Coordinating Supply Networks in Customized Mass Production – A Contract-Based Approach

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Abstract

In the paper we discuss conflicting performance requirements in customized mass production and suggest a novel cooperative planning method for sharing information and coordinating decisions between a focal manufacturer and its suppliers. The method strives to achieve high service level and minimal expected average costs—including production, inventory and potential obsolete inventory costs. A channel coordination mechanism drives the overall system towards its right behavior even though the partners make planning and scheduling decisions autonomously. We present the mechanism and discuss its properties on simulated test cases taken from an industrial case study.

Keywords:
Production, Co-operative, Planning

1 INTRODUCTION

Customized mass production is aimed at satisfying volatile demand on a market of mass products where demand appears for a complex and ever changing variety of goods, both for small and large quantities, in hardly predictable temporal patterns. Demand must be fulfilled with mass production efficiency, but in very short times: acceptable delivery times are only fractions of the actual throughput times. The products are typically consumer goods like low-tech electronics, mobile phones, electric bulbs, cosmetics, etc. The market is served by competing **supply networks**. Customer demand is anticipated and satisfied directly by a manufacturer of end-products that works in the focal point of the network, while other members supply the manufacturer with necessary components including packaging materials. Members are autonomous entities most of which being engaged also in other network relations.

Though the ultimate goal of production is to satisfy actual customer orders, all partners are forced to apply also make-to-stock strategies so that they can (1) meet demand in time, (2) satisfy some constraints of mass production technology, and (3) exploit economics of scale. It is inevitable to make even customized products on the basis of forecasts and to keep inventories. However, due to the nature of the market, from certain products or components obsolete inventories may remain, which cannot be sold or used any more.

The motivation of this work comes from a large-scale national industrial-academic R&D project aimed at realizing real-time, **cooperative enterprises**. We focus on the problem of how a focal network as a whole can guarantee short delivery time and high service level while keeping its logistics costs as low as possible. It is assumed that each partner does its best when planning and scheduling its internal operations, and takes responsibility for the quality and execution of its plans. For coordinating local logistics and production related decisions, we suggest here a model that facilitates and sustains **cooperation** among network members. The proposed method extends the information access and decision rights as well as the responsibilities of the partners. The flow of information, commodity and currency between the partners is regulated by **contracts**. Our interest is in designing such protocols and decision models that are applicable under realistic conditions and help to find a suitable performance trade-off for all members of a focal supply network.

2 BACKGROUND AND RELATED WORK

There exists a number of **supply chain management** (SCM) systems that provide technology for information storing, retrieval and sharing in a chain or network. However, these systems are transactional: they do not really support coordinated decision making [1,2]. So-called advanced planning systems are already applicable to solve—albeit in a close-to optimal way—production planning and scheduling problems, but with a local scope [3]. Since objectives are conflicting both at the individual partners and the network level, local optimization may even adversely affect the system's performance—a phenomenon know for long as double marginalization [4]. For handling interdependent logistic performance measures, [1] presented two analytic methods that guaranteed process reliability.

Channel coordination is achieved when the manufacturer and its supplier make local decisions so that their joint profit is maximized. Contracts that associate decision rights with appropriate incentives are just for accommodating different and disparate objectives. There is a variety of contracts both in the theory and practice of supply chains that strive to achieve good system performance while keeping the manufacturer-supplier relation flexible [5]. Whereas contracts in the practice are usually too complex for analytical modeling, most theoretical models work in time-invariant, single- or two-period settings [6]. Contracts appeared in SCM also in a different sense: bidding processes using the so-called contract-net protocol (CNP) have been suggested [2,7]. Since CNP in itself does not facilitate to combine results of local planning processes that have some look-ahead, it was applied either for high-level task allocation or for scheduling-type problems in competitive and reactive environments.

In any case, an integral part of coordination is to decide how much to produce from particular components at a given moment, which is essentially a lot-sizing problem. Results in this field provide a wealth of models, but the realistic variants have high computational complexity [8].

