Planning of outsourced operations in pharmaceutical supply chains

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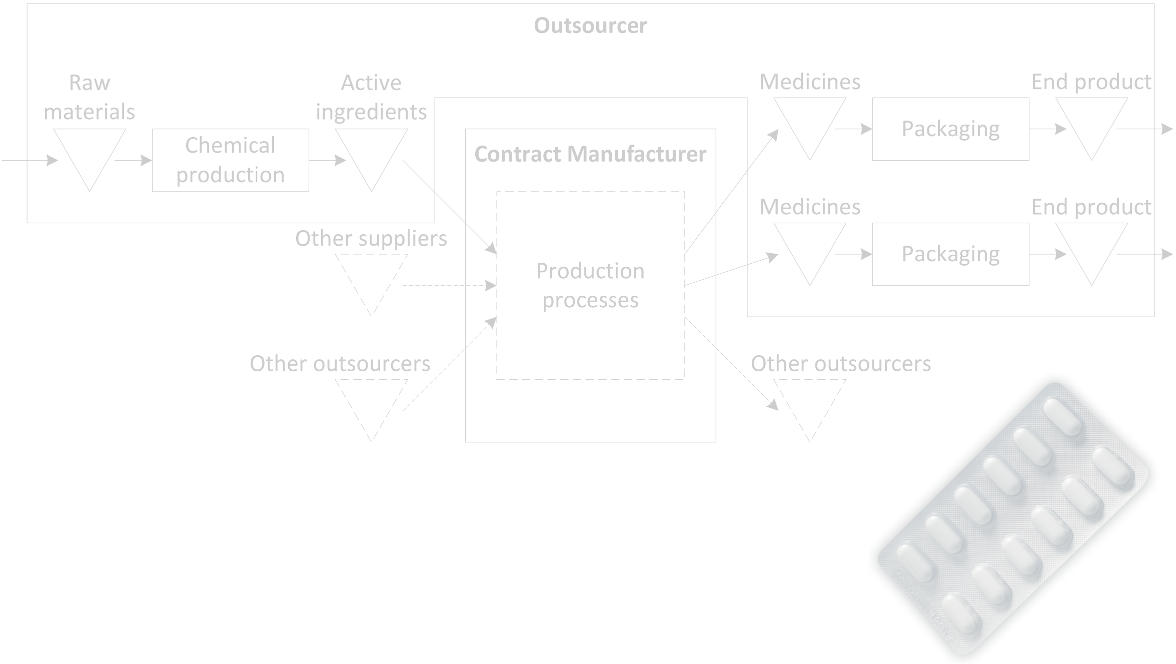
Planning of Outsourced Operations in Pharmaceutical Supply Chains



Youssef Boulaksil

Planning of Outsourced Operations in Pharmaceutical Supply Chains

This thesis is number **D127** of the thesis series of the BETA Research School for Operations Management and Logistics. The BETA Research School is a joint effort of the departments Industrial Engineering & Innovation Sciences, and Mathematics and Computer Science of the Eindhoven University of Technology and the Centre for Production, Logistics, and Operations Management of the University of Twente.

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Youssef Boulaksil

Eindhoven, November 2009

Contents

1. Introduction

This dissertation deals with the planning and control of *outsourced supply chains*, which are supply chains where part(s) of the supply chain is (are) outsourced to a contract manufacturer. The planning and control of a globally dispersed supply chain that is owned by a single company can be already a complex task, but due to limited information transparency and limited control over the detailed planning and priorities at the contract manufacturer, the planning and control of outsourced supply chains gets even more complex. Consequently, it is not obvious how to plan and control outsourced supply chains, as the outsourcer is not the owner of the whole supply chain. Outsourced supply chains are developing in many industries, but we focus in this dissertation on the pharmaceutical industry, where the outsourcing relationship is typically long-term. Therefore, companies are willing to invest in improving the operational performance.

In this dissertation, we review the literature on outsourcing and we find that little is known on the operational planning decisions in an outsourced supply chain. Based on that insight, we conduct case studies at a number of pharmaceutical companies that have an outsourcing relationship, to study the implications of outsourcing on the supply chain operations planning function. Inspired by the insights from the case studies, we conduct a number of studies that all contribute to improving the planning and control of outsourced supply chains. Some of these studies have been successfully implemented in real-life. The remainder of this introductory chapter is organized as follows. In section 1.1, we discuss outsourcing and supply chain management in more detail. In section 1.2, we discuss the motivation and background of the research presented in this dissertation. Then, in section 1.3, we explain the characteristics of the system that we study in this dissertation. Finally, in section 1.4, we discuss the research questions, the used methodologies and the further outline of this dissertation.

1.1. Outsourcing and supply chain management

In the last twenty years, supply chain management (SCM) attracted the attention from researchers and practitioners and has become a visible and popular research area in the field of Operations Management. Globalization, outsourcing, increased volatility of market demand, decreased product life cycles, and developments in information technology contributed to the relevance of supply chain management. Supply chain management deals with the integration of business processes from end customer through original suppliers that provide products, services, and information that add value for customers (Cooper *et al.*, 1997).

Supply chain management is a very broad area and has been studied by different disciplines. In general, supply chain management problems can be divided into three categories (De Kok and Graves, 2003):

- *Supply chain design*, which deals with long-term strategic decisions, such as the decision on the production location, whether to outsource, and the distribution channels.
- *Supply chain coordination*, which deals with medium-term decisions on the contract design, information sharing, and collaboration between supply chain partners.
- *Supply chain operations*, which deals with short-term decisions with respect to matching demand and supply. The focus is on releasing and allocating materials and resources within the supply chain to meet customer demands.

In this dissertation, we focus on planning problems related to *supply chain operations*. More precisely, we concentrate on the Supply Chain Operations Planning function (De Kok and Fransoo, 2003), which coordinates the release of materials and resources in a supply chain such that customer service constraints are met at minimal cost. In this function, the supply chain is modelled as a set of inventory points that are connected based on the bill-of-material characteristics of the various products that are produced in the supply chain.

In order to decide on the release of materials and resources in a supply chain, it is required that the decision maker is able to (frequently) monitor the status of the supply chain. The rapid development of IT applications, particularly the development of Enterprise Resource Planning (ERP) systems, made it possible to have real-time data available for decision making in globally dispersed supply chains. Data on the supply chain status are gathered from the ERP system and are input for the Advanced Planning System (APS), which is a decision support system for the supply chain operations planning function (Stadtler, 2005). The structural framework of APS systems (Fleischmann and Meyr, 2003) is inspired by principles of hierarchical planning (Hax and Meal, 1975), which has been developed as a concept that decomposes a complex planning problem into smaller manageable subproblems while considering their interdependencies and coordinating their decision outcomes.

Advanced Planning Systems (APS) support the supply chain operations planning function by solving the planning problem given the current status of the supply chain and several input parameters, such as the (planned) lead times, capacity constraints, batch sizes, and safety stocks. After solving the planning problem, the planning proposals often have to be controlled, possibly revised by decision makers or planners and sent back to the ERP system for execution. Having access to information on the status of the supply chain is crucial to conduct supply chain operations planning. The supply chain operations planning problem can be modelled in different ways. Two approaches exist for modelling the supply chain operations planning problem. The first approach is based on multi-echelon (stochastic) inventory theory. In this approach, the demand that is fulfilled by the supply chain is modelled as a random variable and the key decisions are the operational order releases and the positioning of inventory at the various inventory points in the supply chain. The logic is based on a line of research that has been initiated by Clark and Scarf (1960). The principles have been implemented in commercial software and have been piloted by Graves and Willems (2000) and De Kok *et al.* (2005). De Kok *et al.* (2005) also consider the operational control of multi-echelon systems.

Another approach is based on mathematical programming formulations, where the planning is done periodically for a specified number of periods in the planning horizon. In this approach, demand is inserted into the model as a point estimate for every period, which later can be updated. Safety stock is an input to the model, determined based on insights from stochastic inventory theory or other approaches, such as Kohler-Gudum and De Kok (2002) and Boulaksil *et al.* (2009a), and the key decisions are the release (production) quantities at several stages in the supply chain. Capacity constraints are modelled explicitly as aggregate constraints. The principles have been implemented in commercial software (mostly using CPLEX solver in combination with 'business rules') including SAP APO, i2, and INFOR (see also Stadtler and Kilger, 2005) and have been implemented at many companies to support the supply chain operations planning function.

In a narrow sense, a supply chain can be 'owned' by one large company with several sites, often located in different countries. Planning and coordinating the materials and information flows within such a worldwide operating company can be still a challenging task. However, the decision making is easier than in case more companies are involved in a supply chain, since the sites are part of one organisation with one board and it is likely that decision makers have full access to information needed for the supply chain operations planning.

Although mostly different companies are involved in a supply chain, most supply chain operations planning concepts (cf. De Kok and Fransoo, 2003) do not assume multiple decision authorities, limited information transparency, and that the operations are performed externally, which is the case when part of the supply chain is outsourced to a contract manufacturer, which is the subject of study in this dissertation.

Outsourcing has been defined by Chase *et al*. (2004) as an 'act of moving some of a firm's *internal activities* and *decision responsibilities* to outside providers'. Outsourcing is a broad phenomenon and it can cover many areas and industries. In the last few years, many papers appeared on the rapid development of outsourcing strategies in various industries (cf. Abraham and Taylor, 1996). In a large body of the literature, outsourcing has been motivated to allow companies to focus on their core competences, which has been recognized in the literature as a critical success factor in the long-term survival of a company (Prahalad and Hamel, 1990; Brandes *et al.*, 1997).

Outsourcing part(s) of the supply chain leads to *outsourced supply chains*. In an outsourced supply chain, multiple companies run operations at various stages of the supply chain and deliver to each other. The outsourcer (the company that outsources) is the owner of the most downstream stage of the supply chain and is partly in control, but may not have access to all status information of the entire supply chain and is definitely not able to decide on priorities and decisions at the lower planning level of the outsourced part of the supply chain. Moreover, in the outsourced part of the supply chain, another decision authority (the contract manufacturer) controls and plans that part of the supply chain, which has different and probably conflicting objectives. These aspects complicate the planning and control of the outsourced supply chain. In other words, outsourcing complicates the release of materials and resources in a supply chain due to the limited information transparency and little control over the outsourced operations. It is not obvious how to deal with these complicating factors in the supply chain operations planning models, whereas more companies face these issues. In this dissertation, we first study the implications of outsourcing on the supply chain operations planning function in more detail. Next, we study how the consequences of outsourced operations affect the performance of supply chain operations planning models and decisions. Then, we conduct a number of studies that contribute to a better planning and control of outsourced operations.

1.2. Motivation and background of the research

In this section, we discuss the practical and theoretical motivation and background of this dissertation. From a practical perspective, this research project has been inspired by the pharmaceutical industry, where outsourced supply chain structures are rapidly developing (see Figure 1.1). More specifically, a worldwide operating pharmaceutical company was involved in this research project. This multinational is a research and development based pharmaceutical company that develops, manufactures, and markets innovative products for humans. Outsourcing is definitely not restricted to the pharmaceutical industry, but in this research project, we base our research on some special manufacturing characteristics of this industry, which we discuss below in more detail as background information for the remainder of this dissertation.

