Order release strategies to control outsourced operations in a supply chain

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Abstract

We consider the situation where an OEM (Original Equipment Manufacturer) outsources some of its production activities to a contract manufacturer who serves more customers on the same capacitated production line. Further, the contract manufacturer is not willing to share all relevant information with the OEM, and therefore, a complex situation arises for the OEM to control the outsourced operations properly.

In this paper, we propose and compare three different order release strategies to plan and control outsourced operations in a supply chain where the contract manufacturer is producing different variants of a certain product. The order release strategies differ in the number of decision levels in the order release system, which are organized in a *hierarchical* way such that the output of each decision level forms a constraint for the lower decision level. We notice that the order release system with one decision level is commonly used in practice.

A simulation study is performed to compare the performance of the different order release strategies such that the probabilistic behaviour of the contract manufacturer is (partly) incorporated and production plans are generated based on (deterministic) mathematical programming models. The results show that the order release system with multiple decision levels performs significantly better than the order release system with only one decision level. Finally, some ideas for future research are discussed.

Keywords:

Ordering Process, Outsourcing, Supply Chain Planning, Simulation, Postponement

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1. Introduction

The concept of Supply Chain Operations Planning (De Kok and Fransoo, 2003) draws the attention of many researchers and practitioners, especially if more than one company, i.e. more decision authorities are involved in controlling a supply chain. The objective of Supply Chain Operations Planning is to coordinate the release of materials and resources in a supply chain such that customer service constraints are met at minimal costs (De Kok and Fransoo, 2003). Controlling a supply chain with multiple and independent decision authorities, i.e. coordinating the order release decisions between different companies in an optimal way is a complex problem, as these decision authorities have different and probably conflicting objectives. Furthermore, none of the decision authorities is willing to share all necessary information to come up with an optimal production plan from a supply chain perspective.

Many companies are aware of the value of information sharing. However, in real-life situations, several barriers exist for supply chain partners to share sensitive information that can be crucial for the partner to plan and control the supply chain in a proper way. Partners can be reluctant to share the necessary information because of fear of information leak or fear of a weak negotiation position (e.g. Li and Lin, 2006). Moreover, other problems can arise with sharing information. Terwiesch *et al.* (2005) show empirically that when a retailer revises his forecasts frequently (before placing an order), the manufacturer tends to ignore the revisions. Also, when a manufacturer has low delivery reliability, the retailer tends to inflate his forecasts to ensure sufficient supply.

The approach that we follow in this paper to model the Supply Chain Operations Planning problem is based on mathematical programming principles (e.g. De Kok and Fransoo, 2003; Spitter, 2005). In this approach, demand is inserted into the model as a point estimate for every period and the order release quantities towards the supply chain network are the key decisions. Lead times are either modelled as deterministic input parameters (e.g. Spitter, 2005) or are observed as output variables of the model (e.g. Stadtler, 2003). The advantage of this approach is that (aggregate) capacity constraints can be modelled explicitly. This modelling approach has been implemented in commercial software, the so-called Advanced Planning and Scheduling (APS) systems, many of which use CPLEX solver technology (www.ilog.com).

In this paper, we consider the situation where an OEM (Original Equipment Manufacturer) uses an APS system to plan and control his supply chain, but where part of the production activities (of a certain product with several variants) have been outsourced to a contract manufacturer who provides his capacity for third parties. The contract manufacturer performs the production activities on a capacitated production line on which multiple customers are served. Since the two companies are completely independent, i.e. controlled by different decision authorities with (possibly) conflicting objectives, the contract manufacturer is not willing to share all relevant information with the OEM. Therefore, a complex situation arises for the OEM to release orders to the contract manufacturer in an optimal way, whereas the performance of a supply chain (in terms of total inventory holding costs) depends critically on how the order decisions are coordinated.

Order release decisions between multiple and independent companies in a supply chain who are linked via a material flow, but who do not have full access to all necessary information, can be coordinated in different ways (Li and Whang, 2007). In this paper, we discuss three alternative order release strategies that consist of respectively one, two or three decision levels which are organised in a hierarchical way. The order release strategies build on insights gathered from the literature on postponement and on the value of sharing information. Besides the presentation of the mathematical model that underlies the different order release strategies, we also perform a simulation study to show the differences between the different order release strategies in terms of total supply chain costs. It turns out that the hierarchical ordering system with three decision levels performs significantly better than an ordering process that consists of less decision levels.

This paper is organised as follows. Section 2 describes the system that we consider in more detail. Then, section 3 discusses the three order release strategies that are part of this study. Section 4 discusses the relevant literature and shows the contribution of our paper to existing work. The developed mathematical model for controlling the considered system is discussed in section 5. Section 6 shows the results of a simulation study, and finally, section 7 draws some conclusions based on this paper.

2. System under study

For several reasons, many companies outsource production activities to contract manufacturers (see e.g. Holcomb and Hitt, 2007; Razzaque and Sheng, 1998; Schniederjans and Zuckweiler, 2004), which means that the control and execution of different stages in the supply chain belong to different companies. These different companies maximize their own profits by taking independent decisions which may result in operational inefficiencies for the supply chain as a whole. To reduce these inefficiencies, many papers propose to coordinate decisions made at the several stages in the supply chain (e.g. Schneeweiss and Zimmer, 2004). We refer the reader to Li and Wang (2007) for a review of coordination mechanisms in supply chains.

In this paper, we consider a supply chain that consists of an OEM (Original Equipment Manufacturer) that develops and markets a product with different variants, which only differ in the amount of raw material. Think of a medicine with different strengths or paint jars with different volumes. To benefit from capacity pooling, the production of the variants of the product is outsourced to a contract manufacturer who serves more customers on the same capacitated production line. The OEM faces stochastic demand for the different variants of the product and the order releases towards the contract manufacturer are based on a (deterministic) mathematical programming model, which are nowadays widely implemented in so-called Advanced Planning and Scheduling systems (Stadtler and Kilger, 2005).