3 REQUIREMENTS FOR COOPERATIVE PLANNING

We depart from a focal network of autonomous partners. The network is reconfigured time and again, but we consider the stable periods of its operation when suppliers are contracted for producing particular components. There is no overlap between the channels—hence suppliers are not competitors. They compete at reconfiguration, but this network design problem is out of our present scope. (Note that emergent synthesis of focal networks is suggested by [9], while [10] applies constraint-based optimization for supplier selection and negotiation.) The suppliers may serve several manufacturers acting on different markets. In fact, any firm may fill in both roles in different nets.

The question for all partners can be put simply as how much and when to produce so that they can satisfy demand; neither more, nor less, neither earlier, nor later. Each partner must find its own trade-off between its (1) service level as well as (2) production and logistic costs. A network-wide solution emerges from the interaction of local decisions. The problem is essentially a distributed planning problem: network members would like to exercise control over some future events based on certain and uncertain information (about products, technologies, resource capabilities, sales histories vs. demand, resource and material availability). The partners can cope with uncertainties by information exchange and cooperation. The main requirements towards a cooperative planning mechanism are as follows:

- **Autonomy** of network partners should be respected.
- **Service level** of the overall network should be guaranteed at a predefined, reasonably high value.
- **Channel coordination** should be approached and sustained on the long run. Though, a realistic target is rather minimal total cost than maximal profit.
- **Sharing** of market **risks** ought to be facilitated between the manufacturer and the suppliers.
- **Aggregation** at multiple levels is to be supported.
- **Adequacy** with (quasi-) standard production planning and scheduling information stored in local systems.
- **Rolling horizon** planning is necessary to account for unexpected changes on a regular basis.
- Solution **efficiency** is essential because decisions are made under the pressure of time, interactively.

Channel coordination on a longer horizon requires the sharing of medium-term production plans and risk-related information about future demand. Solution efficiency, on the other hand, calls for **symmetric** information between the manufacturer and the suppliers; otherwise the decisions models would be too complex. Hence, some mutual trust is a prerequisite for meeting the above requirements. In relatively stable focal networks, there is a willingness to share private information.

4 MODEL OF THE COORDINATED CHANNEL

Our channel coordination model is aimed at deciding the amount of components to be produced by a supplier given medium-term demand of the manufacturer. Taking risk neutral partners, the objective is to minimize the average of expected total cost. Service level is handled in the cooperative planning framework (see Sect. 5).

The model considers single component, discrete, finite rolling horizon **component forecast**. Production is uncapacitated, and it is assumed that throughput time of components (manufacturing plus shipment) is no longer than the planning time unit—one week in our case. Due to changes of customer expectations, demand for a product may suddenly cease and this **run-out** results in obsolete inventory. Hence, we have identified two types of demand uncertainty: (1) quantity fluctuation, and (2) unexpected run-out. The loss caused by run-out is measured by the production cost of the obsolete inventory. This cost represents both material and labor expenses and can be reduced with salvage value, etc.

We assume a **one-point inventory** between the manufacturer and the supplier. The manufacturer's immediate requests are represented by **call-offs**. Call-offs are responded by just-in-time delivery from the inventory. Call-offs arrive in the period of planning, so do not affect the lot sizing problem of the supplier.

The component forecast is derived from the manufacturer's medium-term **master plan** (MP) that determines its output. This forecast is uncertain—it changes week by week—but represents the actual best knowledge of the manufacturer. Since forecasts are rooted in the MP, they do not carry valid statistical information, such as standard deviation. Nevertheless, the demand is not deterministic, either. We propose a heuristic policy that minimizes the expected average cost—either by the length of the expected supply period or by the produced quantity.

This version of the model considers only one component, which means that there are no "speculative motives". Hence, it is always preferable to produce at a later period rather than producing earlier and holding stock. Figure 1 shows the basics of the model, whose parameters and variable are the following:

- n length of the horizon,
- F_i forecast for the week 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,
- x length of the forecasted period for which component supply is produced (decision variable).

