are standard materials and the demand of the end products can be aggregated. In the framework proposed below we do not tackle this issue. The production-related decisions (plans, lot sizes) have to be made in medium term aligning the conflicting aims of flexibility and economic efficiency. In short term, the challenge is to organize smooth operation of the network, i.e., production as planned should not stop anywhere due to material shortage.

Following the above requirements, we propose a *logistics framework* for coordinating the manufacturer's and the supplier's decisions along a supply channel. The aim of this framework is (1) to minimize overall costs including setup, inventory holding and expected obsolete inventory costs, while (2) providing extremely high

(98-99%) service level towards the customers. The key idea is to establish a *one-point inventory system* between companies, whose management needs coordination, truthful information sharing, and optimization. The logistics framework consists of two levels:

1. On the *scheduling platform*, the supplier meets the exact, short-term component demand of the manufacturer. This demand is generated from the actual production schedule of the manufacturer in form of *call-off*s and is satisfied by direct, just-in-time delivery from the inventory. On this platform, decisions are made on a daily basis, with a short term (1-2 weeks long) horizon. With this short look-ahead, demand uncertainty is hedged by appropriate safety stocks.

2. On the *planning platform*, the supplier builds up and maintains the one-point inventory. So as to be able to do that, the supplier receives information from the manufacturer concerning demand forecasts and the chances of product run-outs. The component demand is generated from the *master production plan* of the manufacturer that determines its planned output for a longer horizon. On this platform, decisions are made in a weekly cycle.

Note that this framework detaches the two main, conflicting objectives and makes both of them manageable: while service level is tackled at the scheduling platform, cost-efficient production is the main concern at the medium-term planning platform.

3. LOT SIZING CONSIDERING RUN-OUT

This chapter presents a portfolio of methods that are aimed to facilitate optimal *planning level* decisions in the above framework. These decisions are basically lot sizing decisions, to be made by the supplier who is responsible for maintaining the one-point inventory. The models consider single components, discrete, finite (medium-term), rolling horizon component forecast and no inventory limits. We also assume infinite production capacities at the supplier's side, and that lead-time of components (manufacturing plus shipment) fits into one planning time unit.

The *component forecast*, which is derived from the manufacturer's medium-term master production plan, is the basic input for supplier's lot sizing problem. This plan is uncertain, but does not provide valid statistical information (such as standard deviation). Hence, the uncertainty of component forecast is captured by the *probability of run-out*. Since the models consider only one product, there are no "speculative motives": it is always preferable to produce at a later period than producing earlier and holding stock.

3.1 Wagner-Whitin with run-out (WWr)

The standard, widely applied Wagner-Whitin inventory handling method uses a dynamic programming approach to minimize the total cost in the given horizon and to determine the times of the necessary setups (Wagner, 1958; Hopp, 1996). Here, we introduce the probability of run-out to this standard model. Since this model is discrete, we assume the *Wagner-Whitin property*, which can be derived from the lack of speculative motives: for every time unit of the horizon either the production is zero or the expected inventory carried to the next time unit is zero. Our model differs from the standard one in several ways: (1) we consider the probability of run-out and the cost of obsolete inventory, (2) we include one time unit for lead-time and (3) we consider linearly decreasing inventory within a time unit. The parameters and variables of the model are the following:

Table 1 – Notation

n	length of the horizon
F_i	forecast for time unit i
h	inventory holding cost per piece per time unit
c_s	setup cost
c_p	production cost per piece
p	probability of run-out in an arbitrary time unit

Let's suppose that we produce in time unit $t \in \{0,K,n\text{-}1\}$ for the time units $\{t+1,K,t+j\}$ for some $j \in \{1,K,n\text{-}t\}$. This implies two things: (1) the expected inventory at the beginning of time unit $t+1$ is zero (from the Wagner-Whitin property) and (2) the product has not run out until the beginning of the time unit t (which has a probability $(1-p)^t$). Fig. 1 presents this situation.