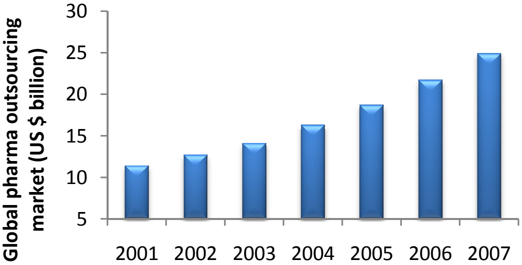
Several authorities impose very strong regulations to the pharmaceutical industry (Shah, 2004). Before being able to produce (internally or externally), several approvals are required to ensure a high level of quality standards. High investments in terms of time and money are needed in order to get the approvals. Therefore, once an approval is given, the approved source is used for a long period (at least 5 years). The strong regulations also result into strict quality checks during the manufacturing process, which extend the already long production lead times substantially.

Because of the strong regulations and the high investments to get approval from the authorities, also the outsourcing relationship is for long-term.

Due to the high setup costs and times, production runs are typically performed in (fixed) large batch and campaign sizes. Moreover, the supply chain structure is highly divergent. At the most upstream stage, only a limited number of SKUs are input to the first production process and at the most downstream stage, thousands of SKUs are sent to the end customers. This is because the products are sold in many different countries with different language texts on the medicine boxes, but also many medicines contain the same active ingredients. The finished products are sold to end customers, which are hospitals, pharmacists, and wholesalers. These customers (especially the hospitals) charge very high fines in case the pharmaceutical company is not able to satisfy the demand, which means that the service level requirements are very high.

In this industry, production activities are outsourced mainly for three reasons. First, proprietorial legislation enforces a pharmaceutical company to outsource the production activities to a contract manufacturer that owns the patent for specific technologies that are needed to perform the production activities. The second reason for outsourcing is motivated by technological or capacity restrictions. Internal capacities may be not sufficient or very specific expensive underutilized technologies may be required to perform the production, which can be done by a contract manufacturer at a much lower price due to the capacity pooling effect. The third reason for outsourcing is to have an external source producing the same product next to an internal source to share the supply uncertainty. Especially for strategic products or when a high service level is required, a pharmaceutical company is not willing to rely on a single (internal) source.

Outsourcing is rapidly developing in many industries (Barrar and Gervais, 2006). The market value of outsourcing in the United States is currently estimated between \$200 and \$300 billion (see Chapter 1 of Barrar and Gervais, 2006). A recent study of Frost and Sullivan (2008) shows that the global pharmaceutical outsourcing market increased from \$11.4 billion in 2001 to \$24.9 billion in 2007 (see Figure 1.1) and it is expected to increase for a longer period. Therefore, this dissertation is highly relevant for the pharmaceutical industry. Decision makers and planners in the pharmaceutical industry can benefit from the insights from this dissertation on how to deal with operations planning when part of the supply chain is outsourced to a contract manufacturer. One of the main insights is that the order release function of the supply chain operations planning models should consist of different (hierarchically connected) decisions and should incorporate the uncertain behaviour and capacity allocation of the contract manufacturer. Also, developers of APS systems can benefit from the insights of this dissertation. APS systems have been designed based on the assumption that the production is performed in-house, and therefore, they do not deal with outsourced supply chains.



Source: Frost & Sullivan (2008)

Figure 1.1. Global outsourcing market in the pharmaceutical industry

From a theoretical perspective, this research project was motivated by a number of challenges. First, based on an extensive literature review on outsourcing, research on outsourcing at the operational level is found to be limited. The literature on outsourcing at the operational level uses outsourcing purely as a second source (next to an internal source) to control performances such as the delivery reliability. The way a company should plan and control outsourced operations, once a company has outsourced the production activities to a contract manufacturer for a long-term has not been researched as such. Current supply chain operations planning models (cf. De Kok and Fransoo, 2003) do not consider outsourcing explicitly and assume (mostly implicitly) that the lower planning level and the operations are conducted within the same company with full information availability and full control over the operations.

The planning and control of outsourced supply chains is different from and more complicated than the planning and control of internal operations, mainly because of the limited information transparency, limited control over the detailed planning, and contractual obligations. Therefore, the supply chain planning models in the literature are little useful for the planning and control of outsourced supply chains. Moreover, the main implications of outsourcing on supply chain operations planning are also not clear. Consequently, it is not a priori obvious what the implications are of outsourcing on the supply chain planning function and how to plan and control outsourced supply chains. This is the first motivation for this research project.

As discussed above, one of the three reasons for outsourcing is to have another source next to an internal manufacturing source to share the supply risk. This results in a dual sourcing setting, which has been mainly studied in the inventory control literature. In contrast to many single source models, where the optimal control policies are available, results for dual sourcing models are limited to very special cases. Therefore, contributing to the theory on dual sourcing is the second theoretical motivation for this research. In the case studies, we noticed that the outsourcer has to make capacity reservation decisions under (capacity) uncertainty, as the capacity allocation by the contract manufacturer is not known in advance. The literature on inventory control with stochastic capacity (and demand) has been studied without considering capacity reservation, which is another motivation for this research project.

1.3. System under study

As mentioned earlier, in this dissertation, we study the supply chain operations planning problem in the case that part of the supply chain is outsourced to a contract manufacturer. An abstracted (possible) illustration of the goods flow of an outsourced supply chain is presented in Figure 1.2. After producing the active ingredients (substances in a medicine that are pharmaceutically active), the outsourcer sends these to the contract manufacturer to perform the production activities. For the production process, additional materials are needed, which are ordered from other suppliers by the contract manufacturer. The production process at the contract manufacturer is assumed to take a fixed lead time, which is also defined in the contract. Moreover, due to the high setup costs and time, the contract manufacturer produces in multiples of a fixed batch size. The contract manufacturer usually produces a number of medicines (with different strengths) out of one active ingredient. After performing the production process, the products (medicines) are sent back to the outsourcer with which the outsourcer can satisfy end-customer demand directly or after a further processing (packaging) of the medicines. The end-customer demand is not known in advance and is therefore uncertain. The cumulative lead time of such a supply chain is often longer than a year, whereas the customer lead time is about 2 months.

Figure 1.2 also shows that the contract manufacturer produces for other outsourcers on the same production line. Therefore, the contract manufacturer needs to allocate the production capacity to the different outsourcers. This is done without announcing what the allocation rules and priorities are. Moreover, the contract manufacturer requires that all outsourcers share their advance demand information, which is considered as reservations for (future) capacity. These reservations are needed by the contract manufacturer to conduct its capacity planning and to plan the supply of the additional materials that are needed for the production process. The dashed lines in Figure 1.2 show the part that is out of control of the outsourcer. Furthermore, a contract describes a number of agreements between the outsourcer and the contract manufacturer, which we will discuss in the next chapter in more detail.

Forecasts of future end-customer demands are available and are subject to changes over time. The actual demand can be different from the forecasted value, which is the result of demand uncertainty. The objective is to control the system (the outsourced supply chain) and to satisfy the end-customer demand by keeping the total relevant costs at a minimum level. The total relevant costs consist of costs for keeping products on stock at different stages in the supply chain, including safety stocks to hedge against demand uncertainty, and penalty costs for not being able to satisfy end-customer demand. The penalty costs are a representation for the loss of goodwill, but they can also represent a fee that the outsourcer has to pay in case of inability to fulfil the demand.

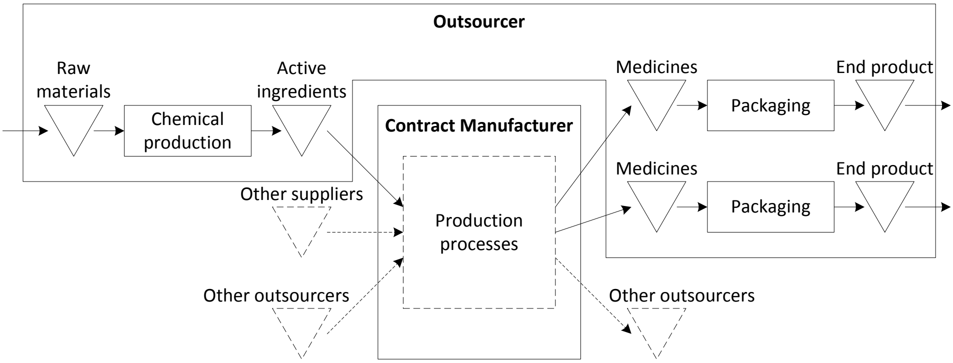


Figure 1.2. The structure of the outsourced supply chain

1.4. Research questions, methodologies and outline of dissertation

The research presented in this dissertation aims at developing models that can deal with planning and control of outsourced supply chains. The contract manufacturer can be the only source of supply or exist next to an internal manufacturing source. First, we need to have a clear understanding of the implications of outsourcing on the supply chain operations planning models. We find out that the order release function when controlling an outsourced supply chain is different from the order release function when controlling the company's own manufacturing plant due to several reasons, the primary ones being limited information transparency, uncertain capacity allocation, and contractual obligations. We will not consider strategic behaviour (in the game theoretic sense) to be able to focus purely on the decentralized and uncoordinated decision making. Extensive research has been conducted on the modelling of strategic behaviour and results have been obtained by using various forms of contracts to limit the influence of strategic behaviour. Hence, the objective of this dissertation is to get insights into the effects of the implications of outsourcing on the supply chain planning models by which the supply chain operations planning models can be improved.

In achieving this objective, we raise a number of research questions that will be addressed in different ways in the upcoming chapters. Furthermore, different research methodologies have been applied in the different chapters. We have used case study research, computer simulation, and analytical modelling as methodologies in our research, which all provide valuable insights towards understanding the planning and control of outsourced supply chains. Below, we discuss the research questions and the applied research methodologies in more detail.

1.4.1. Implications of outsourcing on supply chain operations planning

Most supply chain operations planning models (cf. De Kok and Fransoo, 2003) assume that the supply chain is planned at some level of aggregation and that further coordination is conducted at a more detailed level by lower planning levels. These concepts (mostly implicitly) assume that the lower planning level and the operations are conducted within the same company with full information availability and full control over the operations. These two aspects do not apply when the operations are outsourced to a contract manufacturer, which is an independent company with different and likely conflicting objectives. Therefore, before modelling can start, we need to know what the implications are of outsourcing part(s) of the supply chain to a contract manufacturer. Consequently, the first research question addressed is:

1. What are the main implications of outsourcing on the supply chain operations planning function?

We deal with this question in two ways. First, we conduct an extensive literature study on outsourcing research to investigate what has been documented on the implications. We identify that little is documented on outsourcing from the operational planning and control perspective. Moreover, in the formal modelling literature, outsourcing is considered exclusively as a second external source in addition to the internal manufacturing source to control some performances. Second, we conduct two extensive case studies into outsourced supply chains at a number of pharmaceutical companies, where the contract manufacturer is the only source of supply. The case studies involve a number of essential processes that are closely related to the supply chain operations planning process, namely contracting, performance measurement, information sharing and availability, and the distribution of planning authority between the outsourcer and the contract manufacturer.

One of the main insights from the case studies is that in an outsourcing relationship, the order process consists of different hierarchically connected decisions in time. Hence, the order release mechanism requires a richer and more developed communication and ordering pattern than commonly assumed. These and additional insights show the complexity and implications of outsourcing from an operational planning perspective. The literature study and the case studies are discussed in Chapter 2 and the content of this chapter has also been presented in Boulaksil and Fransoo (2008a).