In absence of speculative motives, at decision time the stock is below a given safety stock level—practically considered zero. Since the throughput time is no longer than the time unit, $x \geq 1$ (because later the supplier will not have time to produce the next week's demand) and $F_1 > 0$ (no speculative motives). We assume that the call-offs (F_0) can be satisfied from the stock. In special cases, one can use different p_i for each time unit.

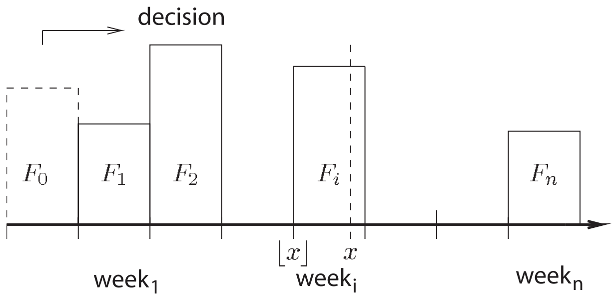

Figure 1: The planning horizon.

$\overline{F_i} := \sum_{k=1}^{i-1} F_k$ expresses the accumulated forecast of the first $i-1$ weeks and $q(x) := \overline{F_i} + yF_i$ is the production quantity, where $i := \lfloor x \rfloor + 1$ and $y := \{x\}$. Hence, the supplier produces all quantities of the first $i-1$ weeks, and the y proportion of the i. week's demand. Figure 2 shows the expected decrease of the inventory level.

If we do not consider run-out, and assume linearly decreasing inventory within a time unit, the expected storage cost in the first l ($l < i$) time unit is:

$$SC(l,x) = h \sum_{k=1}^{l} \left(q(x) - \overline{F_k} - \frac{F_k}{2} \right).$$

Hence, the expected storage cost with run-out is:

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

where $p(1-p)^{k-1}$ expresses the probability that the product runs out on week k, and probability $(1-p)^i$ that it is still saleable on week i. The cost of the obsolete inventory can be determined similarly:

$$OC(x)=c_p \sum_{k=1}^{i-1} p(1-p)^{k-1} \left(q(x)-\overline{F_k} \right) + c_p p(1-p)^{i-1} y F_i \,.$$

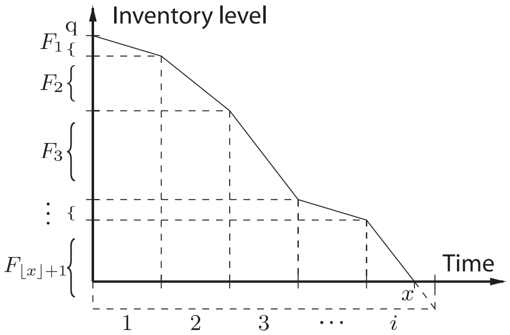

Figure 2: Expected inventory level.

Thus we obtain piecewise continuously differentiable average cost functions $AC_x(x)=\left(c_s+SC(x)+OC(x)\right)/x$ and $AC_q(x)=\left(c_s+SC(x)+OC(x)\right)/q(x)$. Either function can be minimized efficiently by searching through the roots of their derivative and the borders of the intervals. The solution is the optimal quantity that the supplier should produce during the next period. The model is **hybrid**: continuous material flow (x, q) is controlled in discrete time units, by discrete forecasts and actions. This property greatly reduces computational complexity and makes the model practically applicable. It can be extended for more components, where setup cost depends on the actual set of produced components. In this case speculative motives can occur, which leads to a combinatorial optimization problem.