The contract manufacturer also faces stochastic demand of several products from different customers. On average, the contract manufacturer is able to serve the average demands of all customers, but there is a probability that the sum of all orders in a certain time period exceeds the capacity level of the production line on which (all) products are produced. In that case, the contract manufacturer proposes to reschedule some of the OEM's orders, i.e. the order(s) can be advanced, delayed or rejected by the contract manufacturer. This process is completely out of the sight of the OEM and therefore, not impressionable by the customer. Thus, the OEM does not have information about the *available* capacity level for the production of his product at the contract manufacturer in each time period.

Figure 1 shows the (two-stage) supply chain system that we consider in this paper. The intermittent lines in figure 1 demonstrate the parts of the supply chain that are out of OEM's sight. Stage j is the stockpoint of raw materials at the contract manufacturer provided by the OEM. We assume that the supply of raw materials by the OEM to the contract manufacturer is sufficient. Stage *j* consists of several stockpoints: the raw material for the contract manufacturer's production process, stockpoints of some other materials that are needed for the production process (but these materials are ordered and controlled by the contract manufacturer), and materials of other OEM's. The outputs of the production process are three variants of the product that *only* differ in concentration of the raw material, i.e. the variants have different values of the BOM factor and products for other OEM's. These outputs are stored temporarily at the contract manufacturer waiting for shipment back to the OEM. Since these inventories are not *controlled* inventories, they are not shown in figure 1. Stage *i* represents inventories of the three variants at the OEM.

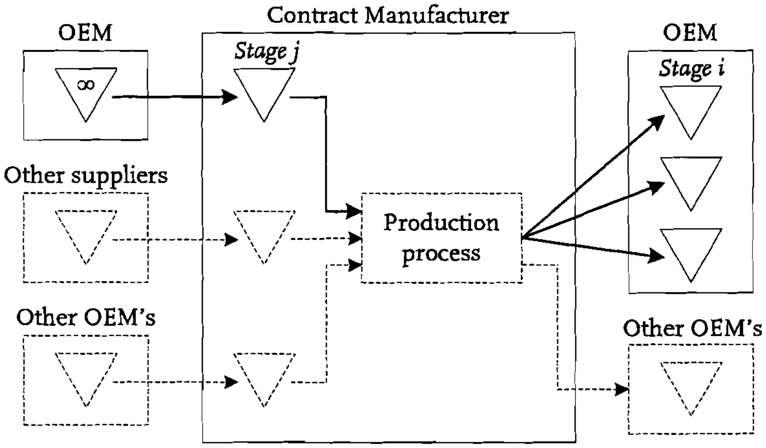


Figure 1. The supply chain considered in this paper

This supply chain is a Make-To-Stock system, as demand for the variants of the product is fulfilled from inventory. Further, the raw materials supplied by the OEM and stored at stage *j* are owned by the OEM, and therefore, the contract manufacturer shares information on the inventory level of the raw material at stage *j* with the OEM. However, since the contract manufacturer's production system has a limited capacity level, the OEM does not know in advance whether its order releases towards the contract manufacturer will be directly accepted or whether the contract manufacturer has to reschedule the order due to capacity restrictions. In the next section, we discuss three different order release strategies that the OEM can follow to control the outsourced operations.

3. Order release strategies

Different order release strategies can be followed to control the supply chain with outsourced operations that we presented in the previous section. We note that due to the underlying technology and economics, all order releases and receipts are in integer multiples of a fixed batch size. First, we start with the most simple order release strategy, which consists of only one decision level. Order release decisions made in practice are mostly according to this order release strategy. Then, the order release strategy will be extended twice by adding additional decision levels.

Order Release Strategy 1

The first order release strategy consists of one decision level, which includes the decisions on how much to release towards the contract manufacturer *per variant of the product* per time period for the whole planning horizon, assuming that the materials will be received after a fixed (planned) lead time. That means that orders that are released at time period t for time period $t+L$ (where L is the planned lead time of the outsourced operations) are considered to be *real orders*, whereas release orders made at time period t for the periods $[t+L+1,t+T]$ (where T is the planning horizon) are *reservations*, i.e. demand information is shared with the contract manufacturer, which is considered to be an early order commitment. The latter information is valuable for the contract manufacturer for two reasons. The first reason is that due to the hidden decisions and priorities made by the contract manufacturer or due to real (but unknown) capacity restrictions at the contract manufacturer, there is a probability that the contract manufacturer is not able to deliver the order(s) in time which deteriorates the delivery performance and results in higher safety stocks. Thus, the reservations are needed to allow the contract manufacturer to make feasible capacity plans and respond to the customers (OEMs) whether their reservation is accepted, changed or rejected.

The second reason is that the contract manufacturer has to control the supply of other materials that are needed to produce the variants of the product, which are ordered at other suppliers (see figure 1). These materials might have a long and uncertain supply lead time, and therefore, reservations by the OEMs are necessary. Note that according to this strategy, all release orders (both orders and reservations) are expressed in number of batches per variant of the product per time period.

Order release strategy 2

The second order release strategy is based on the insight that for the contract manufacturer's capacity planning, the *mix* of the release orders has not necessarily to be specified. That means that when orders are released towards the contract manufacturer at time period t for time periods $[t+L,t+T]$, it is not necessary to specify the release order in number of batches per variant of the product, but only in total number of batches of all variants of the product. This allows the OEM to *postpone* the decision on the *mix* of the release orders to be received at time period $t+L$ to a later moment in time than time period t.