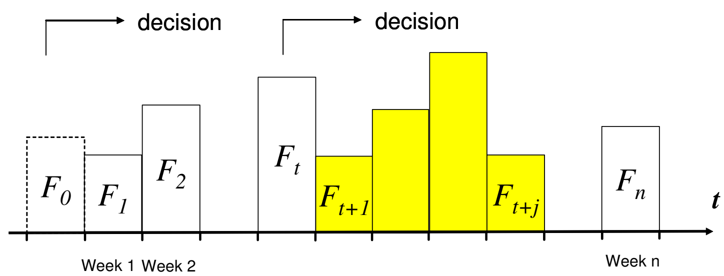

Figure 1 – Planning horizon

Then for every $i \in \{1,K,j\}$ the expected storage cost in time unit $t+i$ is $SC(t,j,i) = (1-p)^i h\left(\sum_{k=i+1}^{j} F_{t+k} + \frac{F_{t+i}}{2}\right)$, where $(1-p)^i$ expresses the probability that the product is still saleable in the time unit i .The cost of obsolete inventory can be determined similarly: $OC(t,j,i) = p(1-p)^{i-1}\sum_{k=i}^{j} F_{t+k}$, where $p(1-p)^{i-1}$ is the probability of running out the product in time unit i . To measure the loss in case of a run-out, the production cost of the obsolete inventory should be included into the total cost—it may represent both material and labor costs, and could be reduced with salvage value, etc. By summing up storage, obsolete inventory and setup costs, we get the total cost for time units $\{t+1,\ldots,t+j\}$: $C_{tj} = c_s + \sum_{i=1}^{j}(SC(t,j,i) + OC(t,j,i))$. Then we can compute for every $t \in \{0,\ldots,n-1\}$ the optimal total cost TC_t in the $\{t+1,\ldots,n\}$ horizon by the following recursion: $TC_t = \min_{j\in\{1,\ldots,n-t\}}\left\{C_{tj} + (1-p)^j TC_{t+j}\right\}$ and $TC_n := 0$. The optimal total cost for the whole horizon will be TC_0. Furthermore, if we note down the optimal j values, we can easily compute both the optimal lot size at the actual time unit and the expected number of setups on the horizon.

3.2 Heuristic approaches

Earlier, we have presented two different heuristics for the lot sizing problem (Váncza, 2006). Both of them compute only the first lot size and disregard the less trusted remote forecasts that used to fluctuate intensely. One of the heuristics minimizes the cost average by the quantity; the other minimizes the cost average by the expected consumption period. This latter one resembles the so-called Silver-Meal heuristic (Silver, 1973). We now recall these methods and analyze their behavior in a nutshell.

The parameters are the same as in the Wagner-Whitin case (see Table 1), but the decision variable x is the length of the expected consumption period which can be any real number between 1 and n. We use some further notations: $S_k := \sum_{l=1}^{k} F_l$ is the accumulated forecast of the first k time units, $i := \lfloor x \rfloor + 1$ and $y := \{x\}$ (the integer part of x plus one and the fractional part of x, respectively). The lot size can be calculated as the forecasted quantity until x: $q(x) := S_{i-1} + yF_i$ (the total amount of the first $(i-1)$ time units and the y fraction of the forecast of time unit i).

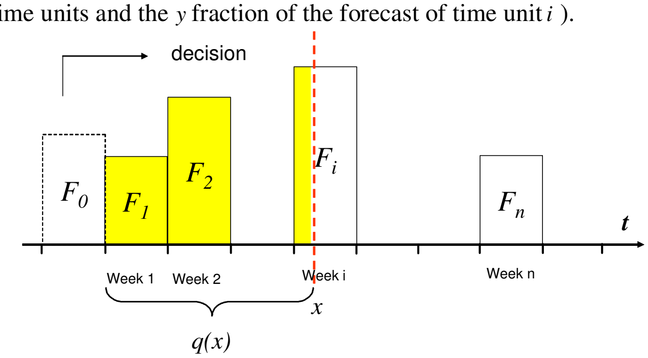

Figure 2 – Average cost minimization

If there were no run-out, then the storage cost in the first l $(l < i)$ time units would be $SC(l,x) = h\sum_{k=1}^{l}\left(q(x) - S_{k-1} - \frac{F_k}{2}\right)$. With run-out, the expected storage cost will be the following:

$$SC(x)=\sum_{k=1}^{i}\left(p(1-p)^{k-1}SC(k-1,x)\right)+(1-p)^{i}\left(SC(i-1,x)+h\frac{y^2F_i}{2}\right)$$

and the expected cost of obsolete inventory is:

$$OC(x)=c_p\sum_{k=1}^{i-1}\left(p(1-p)^{k-1}\left(q(x)-S_{k-1}\right)\right)+c_p\,p(1-p)^{i-1}\,yF_i\,.$$

Thus we obtain piecewise continuously differentiable average cost functions $AC_x(x)=\left(c_s+SC(x)+OC(x)\right)/x$ and $AC_q(x)=\left(c_s+SC(x)+OC(x)\right)/q(x)$ which can be minimized by searching through the roots of their derivative and the borders of the intervals.

3.3 Choosing the appropriate method and parameter

There are two fundamentally different situations: (1) run-out can occur with a certain possibility, but no further details are known and (2) the fact of the run-out and its date are known, but the demand forecast is uncertain. In the first case—which is the usual situation—one can use both WWr and the AC heuristics with an appropriate p value. In case of the known date of run-out, we distinguish whether the date is *near* or *far*. We regard the date near, if the previous methods (especially WWr) suggest that all forecasted quantities have to be produced immediately in one lot. If the date is far, then the previous methods can be used henceforward. Additionally, the formulas can be used with different probabilities in various time units.

However, if the date is near, then finding the appropriate lot size is much more subtle: over-planning leads to obsolete inventory, while under-planning may lead to costly additional setups. In this case, the horizon can be considered one period long; hence we propose a variant of the standard *newsvendor* model (Hopp, 1996) which minimizes the expected total cost in one period with uncertain demand. Naturally, this requires more/different information than the other situations.