1.4.2. Order release strategies to control outsourced operations

As discussed earlier, one of the main implications of outsourcing on the supply chain operations planning models is the fact that the order release function is different and more complicated when controlling an outsourced supply chain. Then, the question is whether and to what extent a more complicated order release function improves (or deteriorates) the performance of the supply chain operations planning models. Therefore, following the case studies, we make the modelling assumptions explicit and develop a formal model that incorporates more advanced order release functions. Hence, the second research question is (in two parts):

2. How should the supply chain operations planning models be adapted to incorporate outsourcing in the planning models? And what is the impact of adding these aspects on the performance of the supply chain operations planning models?

These questions are addressed in Chapter 3. In that chapter, we discuss, develop and measure the performance of three different order release strategies to control outsourced operations based on insights from Chapter 2. The order release strategies differ in the number of decision levels and they incorporate the probabilistic behaviour of the contract manufacturer. The production plans are generated based on deterministic mathematical programming principles (mixed-integer programming) and the performance analysis is done by a simulation study in which the model is solved in a rolling horizon setting to incorporate the effect of stochastic demands. Based on a numerical study, we show that a more advanced order release strategy that captures the characteristics of outsourcing performs significantly better than a simpler strategy that is commonly used in practice. We also discuss the conditions for a successful implementation of the more advanced order release strategy. This chapter also appeared as Boulaksil and Fransoo (2009).

1.4.3. Dual sourcing with contract manufacturing

As discussed earlier, one of the reasons for outsourcing is to have another external source next to the internal manufacturing source to limit the supply uncertainty for strategic products. However, as we have observed in a case study, the two sources have different characteristics, cost structure, and constraints. From the literature, we know that the optimal control policy is generally not known for a dual sourcing setting due to its complexity. Still, the decision maker needs to allocate the production volume among the sources in a smart way. Therefore, the third research question we address is:

3. In case a contract manufacturer exists next to an internal manufacturing source, how to allocate the production volume over the two sources in a smart way?

Chapter 4 is devoted to this research question. In that chapter, we consider the case where the outsourcer faces stochastic demand, inaccurate demand forecasts, and has outsourced some production activities to a contract manufacturer. The outsourcer has two different supply sources for the same product: its own manufacturing plant and the contract manufacturer. The two sources are constraining the supply quantities in different ways. Its own manufacturing plant is more rigid, cheaper and capacitated, whereas the contract manufacturer benefits from capacity pooling effects and is more flexible but more expensive. A mathematical programming model for the considered dual sourcing setting is proposed and based on data from a real-life situation; we compare the performance of two different allocation strategies by a simulation study in which we solve the model in a rolling horizon setting. The results show that a rigid allocation strategy (the cheaper source supplies each period a constant quantity) performs substantially better than the dynamic allocation strategy (the allocation quantities are dynamic) if the parameters are chosen properly. This chapter also appeared as Boulaksil and Fransoo (2008b).

1.4.4. Capacity reservation and utilization under uncertain capacity allocation

Another important implication of outsourcing that also follows from the case studies is the fact that the contract manufacturer produces for a number of outsourcers on the same capacitated production line. That means that the contract manufacturer needs to allocate its production capacity among the outsourcers, which is done based on rules and priorities that are unknown to the outsourcers. The contract manufacturer is not willing to share this information with the outsourcers, also because some outsourcers are competitors and the capacity allocation share of the competitor might be sensitive information. Therefore, the allocated capacity for the outsourcer is not known in advance, also because the outsourcer has no information about the reservations of the other outsourcers.

For capacity planning purposes, the contract manufacturer requires that all outsourcers share their advance demand information, which is considered as capacity reservation, prior to ordering. Then, the contract manufacturer responds to the capacity reservations by acceptance or (partial) rejection based on the capacity allocation decision. The accepted reservation is the upper bound for the order quantity that follows later. From the outsourcer's perspective, he needs to make a reservation decision under capacity uncertainty, i.e., without knowing what part of the reservation will be accepted. Therefore, the fourth research question addressed is:

4. What is the structure of the optimal reservation and order policies for the outsourcer to control the outsourced supply chain?

This question is addressed in Chapter 5. In that chapter, we study this problem from the perspective of the outsourcer which faces stochastic demand and stochastic capacity allocation from the contract manufacturer. A single-item periodic review inventory system is considered and we assume linear inventory holding, backorder, and reservation costs. We develop a stochastic dynamic programming model for this problem and characterize the optimal policies. We conduct a numerical study where we also consider the case where the capacity allocation is dependent on the demand distribution. For that case, we show the structure of the optimal policy based on the numerical study. Further, the numerical results reveal several interesting managerial insights, such as that the optimal reservation policy is little sensitive to the uncertainty of the capacity allocation from the contract manufacturer. In that case, the optimal reservation quantities hardly increase, but the optimal policy suggests increasing the utilization of the allocated capacity.

1.4.5. Capacity flexibility allocation

Earlier, we discussed the fact that the outsourcers are obliged to reserve capacity prior to ordering. After collecting the reservations, the contract manufacturer informs each outsourcer about the accepted reservation, based on its capacity planning. The accepted reservation forms the upper bound for the order that follows later. Since the reservations and orders are uncertain, the contract manufacturer needs to make the acceptance decision under uncertainty. The more the contract manufacturer accepts from an outsourcer, i.e., the more capacity flexibility allocated to an outsourcer, the more risk is taken by the contract manufacturer, as the outsourcer might not fully utilize the accepted reservation quantity. However, the outsourcer is willing to pay an additional amount to compensate the contract manufacturer for that risk. Assuming that the outsourcers have different levels of uncertainty, we raise the following fifth research question:

5. How should the contract manufacturer allocate its capacity flexibility to the different outsourcers?

Chapter 6 is devoted to this research question. In that chapter, we study the outsourced supply chain from the contract manufacturer’s perspective that serves a number of outsourcers on the same production line. The outsourcers have different levels of demand uncertainty and the contract manufacturer faces the question of how to allocate the contractual capacity flexibility in an optimal way. We develop an integer programming model, which optimizes the allocation of capacity flexibility by maximizing the profit. Offering more flexibility to the more risky outsourcer generates higher revenue, but also increases the lost sales costs. The allocated capacity flexibilities are input (parameters) to the lower decision level, where the operational planning decisions are made and demands are observed. The simulation results reveal interesting managerial insights, which are helpful for managers of contract manufacturers when having contract negotiations with the outsourcers. This chapter also appeared as Boulaksil *et al.* (2009b).

Finally, in Chapter 7, we summarize the main contributions of this dissertation. In addition, we discuss the managerial implications of this research and some ideas for future research on the topics that we discussed in this dissertation.

2. Implications of outsourcing on operations planning – findings from the pharmaceutical industry[1]

In this chapter, we address the first research question of this dissertation, namely: *What are the main implications of outsourcing on the supply chain operations planning models?* In Chapter 1, we discussed that manufacturing companies increasingly outsource parts of their supply chains to contract manufacturers. Various theories on the benefits, reasons, and risks of outsourcing have been developed, discussed, and analyzed in a wide body of literature. In this chapter, we provide a distinctive view on the literature on outsourcing research and we identify that little is known on outsourcing at the operational level. Moreover, in the formal modelling literature, outsourcing is considered exclusively as a second external source in addition to the internal manufacturing source. The objective of this chapter is to contribute to the understanding of the implications of outsourcing at the operational planning level. Therefore, we conduct two extensive case studies into outsourced supply chains in the pharmaceutical industry, where the contract manufacturer is the only source of supply. The main insight is that in an outsourcing relationship, the order process consists of different hierarchically connected decisions in time, hence requiring a richer and more developed communication and ordering pattern than is commonly assumed. These and additional insights show the complexity and implications of outsourcing from an operational planning perspective. This understanding is also essential to better take the strategic outsourcing decision and to further develop supply chain decision support tools that explicitly incorporate outsourced operations.

2.1. Introduction

Outsourcing has been defined by Chase *et al*. (2004, p.372) as an 'act of moving some of a firm's internal activities and decision responsibilities to outside providers'. Outsourcing is a broad phenomenon and it can cover many areas and industries. In the last few years, many papers appeared on the development of outsourcing strategies in various industries, which also show that outsourcing is developing in many industries in the last few years. Abraham and Taylor (1996) provide evidence of rising outsourcing of business services in thirteen U.S. industries and Helper (1991) documents the increased outsourcing of parts in the U.S. automobile sector. A survey in 1997 of more than 600 large companies by the American Management Association finds that substantial numbers of companies are now outsourcing in many areas (information systems, finance, accounting, manufacturing, maintenance, and personnel). Among manufacturing companies, more than half had outsourced at least one component of their production process (Bryce and Useem, 1998).

Outsourcing decisions and strategies have been widely investigated and documented in the literature. Based on a survey of more than 1,200 companies, Deavers (1997) identifies five main reasons for outsourcing: improving company focus, accessing world-class capabilities, acceleration of benefits from reengineering, sharing of risk and freeing of resources for other purposes. In many papers, outsourcing has been mainly motivated by a trade-off to allow companies to focus on their core competences. The idea of focusing on core competences has been recognized in the literature as a critical success factor in the long-term survival of a company (Prahalad and Hamel, 1990; Brandes *et al.*, 1997). Some papers consider the managerial implications of outsourcing, like the loss of control and the focus on core activities (Momme, 2002).

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[1] The results in this chapter have also been presented in Boulaksil and Fransoo (2008a).

Other papers focus on strategic implications (Quinn and Hilmer, 1994), the financial and human resource implications (Lever, 1997) or the outsourcing of logistics functions to service providers (Rabinovich *et al*. (1999); Andersson and Norrman (2002)). Besides the motivations and implications of outsourcing, many papers have looked into the benefits of outsourcing (cf. Jiang *et al.*, 2007) and the risks of outsourcing (cf. Schniederjans and Zuckweiler, 2004).

Although some review papers (cf. Kremic *et al*., 2006) have sorted the literature on outsourcing in different ways, we are specifically interested in the distinction between *strategic outsourcing decisions*, which are decisions related to whether to outsource or not, and the *operational planning and control of outsourced operations*, which are operational issues that follow after the outsourcing decision. Strategic outsourcing decisions have been mainly motivated by the transaction cost theory (Holcomb and Hitt, 2007), resource-based view (McIvor, 2009), and the focus on the core competences (Prahalad and Hamel, 1990). The literature on the operational planning and control of outsourced operations is found to be scarce. We organize the literature accordingly and we bridge between two large and different streams within the literature: the stream of papers that develops insights based on empirical studies (also case studies) and the stream of papers that develops insights based on formal modelling studies. Although these two different streams have different theoretical backgrounds and methodologies, they both study the outsourcing phenomenon. Based on this literature review, we identify a gap in the literature on outsourcing. To our knowledge, no empirical studies have been documented in the literature on (the implications of) outsourcing from the operational planning and control perspective. Given that a manufacturing company has outsourced part of its supply chain to a contract manufacturer, how to plan and control this supply chain? How to incorporate the outsourced operations in the outsourcer's supply chain planning models? These are questions that remain unanswered in the literature. Therefore, the objective of this chapter is to gather insights on the implications of outsourcing on the operational planning level, i.e., how the operational planning function is complicated due to the outsourcing decision that has been made in the past.

To gather these insights, we conducted two extensive case studies at three pharmaceutical companies and we studied the operational side of manufacturing outsourcing and the implications and complexity of outsourcing from an operational planning perspective. The insights gathered from the case studies are contributing to the knowledge on operational planning and control of outsourcing and they are helpful to incorporate outsourced operations in supply chain planning modelling, as the supply chain planning models mostly assume that the production is performed in-house (cf. De Kok and Fransoo, 2003).