However, when the OEM postpones the decision on the mix of the released orders to a later moment in time than t, we require that the mix of the (final) released orders should be equal to the initially ordered total number of batches of all variants of the product. The option of postponing the mix of the order might be beneficial, as the moment in time that the mix of the order release is determined, more accurate demand information is available.

This order release strategy includes two decision levels, as at time period t two sets of decisions have to be made: release decisions for the time interval $[t+L,t+T]$ in total number of batches of all variants of the product and the decisions on the mix of orders to be received at time period $t+M$ where $M<L$. Compared with order release strategy 1, the order release decisions are now decoupled into two decisions where the first decisions are more aggregate than in order release strategy 1 and the specification of the order is postponed to a later moment in time. These decision levels are hierarchically organized, as the first decisions are constraining the second decisions, i.e. only the mix of the order is allowed to be determined and not the total volume.

Order release strategy 3 (ORS 3)

The third order release strategy contains three decision levels. The first decision level are order release decisions at time period t for time periods $[t+L,t+T]$ which are real orders and reservations, again in total number of batches of all variants of the product. The second decision level is the determination of the mix of the order, i.e. the release quantities per variant of the product, which is the postponement option that we discussed at order release strategy 2. However, when the mix of the (final) order is determined, the initially ordered quantity is now an *upper bound* for the mix, i.e. the

OEM has the option to cancel some batches of some variants of the product if the demand information at that moment in time allows for that.

The advantage of including the cancellation option is that the OEM can adjust the order (by cancelling some batches) based on the most accurate forecast data. From the other side, cancellation leads to a lower utilization of contract manufacturer's production system. However, we have observed in real-life situations where the contract manufacturer is accepting some cancellations, as the contract manufacturer is facing high demand from his customers such that an unfilled capacity slot can be filled by demand from another customer.

Summarizing the discussed order release strategies, three decision levels are considered in the order release strategies:

1. order release decisions (both orders and reservations), which can be either in unit of number of batches per variant or total number of batches of all variants;
2. determination of the mix of the release order, which can be considered as the postponement option;
3. the option to cancel some batches of some variants of the product.

These decision levels are organised hierarchically, which means that decisions made by a higher level form constraints to decisions to be made by lower levels. Figure 2 shows the three order release strategies that we consider in this study schematically.

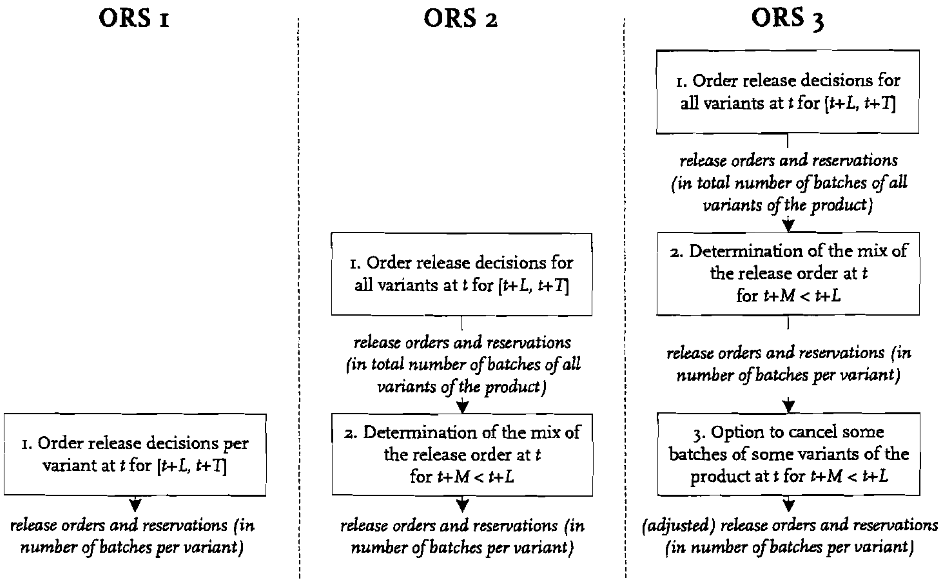


Figure 2. The three order release strategies that we consider in this study, organised hierarchically.

The OEM aims to control the supply chain such that total inventory holding costs (at both stages *i* and *j*, see figure 1) are minimized at a certain customer service level. Therefore, the objective of this paper is twofold.

First, having introduced the three order release strategies as concepts to control outsourced operations in a supply chain system as presented in section 2, the performance of these concepts will be compared in terms of total supply chain inventory holding costs. By doing so, we will be able to determine the added value of each decision level.

Second, till now, we considered orders that are released at time period t for the time interval $[t+L,t+T]$ as order releases towards the contract manufacturer. However, these order releases can be divided into two parts. The order releases done at time period t for time period $t+L$ are *real orders*, whereas order releases done for the time interval $[t+L+1,t+T]$ are reservations. Since the OEM does not have insights into the available capacity at the contract manufacturer, there is a probability that the contract manufacturer will reject or change a certain reservation.

The contract manufacturer's real (available) capacity level is capacitated, but this is unknown to the OEM, and therefore, we consider two scenarios in our study with respect to the contract manufacturer's capacity level. The first one is where the contract manufacturer's capacity level is considered to be infinite, i.e. release orders are generated without any capacity limitations. That means that all reservations are (assumed to be) accepted in one go. The other scenario is where the contract manufacturer's capacity level is considered to be a stochastic variable with a certain distribution. Therefore, we address the question what the effect is of such probabilistic behaviour of the contract manufacturer, i.e. whether a reservation will be directly accepted or not, on the supply chain performance.