While forecasts and most of the parameters are easily accessible in existing enterprise data warehouses, the probabilities of run-out are hard to estimate in general. Fortunately, in typical real-life production plans—where planned manufacturing of a product is sparse and involves large volumes—quantity is almost everywhere zero and the formulas are not too sensitive to the uncertainty. To measure this sensitivity, we propose that an interval around p should be examined instead of only a single value. Any of the methods can compute how changes in p influence the optimal lot size in the specific situation, thus we can get a measure for the *robustness* of the result. The less robust the proposed lot size, the more care is needed from the human experts who reconsider the results.

4. EXPERIENCES WITH INDUSTRIAL DATA

The above methods have been tested together with the industrial partners. The focal manufacturer—who is still responsible for the inventories—has provided the actual data weekly: component forecasts on 9 months long horizon with one week's time unit, inventory levels, production costs, approximated setup and inventory holding costs. We have computed the proposed lot sizes with respect to probability of run-out in the interval $[0, 0.15]$—which took only a few seconds—and discussed the result with the experts of the factory. All the three methods were similar in that with relatively small p values (around 0.05) they have given nearly the same lot sizes calculated by the rules of thumb of the experts. In the other cases, either the forecasts were incomplete, or the experts had some extra knowledge about the demand of the specific product. An interesting further research direction would be to automatically filter out these extreme situations.

Another conclusion is that the result of WWr is more useful, since it can also tell the expected number of the setups on the horizon, which is important practical information. Furthermore, in some cases the heuristics have proposed too large quantities, since they have disregarded the efficiency on the whole horizon.

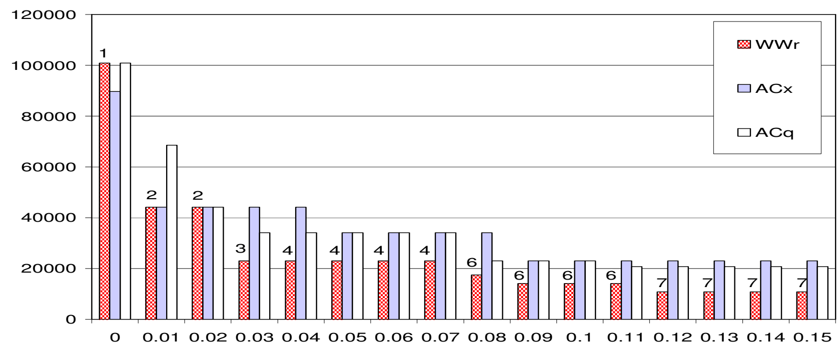

Figure 3 – Lot sizes in function of probability of run-out

An illustrative example of the results can be seen on Fig. 3. The x axis represents the probabilities of run-out, while the y axis indicates the proposed lot sizes according to the different methods. In case of WWr, expected numbers of setups are indicated, too. Note that changing p can cause changes in the lot size, in the number of setups, in both or in neither. In this specific case, the human experts have proposed a lot of 40000 pieces, which was close to our results using $p = 0.02$.

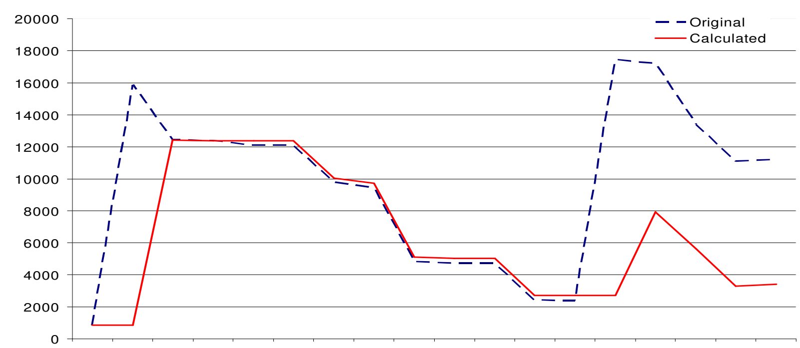

Figure 4 – Original and calculated inventory levels

We have also simulated the methods with historic data sets on a five months long horizon. The goal of these "what-if" experiments was to explore the long-term effect of the novel lot sizing methods, and to compare the hypothetical and the historic inventory levels. When calculating lot sizes, we used 1% run-out probability and a predefined amount of safety stock. Fig. 4 shows a characteristic example comparing the original inventory levels with the simulation of a heuristic method. According to the simulations, calculated hypothetic curves never run under zero—i.e., the novel methods did not cause material shortage.

Due to the promising results, the focal manufacturer has just started to test a pilot software, which also contains the implementation of WWr. In addition, to better analyze the effects of the novel methods and to validate the complete logistics framework, we have defined a multi-agent organizational model of the network (Egri, 2005) and are going to make extensive simulation experiments over the complete data of the previous year's production and inventory histories.

5. CONCLUSIONS

We have suggested a two-level logistics framework for facilitating coordination between enterprises of a supply network and proposed methods for supporting decisions at the planning level. While the industrial deployment of the framework is underway, we extend our research to multi-item supply channels and finite capacities at the suppliers. Since our model is based on information sharing, assumes truthfulness of the partners. As a future work, we will examine the supply relationships with game theoretical tools and design such coordination mechanisms, which inspire enterprises to cooperate in pursuing mutual benefit.

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