This chapter is organized as follows. In section 2.2, we give an extensive review on the literature on outsourcing, where we bridge between the empirical studies and formal modelling parts of the literature and where we distinguish between studies that have looked into strategic outsourcing and papers that studied the operational side of outsourcing. Section 2.3 discusses the case studies and subsequently, section 2.4 discusses the main insights that we gathered from the case studies and shows the theoretical contribution of this chapter. Then, section 2.5 draws some conclusions.

2.2. Literature review

Some papers have reviewed the literature on outsourcing and developed decision frameworks, mainly as a support for managers to assist them in the outsourcing decision process (Kremic *et al.*, 2006; Fill and Visser, 2000; Razzaque and Sheng, 1998). Kremic *et al*. (2006) give an excellent review of the literature on outsourcing and develop a framework to classify whether the considered papers address outsourcing benefits, risks, motivations or factors.

Further, the paper provides an interesting overview of the reasons for outsourcing, which can be summarized in three main blocks: cost, strategy, and politics. However, Kremic *et al*. (2006), but also other review papers do only consider strategic outsourcing decisions, i.e., whether to outsource and e.g., which organization's function to outsource, whereas we are also interested in the papers that study outsourcing from the operational planning level.

In this section, we structure the recent literature on outsourcing research in two ways. First, we distinguish between papers that develop insights based on empirical studies and papers that develop insights based on formal (mathematical) modelling. We did not find the combination of these two streams of literature in earlier work. Second, we distinguish between papers that study the strategic outsourcing decision and papers that study outsourcing from the operational planning and control perspective. Studying the strategic outsourcing decision means that the paper is mainly addressing the question whether to outsource or not. Papers that study outsourcing from an operational planning and control perspective address questions that follow after the outsourcing decision, e.g., the quantities to be ordered at the contract manufacturer or the planning implications of outsourcing.

2.2.1. Strategic outsourcing decision

Since the large majority of the papers on outsourcing consider outsourcing at a strategic level, we divide this large body of literature into papers that mainly consider the motivation for outsourcing, the process of outsourcing, and the result of outsourcing. Table 2.1 shows the classification of the considered papers. It is not our objective to capture the whole literature of outsourcing, as the topic has received a lot of attention in various parts of the literature (cf. Kremic *et al*., 2006), but we mention papers from different streams in the literature to have as much as possible a representative overview of the recent literature to be able to draw valid conclusions. Below, we discuss the main insights that follow from the papers.

Table 2.1. An overview of the outsourcing literature

		Empirical studies	**Formal modelling**
Strategic level	**Motivation**	Holcomb and Hitt (2007); Lankford and Parsa (1999); Quinn and Hilmer (1994); Sanders *et al*. (2007)	Cachon and Harker (2002); Tsai and Lai (2007); Van Mieghem (1999)
	Process	Amaral *et al.* (2006); De Boer *et al*. (2006); Kotabe *et al*. (2007); Momme and Hvolby (2002); McIvor (2000); Vining and Globerman (1999)	Balakrishnan *et al*. (2007); Ngwenyama and Bryson (1999); Schniederjans and Zuckweiler (2004)
	Result	Berggren and Bengtsson (2004); Brandes *et al.* (1997); Bryce and Useem (1998); Jiang *et al*. (2006); Jiang and Qureshi (2006); Marshall *et al*. (2007); Rabinovich et al. (1999)	Kamien and Li (1990); Gorg and Hanley (2005); Abdel-Malek *et al*. (2005)
Operational level		Not available	Bertrand and Sridharan (2001); De Kok (2000); Kim (2003); Lee *et al*. (2002); Kouvelis and Milner (2002); Yang *et al.* (2005)

Motivation – Empirical studies

The Transaction Cost Theory (TCT) has been the dominant theory that explains outsourcing as an economic approach that achieves cost efficiencies by assigning transactions to different governance mechanisms. The theory argues that organizations should consider the level of transaction-specific investment in the economic exchange as the principal determinant of whether an economic exchange should be managed internally within the organization or not (McIvor, 2009). The second theory has been described by more recent research that uses the Resource Based View (RBV) to examine the role of specialized capabilities as a potential source of value creation in relationships between firms (Holcomb and Hitt, 2007). This theory considers an organization as a bundle of assets and resources that, if employed in an optimal way, can create competitive advantage (McIvor, 2009). Another main motivation for strategic outsourcing is that a firm can leverage its skills and resources for increased competitiveness (Quinn and Hilmer, 1994). There are also studies that warn for hidden costs of outsourcing (Sanders *et al.*, 2007). They argue that the strategic outsourcing decision should be flexible and dynamic, rather than rigid and static.

One can conclude that there are mainly two motivators for outsourcing: cost (Holcomb and Hitt, 2007) and strategy (Quinn and Hilmer, 1994; Sanders *et al*., 2007). We refer the reader to Deavers (1997) and Kremic *et al.* (2006) for a more complete overview of reasons for outsourcing. Many papers discuss a firm's wish to save costs as a motivation for companies to outsource (cf. Vining and Globerman, 1999). Outsourcing for cost reasons can occur when the contract manufacturer is so specialized or benefits from economies of scale that the contract manufacturer's fee plus the transaction costs are still lower than producing in-house (Holcomb and Hitt, 2007). Beside costs, strategic reasons are also often mentioned as reason for outsourcing, like focusing on core competencies (Quinn and Hilmer, 1994) or the need for greater flexibility to manage demand uncertainties (Lankford and Parsa, 1999).

Motivation – Formal modelling

In case of competition between companies that are allowed to outsource, economies of scale provide a strong motivation for outsourcing (Cachon and Harker, 2002). Economies of scale means that the cost per unit produced is decreasing in the cumulative production volume and may result in a case where the lower cost company has a higher market share and finally can ask a higher price. Economies of scale provide a strong motivation for outsourcing and companies will strictly prefer to outsource even if outsourcing provides no direct cost advantage, as more benefits will be realized on the long-term (Cachon and Harker, 2002). Papers in this box also studied strategic outsourcing when a company faces a capacity expansion decision, which is the decision whether to expand the own production capacity or to outsource. Mathematical models have been developed to evaluate the benefits of expanding the various kinds of capacity and outsourcing simultaneously (Tsai and Lai, 2007). The value of this option (to outsource) turns out to increase as markets are more volatile or more negatively correlated (Van Mieghem, 1999).

Process – Empirical studies

The strategic outsourcing process is complicated by the cross-functional interdependencies between the production system and internal support functions (Momme and Hvolby, 2002). Therefore, the outsourcing process must be structured carefully, also to decide which activities are the most suitable for outsourcing and which type of supplier should be used. Moreover, many risks are associated with the outsourcing process and outsourcing contracts (Vining and Globerman, 1999), which can be partly managed by investing in processes and information systems and in a good relationship with the contract manufacturer (Amaral *et al.*, 2006).

Another main risk is that a firm outsources an amount that differs substantially from the optimal degree of outsourcing (Kotabe *et al.*, 2007). The outsourcing-performance relationship takes a inverted-parabolic shape, implying that as firms deviate further from their optimal degree of outsourcing, by either insourcing or outsourcing too much, their performance will suffer disproportionately.

Process – Formal modelling

Models have been developed that build upon the transaction cost theory to evaluate different outsourcing strategies to find the minimum cost and the maximum possible profit for each strategy (Ngwenyama and Bryson, 1999). These strategies are associated with different risk profiles, especially when outsourcing takes place between business organizations in different countries or in an international context (Schniederjans and Zuckweiler, 2004). Formal modelling studies on the outsourcing process also focus on the information aspect, namely how incomplete information and information intensity affects the outsourcing decision and which part of the supply chain to outsource (Balakrishnan *et al.*, 2007). In general, incomplete information leads to companies preferring to outsource their back-end rather than their front-end processes.

Result – Empirical studies

The strategic outsourcing decision cannot be taken without insights on the possible result of that decision. Outsourcing can improve a firm's cost efficiency, but there is no evidence that outsourcing improves firm's productivity and profitability (Jiang *et al.*, 2006). On the other hand, outsourcing can improve customer service and reduce costs (Rabinovich *et al.*, 1999) and might have a positive effect on the outsourcing firms' market value (Jiang *et al.*, 2007). Results based on Japanese manufacturing industries data indicate that (short-term) outsourcing has positive effects on outsourcing firms' market value (Jiang *et al.*, 2007), especially those that developed collaborative relationships with their suppliers (Marshall *et al.*, 2007).

Berggren and Bengtsson (2004) compared the actual outcomes of outsourcing at two leading telecom firms (Nokia and Ericsson), who applied different strategies for production and outsourcing. The authors state that besides the cost advantages, which are often the key driver for outsourcing, firms also have to consider the costs of transferring products, equipment, and knowledge to the contract manufacturer. The authors show that considering these aspects might have led to a strategy that combines external sourcing and in-house production rather than complete outsourcing for the considered firms.

Result – Formal modelling

The option of outsourcing in production planning models results in production smoothing (Kamien and Li, 1990) and in different amounts of safety stocks needed in a supply chain (Abdel-Malek *et al.*, 2005). In an international context, the effect of outsourcing on company level productivity is dependent on the nature of the outsourced inputs (services or tangibles) and on the company's export intensity (Gorg and Hanley, 2005). Outsourcing of materials provides significant productivity gains, but this effect holds only for plants with low export intensities.

2.2.2. Operational planning and control of outsourced operations

The second part of the literature review considers the literature on the operational planning and control of outsourced operations. Several formal modelling studies have been conducted on outsourcing on the operational level and below, we discuss their main insights.

Formal modelling

All studies that appeared in this part of the literature consider the *option* of outsourcing next to an internal manufacturing source to achieve a certain objective, such as the minimization of the makespan for the order due dates (Lee *et al.*, 2002) or which orders to outsource in case the order arrival rate is greater than the service rate (Bertrand and Sridharan, 2001).

Other studies have made explicit under which conditions to outsource *part* of the production volumes (e.g. De Kok, 2000; Yang *et al.*, 2005). Kouvelis and Milner (2002) show that greater demand uncertainty increases the reliance on outsourcing, whereas greater supply uncertainty increases the need for vertical integration.

2.2.3. Insights from the literature

In this section, we sorted the literature on outsourcing research in a unique way. From one side, we considered the literature on the strategic outsourcing decision and the literature on the operational planning and control of outsourced (manufacturing) operations. We have seen that the strategic outsourcing decisions have been widely investigated and documented in the literature. The main research questions addressed in that part of the literature are theories behind outsourcing (cf. Holcomb and Hitt, 2007), whether to outsource or not and related issues such as: the risks that are associated with outsourcing (Schniederjans and Zuckweiler, 2004), the conditions for successful outsourcing (Van Mieghem, 1999), which activities to outsource (e.g. Quinn and Hilmer, 1994; Balakrishnan *et al*. 2007), how much to outsource (Kotabe *et al.*, 2007) and the results of outsourcing (e.g. Berggren and Bengtsson, 2004; Brandes *et al.*, 2007). All the papers in this stream of the literature assist the manager in taking the outsourcing decision, i.e., whether to make-or-buy, whether to perform the production in-house or to whether to purchase the materials externally.