Outsourcing the final stage of manufacturing operations, which typically includes packaging, is very common in process industries such as pharmaceuticals, food, and beverages. According to our observations, most companies deploy a coordination model that is similar to order release strategy 1. Moving to a more advanced order release strategy (such as order release strategies 2 and 3) requires more sophistication in the supply chain planning function and more frequent and subtle exchange of information with the contract manufacturer. In this study, it is our objective to investigate how substantial the benefits are, such that the OEM can make a trade-off.

4. Literature review

A large number of papers treat the problem of supply chain planning. De Kok and Fransoo (2003) discuss the Supply Chain Operations Planning problem extensively. The objective of Supply Chain Operations Planning is to coordinate the release of materials and resources in a supply chain network such that customer service constraints are met at minimal costs. De Kok and Fransoo (2003) discuss different approaches for modelling the Supply Chain Operations Planning problem, namely the approach that is based on stochastic multi-echelon inventory theory and the approach that is based on mathematical programming principles. Our paper is closely related to the latter approach. Mula *et al.* (2006) review some of the existing literature of production planning under uncertainty and classify existing models for production planning under uncertainty in a scheme. However, the models discussed in Mula *et al.* (2006) and De Kok and Fransoo (2003) do not explicitly distinguish between supply chains that are controlled by one and those that are controlled by multiple companies with different objective functions. Furthermore, the models that are discussed in the two papers consider order release decisions based on one decision level, which we also examine in this study, but we extend the order release decisions that result from multiple decision levels.

In our research setting, we consider the production planning problem of an OEM who outsources some production activities to a contract manufacturer. Most papers that appeared on production planning models with outsourcing consider outsourcing as an option to cover excess demand, i.e. as a strategic or tactical decision (Kamien and Li, 1990; Van Mieghem, 1999; Bertrand and Sridharan, 2001; Yang *et al.*, 2005) or consider outsourcing as a faster and more expensive secondary supply source (e.g. Fuduka, 1964; Whittemore and Saunders, 1977), whereas little has been written on how to control outsourcing on the operational level, which is subject of our study.

The outsourcing problem has been addressed from different perspectives. Kamien and Li (1990) present conditions under which outsourcing should be carried out. More precisely, they develop a model in which subcontracting is explicitly considered as a production planning strategy. Based on a dynamic programming approach, they show that subcontracting reduces variability in production and inventory, and hence, contributes to production smoothing. Van Mieghem (1999) develops a two-player game-theoretical model to analyse outsourcing conditions for three types of contracts between a manufacturer and his subcontractor. This study shows that contracts with flexible or negotiable outsourcing costs are preferable over contracts with pre-fixed outsourcing costs.

Bertrand and Sridharan (2001) study a situation where the order arrival rate at a certain firm is greater than the service rate which makes subcontracting necessary. They develop four heuristic decision rules with varying informational needs and complexity to determine when and which orders should be subcontracted. Yang *et al.* (2005) study the optimal production-inventory-outsourcing policy for a firm with Markovian in-house production capacity that faces independent stochastic demand and has the option to outsource.

In contrast to these papers, in our research setting, the contract manufacturer is the only source for producing the variants of the product, and therefore, we do not consider outsourcing as an option or the decision whether to outsource or not. Furthermore, although these papers are dealing with the outsourcing problem, they do not address the order release problem towards the contract manufacturer explicitly.

Another stream of papers that is related to our research problem deals with collaborative planning where the production planning problem of two independent players in a supply chain is studied (Bhatnagar *et al.* (1993); Dudek and Stadtler (2005)). The study of Dudek and Stadlter (2005) proposes a non-hierarchical, negotiation-based scheme which can be used to synchronize plans between two independent supply chain partners linked by material flows. The problem they studied is close to our work, but Dudek and Stadtler's approach requires that the partners evaluate each other proposals till a consistent overall plan is achieved.

Order release strategies 2 and 3 (that we propose in this paper) are partly based on the literature on the value of postponement. Although several papers discuss the added value of postponement (e.g. Caux *et al.*, 2006; Lee, 1996), the paper of Lee and Tang (1997) is the paper that models generally the costs and benefits associated with postponement. The authors analyse the optimal point of product differentiation and derive managerial insights from the properties of the optimal point of product differentiation. They conclude that delayed product differentiation can be viewed as a strategy for a company to improve the service level and reduce inventories when dealing with product proliferation. However, most studies on postponement assume that the production capacity is unlimited, whereas we also consider the situation where the contract manufacturer's capacity level is limited, but uncertain. The reader is referred to Yang *et al.* (2004) for a more detailed literature review on postponement strategies.

The order release strategies that are considered in this paper release at time period t the reservations for the periods $[t+L+1,t+T]$. The concept of reserving a capacity slot before the *real order* is placed has been considered in many papers that appeared in the supply chain contracts literature, in the literature on the value of information sharing and in some papers that deal with real options. In the literature on information sharing, Lee *et al.* (2000) study the benefit of information sharing in a two-stage supply chain and conclude that information sharing is beneficial to the manufacturer, but not to the retailer. In the study of Lee *et al.* (2000), the production capacity is considered to be infinite; whereas Gavirneni *et al.* (1999) show that information sharing is also beneficial for the manufacturer in a limited capacity setting. Spinler and Huchzermeier (2006) develop an analytical framework to value options on capacity for the production of non-storable goods or dated services. They determine the optimal reservation quantity and the seller's tariff by game theoretic modelling of market interactions between buyer and seller.

In the supply chain contracting literature, it is often proposed that a manufacturer should prefer contracts that make it attractive to retailers to commit their orders in advance (reservations). These types of contracts are called the quantity-flexibility contracts. Tsay and Lovejoy (1999) provide a detailed analysis of the quantity-flexibility contract in a multi-period setting. The study of Zhao *et al.* (2007) shows the added value of early order commitment, as they develop an analytical model to quantify the cost savings of an early order commitment in a two-level supply chain where demand is serially correlated. Then, they derive a decision rule to determine whether early order commitment will benefit the supply chain, and accordingly, they determine the optimal timing for early order commitment. In our study, we build on these insights and require the OEM to make reservations, which are early order commitments.