5 COOPERATIVE PLANNING VIA THE CHANNEL

The above channel coordination model gives the core for cooperative planning between the manufacturer and the supplier. Volatile markets call for flexible supply nets, hence suppliers provide not only components but also flexibility as part of their **service**. Main rules regulating this service are as follows (see also Figure 3):

The **manufacturer's responsibility** is to anticipate market demand, do local production planning and scheduling as well as the production of the end-products. Planning and scheduling are performed on different horizons and with different time units (on weekly vs. daily basis). Specifically: (1) In each planning time unit, it generates the medium-term master plan and the F_i component forecasts. (2) It generates short-term schedules and makes component requests in form of daily call-offs. (3) It provides information about the probability of run-out.

The **supplier's responsibility** is to satisfy the short-term request of the manufacturer. Consequently, it has to handle the one-point inventory as follows: (1) It acknowledges call-offs and guarantees their instant delivery. (2) It fills the inventory: each week it determines whether to produce or not, as well as determines the cost-optimal lot size. (3) It plans and schedules its own production according to its own objectives and additional demand.

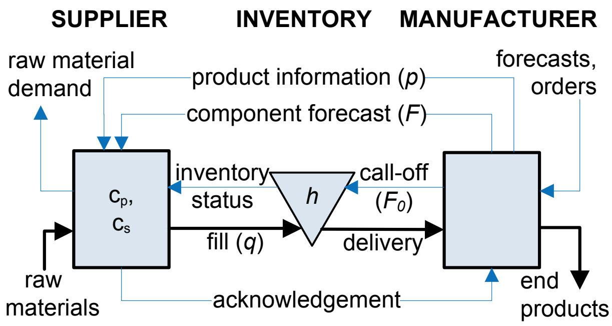

Figure 3: Information and material flows.

Bottom of the service is that production of end-products at the manufacturer must not be stalled by material shortage. Production schedules may change frequently, and the total of call-offs for the actual planning period (F_0) may be more than the amount forecasted before. Hence, as part of the inventory, **safety stock** is needed to avoid short-term stock-outs of components.

The protocol and conditions of the above service are to be fixed by a contract that regulates the flow of information and material between the partners. As for the monetary terms, we suggest to introduce the **cost of flexibility** that has two components:

- The cost of operating on a risky market can be measured by the difference between the optimal expected average cost (see Sect. 4) in risky and risk-free (i.e., where $p=0$) markets.
- Uncertainty in demand quantity can be measured by the variability of the series of component forecasts generated at subsequent planning times.

The cost of flexibility is to be shared on a regular basis. This way the manufacturer has an incentive to make reliable MPs (and component forecasts) while the supplier is interested in producing lots that coordinate the channel. Under normal conditions, no partner is interested in the unilateral deviation from this mode of operation. This is the key of avoiding double marginalization and running the network in a cost-efficient way.

6 CASE STUDY AND SIMULATION EXPERIMENTS

Our channel coordination model has been developed in an R&D project with industrial partners who form a complete focal network. The manufacturer produces altogether several million units/week from a mix of thousands of products. The ratio of customization follows the 80/20 Pareto-principle: they give 80% of the product spectrum, but only 20% of the volume. Setup costs are significant: 10-20% of the total costs, depending on the lot sizes. Since customized products are consumed slower, their smaller lot sizes incur higher average setup costs. Service level requirements are extremely high: some retailers require products in large quantities even within 24 hours.

In parallel to this work we have developed a multiagent organizational model for coordinating planning functions in the supply network [11]. The two-level protocol provides the links for the main local planning functions at the partners. In fact, for channels for standard components the protocol is already under introduction. The supply of non-standard components, especially of packaging materials, is more critical partly due to the production technology (costly setup), and partly due to the behavior of the market (risk of run-out). Hence, in order to verify the coordination model and analyze its sensitivity, we run extensive simulation experiments on historic data of selected product groups. For the above reasons, most experiments were made with coordinating various channels of packaging material supply. We could access all but one input in enterprise data warehouses:

only the probabilities of run-out had to be estimated. For typical MP forecasts—where planned manufacturing of a product is sparse and involves larger volumes—the policy was not too sensitive to the uncertainty. Optimal lot sizes decreased step-wise with p, as a representative diagram on Figure 4 shows.