The literature on outsourcing on the operational level, which deals with outsourcing after having made the outsourcing decision, is found to be scarcer. Once a firm has made the outsourcing decision, the outsourced operations need to be planned and controlled. The studies that appeared on outsourcing on the operational level are all formal modelling studies, where mathematical models have been developed which incorporates outsourcing, whereas (to our knowledge) no studies are documented in the literature that have looked into outsourcing on the operational level from an empirical perspective. This gap is quite remarkable given the enormous amount of literature on outsourcing. Therefore, the literature on outsourcing lacks insights (based on empirical studies) on the process of outsourcing on the operational planning level.

The formal modelling studies that appeared on outsourcing at the operational level consider outsourcing as an option *next to* the internal production system (dual sourcing), i.e., part of the production is outsourced to a contract manufacturer next to the internal production to achieve a certain objective, mostly to cover excess demand or to control the delivery performance towards customers (De Kok, 2000; Bertrand and Sridharan, 2001; Lee *et al.*, 2002) or to deal with uncertainties (Kouvelis and Milner, 2002).

Therefore, there is a need to gather empirical insights on outsourcing at the operational planning level in case the contract manufacturer is the *only* source for performing the production activities. To (contribute to) fill(ing) these gaps in the literature, we performed two extensive case studies to gather empirical insights on outsourcing, i.e., the implications of outsourcing on the operational planning level, *given* that the contract manufacturer is the only supplying source.

2.3. Case studies

2.3.1. Motivation and methodology

As suggested by Yin (1994), the use of case studies is typical in the first theory development stages, when investigating events or phenomena that have little or no theoretical background and no a priori theory can be identified to select case studies and the constructs to be examined. The case study methodology that we use in our studies is similar to that of Eisenhardt (1989), Yin (1994), Voss *et al*. (2002).

Some papers have appeared in the literature that discuss planning issues in the pharmaceutical industry (Ashayeri and Selen, 2003; Papageorgiou *et al*., 2001; Sundaramoothy and Karimi, 2004; Grunow *et al*., 2003), but most of these papers assume that the production is performed in-house and no outsourcing is considered. Sundaramoothy and Karimi (2004) develop a model in which they consider production outsourcing in the pharmaceutical industry, but they address the strategic question whether to undertake the production of a new product in-house or whether to outsource it to a contract manufacturer. That paper considers outsourcing, but it has mainly been approached from a strategic point of view, as outsourcing is not studied as such, but it has been used as a strategy to make the introduction of new products more attractive.

Besides the manufacturing outsourcing in the pharmaceutical industry, there are some studies that consider the outsourcing of research and development activities. Since the pharmaceutical industry is characterized by a large amount of such activities, most papers on outsourcing within this industry deal with the outsourcing of these activities (Higgins and Rodriguez (2006); Jones (2000); Piachaud (2002)). Since these papers are out of the scope of our study, we will not discuss them in more detail.

The choice for the pharmaceutical industry provides a perfect context to identify exemplar cases, as outsourcing and outsourced supply chains are not yet documented and they are rapidly developing in this industry (see Chapter 1). Furthermore, Lurquin (1996) already noticed that supply chain optimization is one of the strategic issues that the pharmaceutical industry will face in the coming years and Shah (2004) also remarked that optimal operational planning is a major research theme in the pharmaceutical industry and it did not receive due attention. Shah (2004) also shows that the use of contract manufacturers forms a source of complexity, as it extends the supply chain coordination problems. The case studies that we describe in this chapter intend to contribute to this line of research.

The case studies were conducted from January 2006 till March 2007. During this period, we were positioned at the outsourcer (the company that outsourced the production activities) and we have visited the contract manufacturers regularly. Further, several managers and planners at different hierarchical levels of the companies were regularly and structurally interviewed. To ensure reliable results, multiple sources of evidence were used. Therefore, besides the interviews, we also performed an extensive documentation study, data analyses, looked into archival data, such as the contracts, and conducted direct observations.

We are aware that care is needed in drawing general conclusions from case studies, as the analysis is based on a limited number of cases. We conduct the case studies to understand the implications of outsourcing on the operational planning, which form a source of inspiration for the research questions that we raise in the various chapters of this dissertation. Despite this, case studies can have high impact and can lead to new insights (Voss *et al.*, 2002), as many concepts and theories that are documented in the literature of Operations Management (e.g. lean manufacturing) have been developed from case studies.

2.3.2. Two case studies

In this section, we describe the two case studies that we performed at three different companies (one outsourcer and two contract manufacturers) that operate in the pharmaceutical industry. We mainly focus on the operational planning process between the outsourcer and the contract manufacturers and the main implications of controlling the outsourced operations. The outsourcer is a research- and development based worldwide operating pharmaceutical company with a global presence in branded prescriptive products. This company plans and controls its global supply chain integrally and has implemented a so-called Advanced Planning and Scheduling tool (Stadtler and Kilger, 2005) to support this. This outsourcer has outsourced some production activities to two contract manufacturers; one is located in Germany and the other one in the United States. The contract manufacturers do not have their own product portfolio, but produce products by providing outsourcing services for other companies (the outsourcers).

In these cases, the outsourcing decision has been made in the past and outsourcing relationships in this industry are typically long-term, as very costly and time-consuming approvals are needed from several authorities to be able to produce at the contract manufacturer. Therefore, the outsourcer and the contract manufacturer typically go for long-term relationships. The outsourcer faces the problem of how to plan and control the outsourced operations. Therefore, insights on outsourcing on the operational level are crucial. In the next two sections, we discuss the case studies in more detail. For confidentiality reasons, we cannot mention the names of the companies or the products.

2.3.2.1. Case study 1

In this case study, we consider the case where the outsourcer has outsourced the production of product A, one of the outsourcer's strategic products, to contract manufacturer CM1, which is located in the United States. This product is a tablet and there are three variants of this tablet (stock keeping units), which differ in the strength of the tablet, i.e., the amount of active ingredient in the tablet. The tablets are sold in boxes that consist of a number of blisters. Each blister contains six tablets. These tablets have a specific serving method, which is patented and owned by contract manufacturer 1 (CM1). Therefore, in this case, the outsourcer was forced to outsource the production activities to this contract manufacturer, which produces several products for several customers on the same production line. That means that the contract manufacturer's production line is not dedicated to this particular outsourcer, which makes it harder for the outsourcer to order, as the allocated capacity is not known in advance. Through a better use of the available information and the contract, the outsourcer will be able to better plan and control the supply chain. This issue will be discussed later more in detail, as it forms one of the main difficulties of planning this supply chain.

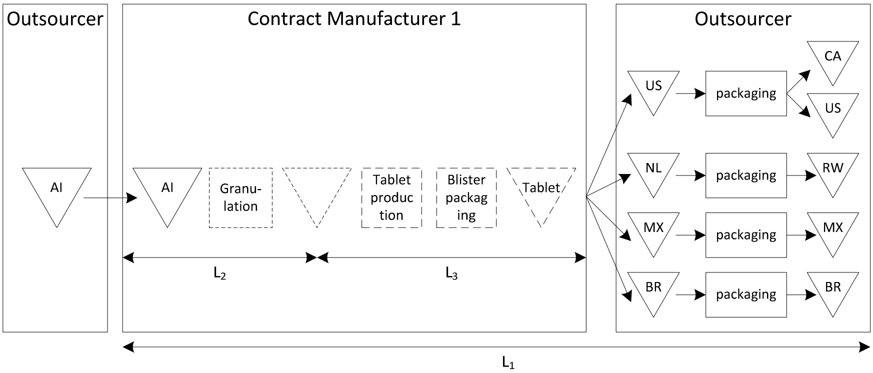

Figure 2.1. The supply chain of product A

Figure 2.1 shows the supply chain (goods flow) of product A. A triangle represents a stockpoint and a box a production unit. The intermittent part of the figure shows the part of the supply chain that is out of sight (and control) of the outsourcer. The outsourcer produces the active ingredient (AI) and sends it to the contract manufacturer. The output of the contract manufacturer's production process is blistered tablets. Then, these tablets are sent to one of the four outsourcer's packaging sites, which are located in the United States, the Netherlands, Mexico, and Brazil. These sites pack the blistered tablets and send them to several national warehouses (the most downstream stockpoints), which are located in Canada (CA), United States (US), MX (Mexico), BR (Brazil), and the rest of the world (RW). These national warehouses keep inventories of the finished products and are responsible for selling the products to the outsourcer's customers.

The contract manufacturer's production process starts with the granulation of the active ingredient. The granulated material is stocked at the intermediate stockpoint. Then, the tablet production process starts and immediately thereafter, the tablets are blistered and country specific text is printed on the blister. Therefore, the contract manufacturer's production process is driven by orders from the outsourcer. These orders are first grouped by the planner (of the outsourcer), as this person is responsible for releasing orders towards the contract manufacturer. The total order lead time for orders from the national warehouses is L_1 time periods (22 weeks).

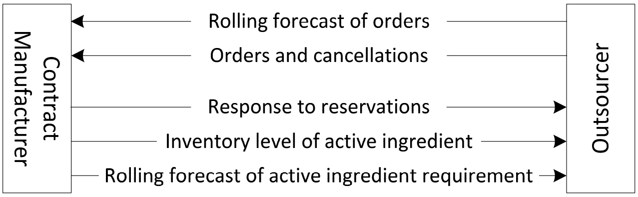

Figure 2.2. Information flow between the two parties

Figure 2.2 shows the information flow between the two parties. The two parties agreed upon communicating these data in the contract. At the beginning of each planning cycle, which is equal to one month, the outsourcer provides the contract manufacturer a 12-months rolling forecast of the outsourcer's requirements, which is based on the demand forecast of end products. These forecasts are basically reservations of capacity slots by the outsourcer, which can be either accepted, changed or cancelled by the contract manufacturer. As discussed earlier, the contract manufacturer serves multiple customers on the same production line. Since the customer's demand is uncertain, it might be that the cumulative reserved quantity by all customers exceeds the contract manufacturer's capacity, which results in some rejections or changes of the reservations.

Another reason for sharing the demand information is the fact that additional materials are needed for producing the tablets. CM1 is namely responsible for ordering these materials, and therefore getting forecast data from the customers is crucial to control the supply of the additional materials.

Once a reservation is accepted, it is considered as an order commitment until a lead time before the delivery date the outsourcer communicates the final orders, which should not deviate more than a predefined amount from the reserved quantities. The outsourcer places orders with a minimum of 90 days lead time before the delivery is required. The contract manufacturer has the right to reject any orders in which the delivery date is earlier than 90 days. However, even after placing the order, the outsourcer has the option to change the ordered quantity up to L_3 periods (=45 days) before the delivery date, i.e., before the tablet production starts (see Figure 2.1). The change (in ordered quantity) is limited to the range between -10% and +25%. In the case the outsourcer decreases the ordered quantity by more than 10%, the outsourcer pays the contract manufacturer a cancellation fee of 30% of the value (price) of the products cancelled.

Further, at the beginning of each planning cycle, the contract manufacturer shares with the outsourcer the inventory data of the active ingredients. These data are needed by the outsourcer to plan its supply chain properly. However, it turns out that in practice this contract manufacturer is always too late with sharing these data, which means that the outsourcer bases the inventory data on an estimate, which is made by subtracting the received quantities from the last shared inventory data. This estimate can deviate from the real inventory level due to varying yields and quality rejections within the contract manufacturer’s process. The last flow of information between the parties is the 12 months rolling forecast of the requirements for active ingredients that is communicated by the contract manufacturer towards the outsourcer.