In our study, we consider both situations where the contract manufacturer's capacity level is either unlimited or limited, but stochastic. Most papers that deal with supply management assume that supply capacity is unlimited or known (Tang, 2006). However, there are some papers (Ciarallo *et al.*, 1994; Parlar and Perry, 1996) that consider supply uncertainty from the perspective of (unexpected) machine breakdowns or other sources of disruptions. Parlar and Perry (1996) model the uncertain availability of each of the *n* suppliers by considering the cases that a supplier can be either 'on' or 'off' in a certain time period. For each of the resulting 2^n states of the system, they analyse a state specific (s,Q) inventory policy. The work of Ciarallo *et al.* (1994) is more close to our approach, as they develop a discrete time model in which the supply capacity is a random variable with known probability distribution. However, in the study of Ciarallo *et al.* (1994), the uncertain capacity problem results from an uncertain production process, due to e.g. manufacturing complexity. They show that in a multi-period and infinite horizon setting, order-up-to policies that are dependent on the distribution of capacity are optimal in spite of a non-convex cost function. However, Ciarallo *et al.* (1994) have not linked the uncertain capacity problem with the problem of lack of information as in our setting; we extend the insight on the effect of uncertain capacity level by comparing the infinite capacity level case with the finite, but unknown capacity level case.

5. Mathematical model

In this section, we present the mathematical programming model that is solved by the OEM to come up with production plans. The system, as shown in figure 3, shows the supply chain considered in the OEM's supply chain planning model. First, we introduce the mathematical model that generates order releases based on order release strategy 1, i.e. based on one decision level. Then, we extend the model by including the other decision levels that we introduced in section 3.

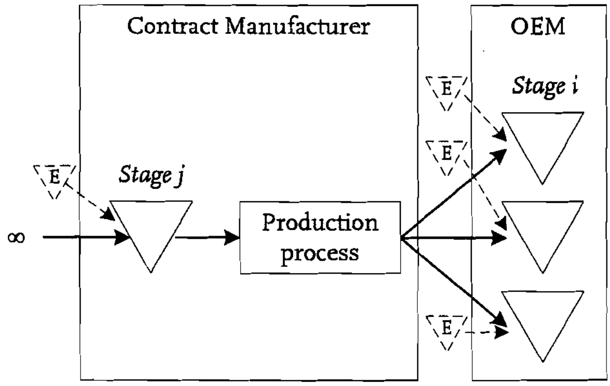


Figure 3. The supply chain considered in OEM's supply chain planning model

Order Release Strategy 1

We consider a two-stage supply chain with infinite supply at stage *j*. Stage *j* consists of the raw material for the contract manufacturer's production process which is supplied by the OEM. The contract manufacturer produces from the raw material a couple of variants of the product that only differ in the amount of raw material. Furthermore, the contract manufacturer produces in fixed batch sizes regardless of which variant of the product is produced. Stage *i* represents the stockpoints of the variants of the product stored at the OEM.

The combination of the fact that external (stochastic) demand arrives at stage *i* and the fact that the contract manufacturer's production process has a lead time can lead to stock outs at both stages in the considered supply chain. Therefore, we introduce dummy stockpoints that can supply these stockpoints with a zero leadtime, but we consider these supplies as being very expensive. We call these supplies *emergency supplies* and they are shown in figure 3 with small triangles with the letter *E*. The main reason of modelling emergency supplies, which are lost sales, is that the amount of emergency supplies will be later used in the simulation study as a measure of performance of the considered supply chain. These supplies can also be seen as consumption of safety stocks, but by this approach, we avoid determining safety stock levels and we enable the model to come up with feasible solutions.

As in many real-life cases, we consider the situation where the supply chain planning problem is solved in a rolling horizon setting. After each solving round, forecasts of the demand and the status information are updated such that a new planning problem arises. Therefore, we define T as the planning horizon, N as the total numbers of items in stage i, i.e. the number of variants of the product. An index j refers to the raw material (an item in stage j) and an index i refers to a variant of the product (an item in stage i).

Equations 1 are the objective functions of the supply chain planning model that minimize total inventory holding costs and emergency shipments costs within the supply chain. τ_i is the inventory holding costs per time period t for item i and ε_i is the emergency shipment costs per time period t for item i where $\varepsilon >> \tau$. $I(t)$ is the inventory level of the item that corresponds to the index at the end of period t and $E(t)$ is the amount of emergency supply in period t, i.e. the lost sales in period t.

$$Min \sum_{i=1}^{N}\sum_{t=1}^{T}\tau_i I_i(t)+\sum_{i=1}^{N}\sum_{t=1}^{T}\varepsilon_i E_i(t)+\sum_{t=1}^{T}\tau_j I_j(t)+\sum_{t=1}^{T}\varepsilon_j E_j(t) \qquad (1)$$

The objective functions (1) are minimized subject to several constraints which will be discussed below. Equations 2 are the so-called balance equations that balance the goods flow from one period to the subsequent period. $I_i(t)$ is the inventory level of item i at the end of period t, $R_i(t)$ is the replenishment quantity of item i in period t, and $D_i(t)$ is the demand forecast for item i in period t. $D_i(t)$ is inserted into the model as a point estimate for every t which is updated after each solving round.

$$I_i(t) = I_i(t-1) + R_i(t) - D_i(t),\ i = 1,\dots,N,\ t = 1,\dots,T \qquad (2)$$