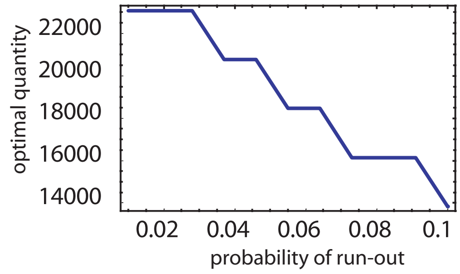

Figure 4: Lot size's dependency on probability of run-out.

The demand forecasts of various components covered a 10 to 21 week long period. We computed component lot sizes with the AC_x and AC_q heuristics for some representative p values from the [0.00005, 0.15] interval. The results were usually similar to each other and did not conflict with inventory handling rationale. Then we simulated the run-outs and computed the average of accumulated costs. Our methods outperformed the practically applied inventory policies almost in each case. This comparison is presented here in an aggregated form where products are characterized by their (1) average forecasted volume and (2) production frequency. After having classified products by deviation from the mean, we formed four categories: high volume-high frequency (HVHF), high volume-low frequency (HVLF), low volume-high frequency (LVHF) and low volume-low frequency (LVLF). Table 1 shows group cardinality, the minimum and maximum improvements on average costs for 1% probability of run-out. The proposed lot sizes have effected lower average costs in 99.4% of the cases (the table contains also the minimal negative value).

		AC_x		AC_q	
Category	#	min	max	min	max
HVHF	5	0	11	9	23
HVLF	2	2	4	12	18
LVHF	2	1	4	12	28
LVLF	21	-3	35	15	61

Table 1: Improvement on average costs in percentage.

We have tested the coordination model also with large series of random forecasts and made sensitivity analysis by all its parameters. An example is shown at Figure 5 where each point represents a mean made on 100 simulation runs for 1000 forecasts.

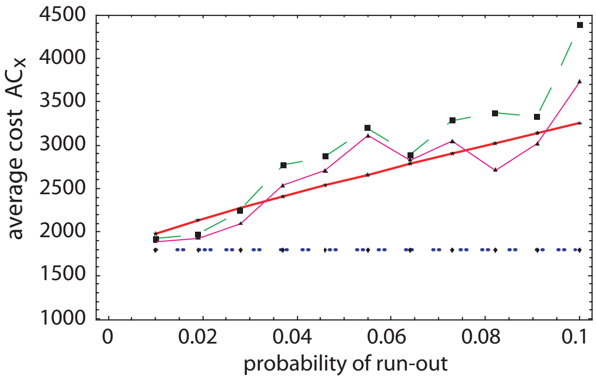

Figure 5: Change in average cost in function of p.

The constant blue (dotted) expresses the average cost on a risk-free market. The almost-linear red (thick) line represents the theoretical expected average cost on risky markets. Purple (thin) curve, which oscillates around the red (thick) one, is the cost measured in simulations. With no regard to run-out, this cost would have been higher, as indicated by the green (dashed) curve. The gap between the blue (dotted) and the red (thick) line is the theoretical difference of the costs of operating in a risk-free and a risky market, while the gap between the purple (thin) and the green (dashed) curve expresses the cost of inconvenient lot sizing.

We used the *Mathematica v5.2* system both for solving the mathematical model and running the simulations.

7 SUMMARY

After giving requirements of cooperative planning in supply networks we suggested a planning mechanism that guarantees service of components while, at the same time, keeps channel costs at a minimum. The method was tailored to the needs of customized mass production where production and logistic objectives are in sharp conflict. We accounted for a novel cost factor: the risk of obsolete inventories. Based on the coordination regime presented here, we are going to establish a portfolio of mechanisms—and contracts, accordingly—that fit specific product and market features as well as manufacturer-supplier relations.

8 ACKNOWLEDGMENTS

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