The information flows, as shown in Figure 2.2, are agreed upon in the contract between the outsourcer and the contract manufacturer. Besides the information flow agreements, there is also a volume agreement between the parties. The contract manufacturer commits an annual manufacturing capacity of X million tablets. If the outsourcer does not order in a year an amount which is at least 90% of the committed capacity, the outsourcer pays the contract manufacturer a capacity reservation fee multiplied with the difference between the committed capacity level and the actual amount ordered for delivery in the same year. If the outsourcer fails to utilize a minimum of 80% of X in a given year, then a new lower capacity will be agreed to by the parties for the future years, without any penalty fee.

Apart from the volume agreement, a performance agreement (delivery reliability) in the contract sets that if the contract manufacturer delivers an order 20 days after or 10 days before the delivery date, the contract manufacturer has pay to the outsourcer a penalty fee of 1% of the value of the products for that delivery for each day that such order is late or early (with a maximum of 20% of the value of the outsourcer's order). On the other hand, if the outsourcer fails to deliver the active ingredients in sufficient quantities to the contract manufacturer, then the outsourcer will be charged with a fee per tablet if the delay resulted in idle time of allocated machine capacity.

The outsourcer measures the delivery reliability of the contract manufacturer by the following measure: number of orders shipped within the promise date (-15 days to 0 days) over the total number of orders promised to ship. Based on a data analysis, it turns out that the delivery reliability was about 27% in 2005. This has mostly to do with the continuous changes the outsourcer makes in the orders that are placed at the contract manufacturer. In section 2.4, we discuss this in more detail.

2.3.2.2. Case study 2

In this case study, we consider the case where the outsourcer has outsourced the production of product B to contract manufacturer CM2, which is located in Germany. Product B is a parenteral product (a liquid in which the active ingredient is dissolved) and it is also considered as one of the outsourcer's strategic products. Product B has three variants that differ in the concentration of the liquid. In this case, the outsourcer benefits from the capacity pooling effect at CM2, which produces several products for several customers on the same production line. That means that the outsourcer does not know in advance which part of the capacity is available for the production of product B. Neither does CM2 know that exactly in advance, as CM2 first collects all demand data (orders) of all customers and in the case of a capacity shortage, some changes or rejections will be issued towards the customers. This is actually the same situation as in case study 1 and we will discuss this issue in more detail in the next section, as it forms one of the main difficulties of planning outsourced operations in a supply chain.

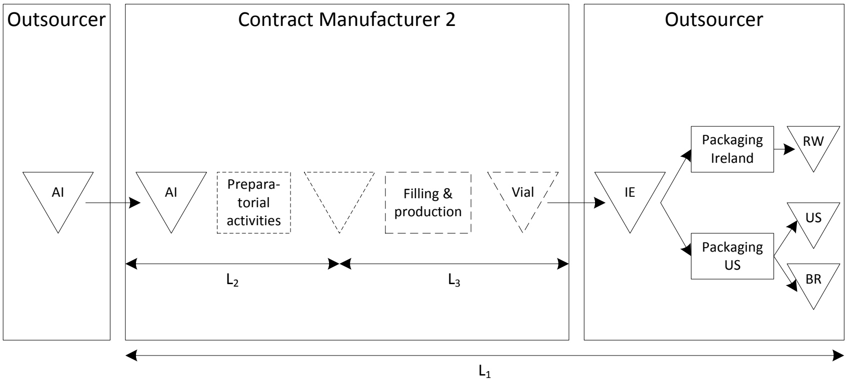

Figure 2.3. The supply chain of product B

Figure 2.3 shows the goods flow of product B. The outsourcer produces the active ingredient (AI) and sends it to CM2, which produces vials with the liquid in which the active ingredient is dissolved. For this production process, CM2 also needs additive materials which are ordered by CM2. The output of the contract manufacturer's production process is vials, which are sent to the outsourcer's production site in Ireland. This site ships the vials to the packaging site in the US, which packs the vials for the national warehouses in Brazil and the United States. Further, the site in Ireland packs the products for all other national warehouses (RW). The national warehouses keep inventories of the finished products and sell the products to the outsourcer's customers, which are mostly hospitals, pharmacies or wholesalers.

The contract manufacturer's production process starts with some preparatory activities, which are weighting, compounding and filtration of the required materials for the production process. After the preparatory activities, the materials are stocked at the intermediate stockpoint. Then, the filling of the liquid starts and some other processes follow, after which the vials are ready to be shipped to the outsourcer.

In contrast to the previous case, the formal contract between the outsourcer and CM2 describes only two agreements from a logistics point of view. The first agreement is that the contract manufacturer will undertake the manufacturing after receiving an order from the outsourcer. The second agreement is that the contract manufacturer will supply the vials to the outsourcer and that the outsourcer will pay for all products for which orders have been placed.

So, the formal contract does not describe volume agreements or agreements on the logistics performance or penalty for any failure. However, there is an informal document of one page that describes some informal agreements. The informal agreement describes the fact that the outsourcer shares on a monthly basis accurate and timely demand forecasts with a horizon of 18 months. Further, the informal agreement also describes that CM2 is responsible for ordering the additional materials that are needed for the production of the vials.

The contract manufacturer's production process is driven by orders from the outsourcer. The lead time for orders from the contract manufacturer's production process (i.e., $L_2 + L_3$ in Figure 2.3) is 20 weeks. The information flow between the two parties shows similarities with the previous case. At the beginning of each planning cycle, which is equal to one month, the outsourcer provides the contract manufacturer a 18-months rolling forecast of the outsourcer's requirements, which is based on the demand forecast of end products. These forecasts are basically reservations of capacity slots by the outsourcer, which can be accepted, changed or cancelled by the contract manufacturer as a result of its capacity planning.

Once a reservation is accepted, it is considered as an order commitment till the outsourcer later (lead time periods before the delivery date) communicates the final orders, which should not deviate from the reserved quantity. In this case, no limits are defined for the deviation, which means that the outsourcer can change or even cancel orders. Table 2.2 shows the number of orders that have been changed or cancelled in the period June 2006 – February 2007. The first column shows the total amount of orders that have been placed at the contract manufacturer. Out of this total number of orders, the second column shows the number of orders that have been changed, the third column shows the number of new orders that have been issued, and the fourth column shows the number of orders that have been cancelled. A change of an order means that the delivery date or the ordered quantity has been changed.

Contract Manufacturer 2 also shares with the outsourcer the inventory data of the active ingredients which is needed by the outsourcer to plan its supply chain properly.

Table 2.2. The number of changes in the orders placed at CM2

	Number of orders	**Number of changes**	**Number of new orders**	**Number of cancellations**
June 2006	38	10	0	0
July 2006	60	13	5	3
August 2006	62	57	7	8
September 2006	62	7	0	3
October 2006	64	28	1	2
November 2006	64	18	0	9
December 2006	63	31	3	7
January 2007	45	6	0	2
February 2007	46	7	2	5

2.4. Insights from the case studies

In section 2.3, we discussed two cases where a pharmaceutical company outsourced the production activities of two different products to contract manufacturers. These case studies described the supply chain structure of the outsourced operations, the agreements between the parties, and the information flows between the parties. The aim of this chapter is to provide insights into the outsourcing relationship and the main difficulties of planning outsourced operations in supply chain planning models. These insights will be discussed in this section.

Many papers that deal with outsourcing or contract manufacturing consider a buyer-supplier relationship with the contract manufacturer, which means that the contract manufacturer is the supplier of some products for the outsourcer. See e.g. Lankford and Parsa (1999) who state that outsourcing is the 'procurement of products or services from sources that are external to the organization'. In the case studies that we performed, we have seen that there is a supplier-buyer-supplier relationship, which means that the outsourcer is not only the buyer of the contract manufacturer, but also the supplier of the main materials for the contract manufacturer. This makes the relationship more complex, as the contract manufacturer does not only receive orders from the outsourcer, but places also orders at the outsourcer to receive the main materials and we have not seen this documented in the literature. An advantage of the supplier-buyer-supplier relationship is that both parties have an incentive to share relevant data to eliminate inefficiencies in the supply chain. Furthermore, having such a relationship means that by outsourcing, the outsourcer basically hires capacity and does not buy materials.

<u>Observation 1:</u> An outsourcing relationship is not necessarily a buyer-supplier relationship, but can be also a supplier-buyer-supplier relationship. In such relationships, the focus is more on the capacity management, as input materials are supplied by the outsourcer.

Another insight follows from the fact that the contract manufacturer produces on the same (capacitated) production line for multiple customers, as outsourcing is mostly beneficial due to capacity pooling effects at the contract manufacturer. Further, the contract manufacturer faces stochastic demands from all its customers and faces the task to allocate the capacity to the customer's demand. This task is executed by the contract manufacturer independently. If the contract manufacturer faces capacity shortages, i.e., if customer demands are higher than the available capacity, the contract manufacturer allocates the shortages based on rules and priorities that are unknown to the customers. These shortages result in rejections of or changes in the customer's orders, which complicates the order release strategy of the customers.

On the other hand, the outsourcer, that plans and controls its supply chain based on an Advanced Planning and Scheduling tool, models the contract manufacturer as a resource with a known (fixed) capacity level. This is not an appropriate reflection of the real life situation, as the available capacity level for the outsourcer is not known (as due to possible capacity shortages, a probability exists that some orders will be changed or even rejected) and therefore, it is hard for the outsourcer to release optimal or even feasible quantities towards the contract manufacturer. In practice, the outsourcer releases orders (reservations and orders) towards the contract manufacturer, but as Table 2.2 shows, these release orders are followed-up with a lot of changes. Almost half of the orders in the period June 2006-February 2007 were changed due to the inappropriate order release mechanism. This huge number of changes after releasing the order results in a nervous ordering behaviour from the outsourcer (i.e., a lot of communication on a particular order between the outsourcer and the contract manufacturer) as a reaction on the behaviour of the contract manufacturer. In case study 2, we have quantified this behaviour by showing the number of changes that are issued over a period of 9 months and in case study 1, this behaviour mainly led to the poor performance of the contract manufacturer.

<u>Observation 2:</u> In case the contract manufacturer produces on a non-dedicated production line and plans its capacity independently and based on unknown rules and priorities, the outsourcer is faced with uncertain available capacity from the contract manufacturer side.

<u>Observation 2a:</u> Because of the uncertain available capacity of the contract manufacturer, it is crucial that the outsourcer's order release mechanism incorporates this uncertainty by e.g., inflating the released order quantity or by keeping more safety stock. By not doing so, a nervous ordering behaviour results, as the outsourcer reacts to the "arbitrary" behaviour of the contract manufacturer.

Both cases show that the contract manufacturer produces several variants of the product, which differ in the concentration of the active ingredient in the variant. This results in medicines with different strengths, which is common in the pharmaceutical industry. Actually, product differentiation is also known in other industries. In both case studies, we have seen that the production process at the contract manufacturer can be divided into two parts: the first part that is not variant dependent and the second part that is variant dependent. However, the outsourced part of the supply chain is completely order driven, which means that the outsourcer reserves and orders in batches per variant, whereas the outsourcer can basically *postpone* this decision till the second part of the production process starts at the contract manufacturer. This turns out to be beneficial, assuming that the forecast accuracy improves as the forecast horizon gets shorter. In Chapter 3, we perform a simulation study that shows that the postponement strategy substantially improves the supply chain performance in terms of total supply chain inventories.