Equations 3 represent the fact that item i can be either replenished from the contract manufacturer or (if impossible) via the emergency channel. $P_i(t)$ is the quantity of item i produced by the contract manufacturer in period t and $E_i(t)$ is the quantity of item i shipped via the emergency channel in time period t.

$$R_i(t) = P_i(t) + E_i(t),\ i = 1,\dots,N,\ t = 1,\dots,T \qquad (3)$$

Equations 4 require that the production quantity of item i to be produced by the contract manufacturer in time period t ($P_i(t)$) is an integer multiple of Q_i, the (fixed) batch size of item i. $n_i(t)$ is thus the *number of batches* to be produced of item i in time period t.

$$P_i(t) = n_i(t) \cdot Q_i,\ i = 1,\dots,N,\ t = 1,\dots,T,\ n_i(t) \in \mathrm{N}_0 \qquad (4)$$

Order releases of item i ($r_i(t)$) to the contract manufacturer are arranged by equations 5 where L is the planned lead time of the contract manufacturer's production process.

$$r_i(t) = P_i(t+L),\ i = 1,\dots,N,\ t = 1,\dots,T \qquad (5)$$

After the first solving round, $r_i(t)$ are determined for the length of the planning horizon for all items i. The OEM and the contract manufacturer agree on that order releases within $[t,t+L]$ (where t is the current time period) are not allowed to change, i.e. the order releases are frozen in this time interval. We define T_f as the length of the frozen horizon. Thus, once a release order ($r_i(t)$) is placed at the contract manufacturer, it is frozen for T_f time periods which is equal to the planned lead time L of the contract manufacturer's production process.

The frozen horizon concept is arranged by equations 6, which require that only production quantities after T_f are subject to change. $PP_i(t)$ are planned production quantities of item i in t, whereas production quantities within T_f are frozen ($FP_i(t)$ are frozen production quantities of item i in t) which are inserted into the model based on decisions taken in the past. The binary variable α allows to distinguish between decisions to be made within and after the frozen horizon.

$$P_i(t) = (1-\alpha)\cdot FP_i(t) + \alpha \cdot PP_i(t),\ i=1,\ldots,N,\ t=1,\ldots,T,\ \alpha = \begin{cases} 0 \text{ if } t \le T_f \\ 1 \text{ if } t > T_f \end{cases} \tag{6}$$

$D_j(t)$ is the derived demand for item j (at stage j in figure 3) and is equal to the sum of the released quantities determined by equations 5 multiplied by the BOM factors (β_{ji}). Equations 7 show the relation between the variables.

$$D_j(t) = \beta_{ji} \sum_{i=1}^{N} r_i(t),\ t=1,\ldots,T \tag{7}$$

Like stage i, stage j must also ensure balanced material flows, and therefore, restrictions 8 are introduced.

$$I_j(t) = I_j(t-1) + R_j(t) - D_j(t),\ t=1,\ldots,T \tag{8}$$

Stage j is supplied from a stockpoint with infinite supply capacity, but still, a lead time is required to ship the materials from the OEM to the contract manufacturer. Therefore, emergency supplies ($E_j(t)$ are emergency receipts of item j in period t) are also modelled at stage j to ensure that the model gives feasible solutions. $FR_j(t)$ are frozen receipts of item j in period t which are determined in previous solving rounds and which are not allowed to be changed. $PR_j(t)$ are planned receipts of item j in period t. θ is a binary variable with the same function as α. Then, equations 9 determine the replenishment quantities ($R_j(t)$) of item j in period t.

$$R_j(t) = (1-\theta)FR_j(t) + \theta \cdot PR_j(t) + E_j(t),\ t = 1,\dots,T,\ \theta = \begin{cases} 0 \text{ if } t \le L_j \\ 1 \text{ if } t > L_j \end{cases} \qquad (9)$$

Equations 10 are non-negativity constraints for the decision variables.

$$I_i(t), R_i(t), P_i(t), E_i(t), PP_i(t), I_j(t), E_j(t), R_j(t), PR_j(t) \ge 0,\ i = 1,\dots,N,\ t = 1,\dots,T \quad (10)$$

From the order release perspective, the OEM releases every planning cycle for every time period t in the planning horizon orders ($r_i(t)$) to the contract manufacturer which are determined by the planning model that we just discussed. These orders are in number of batches of item i. However, $r_i(t)$ for $t=1,\dots,T_f$ are real orders, whereas $r_i(t)$ for $t=T_f+1,\dots,T$ are reservations, which can be either accepted or changed by the contract manufacturer.

Order Release Strategy 2

In the previous section, we discussed how release orders are generated based on one decision level. Order release strategy 2 allows for postponement of the mix of the order and releases orders in total number of batches of all variants of the product. Thus, instead of releasing $r_i(t)$, i.e. the order release quantity of item i in period t, the OEM now releases $r(t)$ which is equal to

$$r(t)=\sum_{i=1}^{N} r_i(t),\ t=1,\ldots,T. \tag{11}$$

This means that both orders and reservations for item i in period t are not specified in number of batches per variant, but in total number of batches of all variants. $r(t)$ is namely sufficient for the contract manufacturer to make feasible capacity plans and to control the inventories of the other materials. Further, this strategy allows the OEM to postpone the decision on the mix of the order. At t, the OEM communicates to the contract manufacturer the exact mix of the order to be received at $t=M$ $(M<L)$, i.e. $r_i(M)$ for all i where the mix is determined based on the most accurate demand information.

Order Release Strategy 3

Order release strategy 3 allows also for the option of cancellation of some order releases, which can be incorporated in the model by adding constraints 12,

$$\sum_{i=1}^{N} r_{i,s+1}(t) \le r_s(t),\ i=1,\ldots,N,\ t=1 \tag{12}$$

where $r_s(t)$ is the number of batches to produce at time period t determined in solving round s. That means that in the next solving round $(s+1)$, the number of batches of item i to produce in $t=1$ $(r_{i,s+1}(1))$ can be determined such that it is equal to or lower than $r_s(t)$. The model has now the option to deviate from the previously placed release orders and that deviation is the cancellation of release orders towards the contract manufacturer.

Unlimited versus limited, but unknown capacity level

Since the OEM does not have insight into possible capacity restrictions at the contract manufacturer, it might not be correct to assume that all reservations are (immediately) accepted by the contract manufacturer. Therefore, we consider two scenarios with respect to the contract manufacturer's capacity level: unlimited capacity level and limited, but stochastic capacity level. The latter scenario is more realistic, as it (partly) considers the probabilistic behaviour of the contract manufacturer.

Therefore, constraints 13 are added to the supply chain planning model where the reserved batches of item *i* in period *t* have an upper bound which represents the capacity restrictions at the contract manufacturer, which can be either infinite or a stochastic variable.

$$\sum_{i=1}^{N} r_{i,s}(t) \leq C_s, \quad t = T_f + 1, \ldots, T, \; i = 1, \ldots, N \qquad (13)$$

In the simulation study we discuss in the next section, we compare the situations where reservations are always accepted (i.e. where $C_s = \infty$) with the situation where a probability is included that a reservation is rejected (i.e. where C_s is a stochastic variable).

6. Simulation study

In this section, we discuss the results of a simulation study that we performed to compare the different order release strategies we discussed in this paper. We performed simulations where C_s (see restrictions 13) was either infinite or a random variable with the uniform distribution, i.e. $C_s \sim U\,[0,2]$.

The simulation study is performed by simulating the discussed supply chain planning problem in a rolling horizon setting. We consider a two-stage supply chain (as shown in figure 3) with one item in stage *j* and three items in stage *i*, i.e. three variants of the product are produced out of the raw material. We assume independent and normally distributed (external) demand for items *i*. Table 1 shows the parameters that are used in this simulation study. The coefficient of variation is one of the parameters that changes in the simulation study. Further, we assume that the lead time for stage *j*, i.e. the transportation lead time for the raw materials from the OEM to the contract manufacturer is equal to one time period. The planned lead time of the contract manufacturer's production process is set equal to four time periods (transportation lead time plus production lead time).

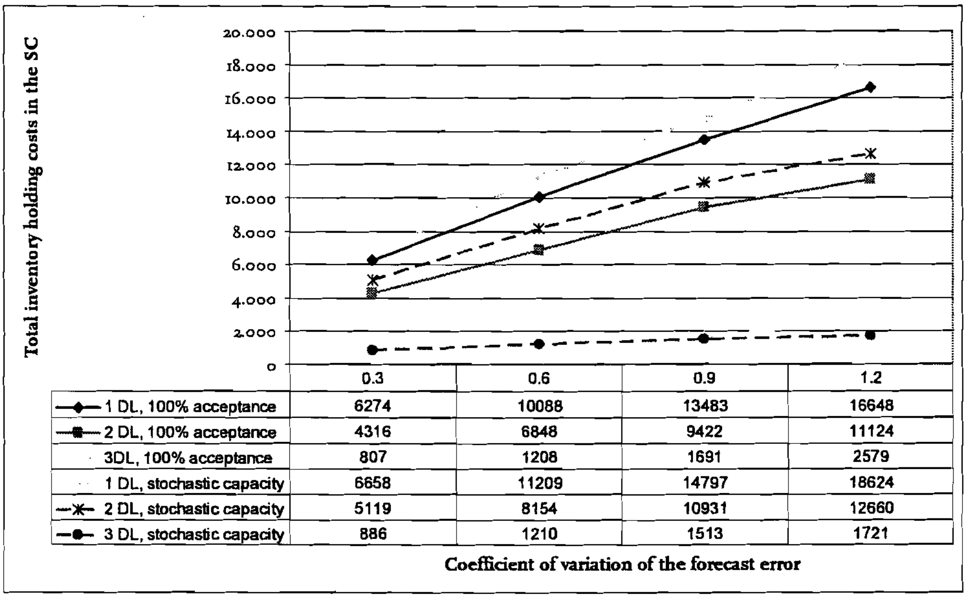
Table 1. Values used in the simulation study

Average demand variant (1,2,3)	250, 500, 100
Batch size	200
Planned lead time	4
BOM factor variant (1,2,3)	0.1, 0.2, 0.3
Target service level (non-stock out probability)	99 %

Figure 4 shows the total inventory holding costs in the supply chain for the different scenarios that we considered in the simulation study. Equation 14 shows how the total inventory holding costs are calculated where s is a certain solving round (one simulation run) and S the total number of runs (the replication length).

$$TIC = \sum_{i=1}^{N} \sum_{s=1}^{S} \tau_i \left(I_{i,s}(1) + E_{i,s}(1) \right) + \sum_{s=1}^{S} \tau_j \left(I_{j,s}(1) + E_{j,s}(1) \right) \tag{14}$$

The reasoning behind this performance measure is that we consider the emergency supplies as the amount of safety stocks that was necessary to achieve a certain customer service level. By adding the safety stocks to the inventory levels, we have one measure for the performance in the supply chain. This approach is in line with the approaches of Kohler-Gudum and De Kok (2002) and Boulaksil *et al.* (2006). The x-axis of figure 4 represents the scenarios we considered in the simulation study, i.e. number of considered decision levels (DL) and the coefficient of variation (CV).