The order release strategy gets more complicated with the cancellation option. After placing orders by the outsourcer, the outsourcer gets the opportunity to change the order quantities or the mix of the variants, as the variant specific part of the production process has not started yet. In practice, it turns out that the outsourcer even cancels some batches without any penalties. In case 1, the change is limited partly by the contract, whereas in the second case, the outsourcer can formally change without limitations. This is accepted by the contract manufacturer, because the contract manufacturer is mostly able to fill the empty capacity slots by demand of other customers. Although cancellations are not formally punished in case 2, the outsourcer is careful with this option to avoid a deterioration of the relationship. On top of that, cancelling too much will probably result in a penalty fee on the long-term. Figure 2.4 shows the (order) decisions that are made by the outsourcer on a time scale.

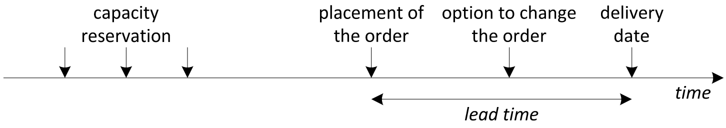

Figure 2.4. Decisions made by the outsourcer on a time scale

<u>Observation 3:</u> The order release process towards the contract manufacturer consists of different connected decisions in time. Therefore, releasing orders towards the contract manufacturer requires a more sophisticated (multi-level) decision process than in case of in-house production.

Another insight that we got from case study 1, which also complicates the planning of the outsourced operations, is the delay of information from the contract manufacturer. In order to plan its supply chain, the outsourcer also needs inventory data from the contract manufacturer (De Kok and Fransoo, 2003). Case study 1 has shown that the contract manufacturer is not able to provide these data on time, which enforces the outsourcer to *estimate* the inventory levels at the contract manufacturer. The estimation is done by adapting the last information that was provided by the contract manufacturer by receipts or shipments in the previous month(s). This estimate is rather accurate in case of no (quality) rejections. However, quality rejections of complete batches occur quite often, which result in substantial errors of the estimation. The issue of delay of information in supply chain planning is not well studied in the literature.

Although studies have been conducted (mainly in the retail business) on the effect of imperfect information on the inventory policy (e.g. Kök and Shang, 2007) and information inaccuracies and errors in inventory systems (Kuang and Gershwin, 2005), to our knowledge, no studies have been conducted on the effect of a delay of information on the performance of supply chain planning models.

Observation 4: The planning of outsourced operations gets complicated by delays in and asymmetries of crucial information.

So far, we discussed the insights that we gathered from the case studies based on similarities that we found between the two case studies. However, the contracts between the parties differ completely in the two cases. The contract with the first contract manufacturer, which is located in the United States, contains a lot of agreements and penalty clauses. Agreements are made on the annual volumes, bounds for the change that can be made in the ordered quantities, the logistics performance, cancellation fees, and penalties for not meeting the logistics performance, and bounds for changes in the volumes. It is striking that in the second case, none of these agreements were made with that contract manufacturer, which is located in Germany, whereas the way the parties control their relationship is rather similar. Although it is commonly known that contracts with and between companies in the United States contain much more agreements, we think that this insight should be further investigated, i.e., whether it is needed to have so many agreements and the effects of setting a lot of agreements on the supply chain performance. This has also been addressed by Jiang and Qureshi (2006), who state that there is a lack of research on the outsourcing contract itself.

Observation 5: Contracts with more tight clauses and more penalty clauses do not necessarily lead to better logistics performance.

2.5. Conclusions

In this chapter, we reviewed the literature on outsourcing research from two perspectives. The first perspective is whether the paper considers strategic outsourcing decisions or operational planning and control of outsourcing. Strategic outsourcing addresses the decision whether to outsource and several kinds of related issues such as the risks associated with outsourcing, the (expected) results of outsourcing, and conditions for successful outsourcing. This stream of papers develops insights that assist a firm's decision to outsource. Outsourcing on the operational level addresses issues that are relevant after having made the outsourcing decision, such as how to manage the outsourcing relationship, how much to outsource, and which orders to outsource. The second perspective is whether the insights from the paper are developed based on an empirical study or based on formal modelling work. We bridge between these two large streams in the literature, as they have different theoretical backgrounds, but they both study the outsourcing phenomenon.

Two main insights have been gathered from the literature review, which have been discussed in section 2.2.3. The first insight is that the literature lacks empirical studies on the effect of outsourcing at the operational level. Outsourcing has mainly been approached from a strategic level, where outsourcing decisions have been studied extensively. Second, the studies that are conducted at the operational level consider outsourcing as a second option in addition to the internal manufacturing capability, in order to make it possible to achieve certain objectives (e.g. to control the customer required lead time, to cover excess demand or to deal with demand uncertainties). These two insights gave rise to performing the two case studies, as there is a need to gather empirical insights into outsourcing at the operational level, especially in case the contract manufacturer is the only source for supplying the materials to the outsourcer.

We discussed the case studies in section 2.3 and showed the supply chain structures of the outsourced operations, the contractual and informal agreements and the information flows between the parties. Based on the case studies, we discussed a number of observations that we explained in section 2.4. These observations give some insights into the implications of outsourcing on the operational planning. We showed that an outsourcing relationship is more complex than a simple supplier-buyer relationship. We also showed that the order process towards the contract manufacturers is complicated by the different connected decisions in time and the uncertainty on the available capacity from the contract manufacturer. This means that the order release process becomes more complicated and should incorporate the capacity uncertainty. Moreover, the order release function becomes a hierarchical process where a higher decision level constrains the lower decision level. We have seen in the case studies that by ignoring this, a nervous ordering behaviour results, which deteriorates the supply chain performance.

3. Order release strategies to control outsourced operations in a supply chain[2]

In Chapter 2, we showed that the outsourcer's order process towards the contract manufacturer is complicated due to the different connected decisions in time and the uncertainty of the available capacity from the contract manufacturer. We concluded that the order release process should become a hierarchical process that incorporates the different aspects of controlling the outsourced operations. In this chapter, we will develop such hierarchical order release process and we consider the second set of research questions: *How should the supply chain operations planning models be adapted to incorporate outsourcing in the planning models? And what is the impact of adding these aspects on the performance of the supply chain operations planning models?*

We consider a manufacturing company that outsources some of its production activities to a contract manufacturer that serves several customers on the same capacitated production line. The contract manufacturer is not willing to share all relevant information with the outsourcer, and therefore, a complex situation arises for the outsourcer to control the outsourced operations properly. In this chapter, we discuss and propose three different order release strategies with the objective to reveal the added value of postponement and cancellation. The order release strategies differ in the number of decision levels, such that the probabilistic behaviour of the contract manufacturer is (partly) incorporated and production plans are generated based on (deterministic) mathematical programming models. Simulation results show that including postponement and cancellation to the order release function (which is an order release strategy with multiple decision levels) leads to a significant improvement of the supply chain performance. We also discuss the conditions for a successful implementation of the more advanced order release strategy.

3.1. 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 (Li and Lin, 2006). Moreover, other problems can arise with sharing information. Terwiesch *et al*. (2005) show empirically that when a retailer revises its 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 its forecasts to ensure sufficient supply.

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[2] The results in this chapter have also been presented in Boulaksil and Fransoo (2009).

In this chapter, we consider the situation where an outsourcer uses an APS system to plan and control its supply chain, but where part of the production activities (of a certain product with several variants) have been outsourced to a contract manufacturer that provides its 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 conflicting objectives, the contract manufacturer is not willing to share all relevant information with the outsourcer. Therefore, it is not obvious for the outsourcer how to optimally control the order releases to the contract manufacturer, whereas the performance of a supply chain (in terms of total inventory holding costs) depends critically on how the order decisions are coordinated.

Coordinating order release decisions between multiple and independent companies in a supply chain which are linked via a material flow, but which do not have full access to all necessary information, is a complex task and did not receive a lot of attention in the literature (De Kok *et al.*, 2005). Order release mechanisms that are discussed in the literature are mainly developed for a job-shop, single-company environment (Bergamaschi *et al.,* 1997). Some work has been done on order release mechanisms from a supply chain perspective (Chan *et al.*, 2001), but in this stream of research, the main assumption is that there is one decision authority that has access to all relevant information in the supply chain and controls the entire supply chain.

The objective of this chapter is twofold. First, we introduce, discuss, and compare the performance of three different order release strategies to control outsourced operations in a supply chain, with the objective to reveal the added value of postponement and cancellation. We also present the mathematical model that underlies the different order release strategies. The order release strategies consist of respectively one, two or three decision levels and they are organised in a hierarchical way and they are built on insights gathered from Chapter 2, the literature on postponement (Lee and Tang, 1997), the literature on the value of sharing information (Lee *et al.*, 2000; Wu and Cheng, 2008), and the insights from the quantity flexibility contracts (Tsay and Lovejoy, 1999). Based on a number of case studies, Chapter 2 contributes to the understanding of the operational implications of outsourcing. That chapter shows that the outsourcer's order release function in an outsourcing environment consists of different hierarchically connected decisions in time, including decisions on capacity reservation and cancellations.

The second objective deals with the fact that the contract manufacturer serves multiple customers on the same capacitated production line and allocates the production capacity based on unknown rules. Therefore, the outsourcer, which releases the orders towards the contract manufacturer, has no information about the available production capacity for the outsourcer in a certain time period. This uncertainty leads to the possibility that part of outsourcer's orders will be rejected by the contract manufacturer. Therefore, the second objective of this chapter is to study (by simulation) the effects of the uncertainty of the available capacities at the contract manufacturer on the supply chain performance.

The approach that we follow in this chapter 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).

This chapter is organised as follows. Section 3.2 describes the system that we consider in more detail. Then, section 3.3 discusses the three order release strategies that are part of this study. Section 3.4 discusses the relevant literature and shows the contribution of our research to existing work. The developed mathematical model for controlling the considered system is discussed in section 3.5. Section 3.6 shows the results of a simulation study, and finally, section 3.7 draws some conclusions based on this study.

3.2. System under study

In this chapter, we consider a supply chain that consists of an outsourcer 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 (e.g. 5 mg vs. 10 mg) or paint jars with different volumes (e.g. 1 vs. 2 liters). To benefit from capacity pooling, the production of the variants of the product is outsourced to a contract manufacturer that serves more customers on the same capacitated production line. The outsourcer 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 outsourcer's orders, i.e., the order(s) can be advanced, delayed or rejected by the contract manufacturer. This process is completely out of sight of the outsourcer and also not impressionable by the customer. Thus, the outsourcer does not have reliable information about the *available* capacity level for the production of its product at the contract manufacturer in each time period.

Figure 3.1 shows the (two-stage) supply chain system that we consider in this chapter. The intermittent lines in Figure 3.1 demonstrate the parts of the supply chain that are out of the outsourcer's sight. Stage j is the stockpoint of raw materials at the contract manufacturer provided by the outsourcer. We assume that the supply of raw materials by the outsourcer 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 outsourcers. 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 outsourcers. These outputs are stored temporarily at the contract manufacturer waiting for shipment back to the outsourcer. Since these inventories are not *controlled* inventories, they are not shown in Figure 3.1. Stage i represents inventories of the three variants at the outsourcer.