	0.3	0.6	0.9	1.2
—◆— 1 DL, 100% acceptance	6274	10088	13483	16648
—■— 2 DL, 100% acceptance	4316	6848	9422	11124
3DL, 100% acceptance	807	1208	1691	2579
1 DL, stochastic capacity	6658	11209	14797	18624
—✳— 2 DL, stochastic capacity	5119	8154	10931	12660
—●— 3 DL, stochastic capacity	886	1210	1513	1721

Figure 4. Total inventory holding costs in the supply chain for the different scenarios

If we consider the case where all reservations are accepted (see 100% acceptance in figure 4) and we consider order release strategy 1 (one decision level), then we see that the total inventory holding costs are an increasing function in CV. This holds also for all other scenarios we studied. The increase of TIC is very obvious if we think of the relation between safety stocks and the standard deviation of demand during the lead time.

Figure 4 also shows the total inventory holding costs when we add another decision level to the order release process (2 DL). In this situation, the OEM releases orders to the contract manufacturer in *total* number of batches instead of a specified order release per variant and postpones the exact mix of the order release to a later moment in time. The final order release is thus based on more accurate forecast data. Based on the results that are shown in figure 4, an average cost saving of 32% can be achieved by adding the second decision level. It is interesting that communicating high level information to the contract manufacturer, which is for the contract manufacturer enough to control its operations, combined with postponement of communicating details of the order leads to a substantially better performance in the supply chain.

Applying order release strategy 3 (with three decision levels) leads to even lower total supply chain inventory costs. The average cost savings compared with order release strategy 2 is about 80% for the studied setting. However, allowing for cancellations means that the contract manufacturer faces more idle capacity slots, i.e. the contract manufacturer reaches a lower utilization of his production system which results in a higher cost price on the long term. Figure 5 shows the average number of batches cancelled by the OEM for the different values of CV. Therefore, the real benefit of this decision level is less than the values shown in figure 4. However, based on this insight, the two parties can make a trade-off between capacity costs (due to lower utilization) and the cost savings in terms of total inventory holding costs.

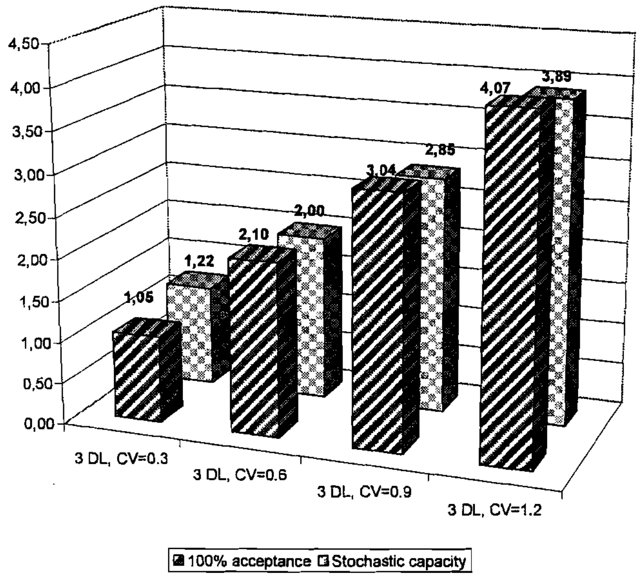


Figure 5. The average number of batches cancelled by the OEM for the situation with 3 decision levels

Figures 4 and 5 also show the results obtained by considering the capacity level of the contract manufacturer as unlimited or limited, but unknown (i.e. as a stochastic variable). Figure 4 shows that for the 1 DL and 2 DL situations on average the total supply chain inventory holding costs increase due to the stochastic capacity of the contract manufacturer. This has to do with the fact that a probability is created that some reservations can be cancelled and therefore the option of emergency supplies is used more often to compensate the cancellations, i.e. more safety stocks are needed to capture the demand during lead time. However, for the 3 DL case (where cancellations are allowed), we see that for CV=0.3 and CV=0.6, the total supply chain inventory costs are indeed higher for the 100% acceptance case, but not for the cases with CV=0.9 and CV=1.2. This is a very interesting result, as this means that in these cases the demand is so uncertain and variable that it is on average better that the contract manufacturer is rejecting some batches due to capacity reasons.

7. Conclusion and future work

In this paper, we considered the situation where an OEM (Original Equipment Manufacturer) outsources some production activities to a contract manufacturer who serves more customers on the same capacitated production line. Since the contract manufacturer is not willing to share all relevant information with the OEM, a complex situation arises for the OEM to control the outsourced operations properly. We proposed and discussed three alternative order release strategies that the OEM can follow to plan and control the outsourced operations in the supply chain. We have seen that the order release strategies differ in the number of decision levels in the order release system, which are organized in a *hierarchical* way such that the output of each decision level forms a constraint for the lower decision level.

A simulation study was performed to compare the performances of the different order release strategies. We have shown that increasing the number of decision levels in the order release strategy leads to substantial lower total supply chain costs. However, for order release strategy 3, cancellations may lead to lower utilization at the contract manufacturer, but an exact trade-off can be made between the cost savings in the supply chain and the costs for the empty slots that result from the cancellations. For a particular setting, we have shown the average number of cancellations when we follow this order release strategy. Our model can be extended by including a cost factor for a cancellation, such that this is incorporated in the order release decisions.

The simulation study was also performed to get insight into the effect of limited, but uncertain capacity level of the outsourced operations. Since the OEM does not have insight into possible capacity restrictions at the contract manufacturer, we compared the situation where we assume unlimited capacity level and limited, but unknown capacity level. It turns out that for our setting, assuming limited, but uncertain capacity level increases total supply chain costs. However, we have seen specific situations where this is not the case. When the demand is very uncertain and cancellations are allowed, it turns out that assuming limited, but unknown capacity level leads to lower supply chain costs.

The results suggest that the benefits of a more complex order release strategy towards a contract manufacturer are substantial and that it is likely to be worthwhile for an OEM to invest in building up capabilities to deal with such more complex release strategies.

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