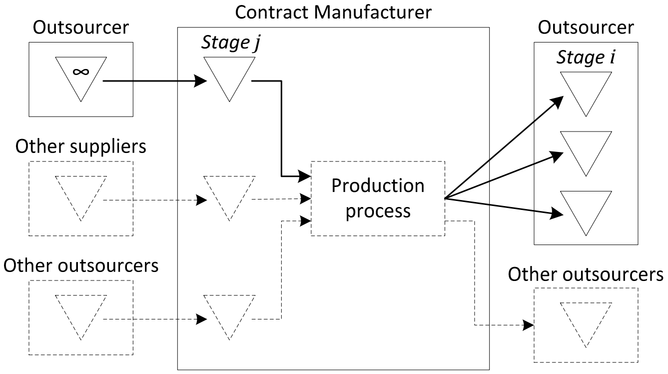


Figure 3.1. The supply chain considered in this chapter

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 outsourcer and stored at stage *j* are owned by the outsourcer, and therefore, the contract manufacturer shares information on the inventory level of the raw material at stage *j* with the outsourcer. However, since the contract manufacturer's production system has a limited capacity level, the outsourcer 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 outsourcer can apply to control the outsourced operations.

3.3. Order release strategies

The literature on order release strategies mainly discusses order release strategies that are developed and which are applicable in a job shop, single company environment. See for a nice overview of these order release strategies the paper of Bergamaschi *et al.* (1997). Some work has been done on order release mechanisms from a supply chain perspective; see Chan *et al.* (2001). However, these order release mechanisms assume one central decision authority, which has access to all relevant information and is able to decide for the whole supply chain. In the stochastic multi-echelon inventory literature (cf. Axsater and Roslin, 1993; Axsater, 2001; Diks *et al.*, 1996), installation stock policies have been developed to deal with decentralized supply chains.

We are unaware of any work dealing with order release strategies in a supply chain and/or outsourcing environment, where a central decision authority is lacking, i.e., where the supply chain partners control their own part(s) of the supply chain. Therefore, we introduce three order release strategies to control outsourced operations based on insights from Chapter 2 and different streams of the literature. First, the literature on postponement (e.g. Lee and Tang, 1997) suggests that delaying the point of product differentiation in a supply chain is one of the strategies to apply when dealing with expanding product variety. We use this insight to study the effect of delaying sharing detailed (order and reservation) information with the contract manufacturer on the supply chain performance (see order release strategy 2). Second, the case studies from Chapter 2 suggest that order release strategies towards contract manufacturers should incorporate capacity reservation and cancellations. Third, the added value of sharing information in a supply chain is extensively studied in the literature (Lee *et al.*, 2000; Wu and Cheng, 2008) and therefore, in our studies, the outsourcer reserves capacity in advance, i.e., before ordering, which allows the contract manufacturer to use this information for its own materials and capacity planning.

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, based on the insights from the literature and the case studies from Chapter 2.

3.3.1. 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 order releases 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 to respond to the customers (outsourcers) 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 3.1). These materials might have a long and uncertain supply lead time, and therefore, reservations by the outsourcers 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. Moreover, orders can limitedly deviate from prior reservations.

3.3.2. 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 outsourcer 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 outsourcer 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 $[t+L+1, t+T]$ 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 $0 < M < L$. 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.

3.3.3. Order release strategy 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 outsourcer 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 outsourcer can adjust the order (by cancelling some batches) based on the most accurate demand forecast information. From the other side, cancellation leads to a lower utilization of the 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 its 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 at a higher level form constraints to decisions to be made at lower levels. This modelling approach is based on heuristics, as we model current practices instead of finding the optimal policies. Figure 3.2 shows the three order release strategies that we consider in this study schematically.

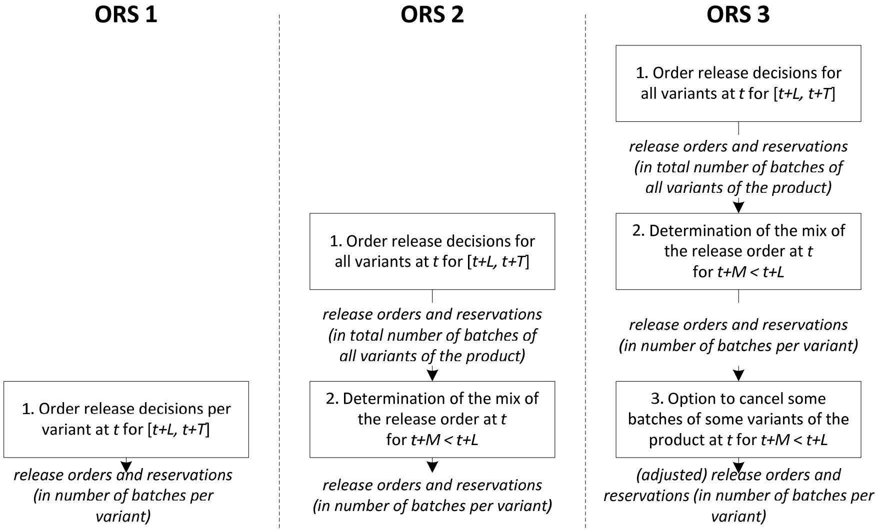


Figure 3.2. The three order release strategies that we consider in this study, organised hierarchically.

The outsourcer aims to control the supply chain such that total inventory holding costs (at both stages i and j, see Figure 3.1) are minimized at a certain customer service level. Therefore, the objective of this chapter 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 3.2, the performance of these concepts will be determined to reveal the added value of postponement and cancellation. The performance is measured 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 outsourcer 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 outsourcer, 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 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 outsourcer can make a trade-off.

3.4. 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. This chapter 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 outsourcer which 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 second 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 its 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 nor 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 Stadtler (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 chapter) 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; Van der Vlist, 1997), the paper of Lee and Tang (1997) is the paper that generally models 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 chapter 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 studies of Zhao *et al*. (2001), Zhao *et al.* (2002) and Zhao *et al.* (2007) show the added value of early order commitment, as e.g. Zhao *et al.* (2007) 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 outsourcer 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. 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.

3.5. Mathematical model

In this section, we present the mathematical programming model that is solved by the outsourcer to come up with production plans. The system, as shown in Figure 3.3, shows the supply chain considered in the outsourcer'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 3.3.

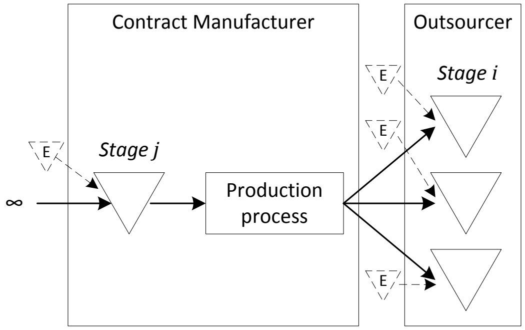


Figure 3.3. The supply chain considered in the outsourcer’s supply chain planning model

3.5.1. 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 outsourcer. 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 outsourcer.

As discussed earlier, we develop a mathematical programming model for the supply chain under consideration. We consider a lost sales situation, i.e., demand is lost if the demand exceeds the available inventory. This situation is inevitable due to the stochasticity of demand (during the lead time). In order to avoid the model planning lost sales (as much as possible), we incorporate high lost sales costs. Further, the performance of the supply chain is measured by the non-stock out probability (as a service level), which is deteriorated by the lost demand. To be able to measure the performance of the supply chain, we model *emergency supplies*, which are supplies with zero lead time. In the simulation studies, the amount of emergency supplies is stored to be able to measure and control the performance of the 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).

Equation 3.1 is the objective function of the supply chain planning model that minimizes the 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.

$$Min \sum_{i=1}^{N}\sum_{t=1}^{T}\tau_i I_i(t) + \sum_{i=1}^{N}\sum_{t=1}^{T}\varepsilon_i E_i(t) + \sum_{t=1}^{T}\tau_j I_j(t) + \sum_{t=1}^{T}\varepsilon_j E_j(t) \tag{3.1}$$

The objective function (3.1) is minimized subject to several constraints which will be discussed below. Equation 3.2 is the balance equation that balances 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.

$$I_i(t) = I_i(t-1) + R_i(t) - D_i(t), i = 1, \dots, N, t = 1, \dots, T \tag{3.2}$$

Equation 3.3 represents 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.

$$R_i(t) = P_i(t) + E_i(t), i = 1, \dots, N, t = 1, \dots, T \tag{3.3}$$

Equation 3.4 requires 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.

$$P_i(t) = n_i(t) \cdot Q_i, i = 1, \dots, N, t = 1, \dots, T, n_i(t) \in \mathbb{N} \tag{3.4}$$

Order releases of item i ($r_i(t)$) to the contract manufacturer are arranged by equation 3.5 where L is the planned lead time of the contract manufacturer's production process.

$$r_i(t) = P_i(t+L), i = 1, \dots, N, t = 1, \dots, T \tag{3.5}$$

After the first solving round, $r_i(t)$ are determined for the length of the planning horizon for all items i. The outsourcer 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. Thus, once a release order ($r_i(t)$) is placed at the contract manufacturer, it is frozen for L time periods, which is the planned lead time of the contract manufacturer's production process.

The frozen horizon concept is arranged by equation 3.6, which requires that only production quantities after L are subject to change. $PP_i(t)$ are planned production quantities of item i in t, whereas production quantities within L 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 parameter $\alpha \in \{0,1\}$ allows to distinguish between decisions to be made within and after the frozen horizon.

$$P_i(t) = (1-\alpha)FP_i(t) + \alpha PP_i(t), i = 1, \dots, N, t = 1, \dots, T, \alpha = \begin{cases} 0 \; if \; t \leq L \\ 1 \; if \; t > L \end{cases} \tag{3.6}$$

$D_j(t)$ is the derived demand for item j (at stage j in Figure 3.3) and is equal to the sum of the released quantities determined by equation 3.5 multiplied by the BOM factors (β_{ji}). Equation 3.7 shows the relation between the variables.

$$D_j(t) = \beta_{ji} \sum_{i=1}^{N} r_i(t), t = 1, \dots, T \tag{3.7}$$

Like stage i, stage j must also ensure balanced material flows, and therefore, restriction 3.8 is introduced.

$$I_j(t) = I_j(t-1) + R_j(t) - D_j(t), t = 1, \dots, T \tag{3.8}$$

Stage j is supplied from a stockpoint with infinite supply capacity, but still, a lead time is required to ship the materials from the outsourcer 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 parameter with the same function as α. Then, equation 3.9 determines the replenishment quantities ($R_j(t)$) of item j in period t.

$$R_j(t) = (1-\theta)FR_j(t) + \theta PR_j(t) + E_j(t), t = 1, \dots, T, \theta = \begin{cases} 0 \; if \; t \leq L_j \\ 1 \; if \; t > L_j \end{cases} \tag{3.9}$$

Equation 3.10 represents the non-negativity constraints for the decision variables.

$$I_i(t), R_i(t), P_i(t), E_i(t), PP_i(t), I_j(t), E_j(t), R_j(t), PR_j(t) \geq 0, i = 1, \dots, N, t = 1, \dots, T \tag{3.10}$$

From the order release perspective, the outsourcer 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 $t = 1,\ldots,L$ are real orders, whereas $r_i(t)$ for $t = L + 1,\ldots,T$ are reservations, which can be either accepted or changed by the contract manufacturer.

3.5.2. 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 outsourcer now releases $r(t)$ which is equal to

$$r(t) = \sum_{i=1}^{N} r_i(t)\,, t = 1, \ldots, T \tag{3.11}$$

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 outsourcer to postpone the decision on the mix of the order. At t, the outsourcer communicates to the contract manufacturer the exact mix of the order to be received at $t + M$ ($M < L$), i.e., $r_i(t + M)$ for all i where the mix is determined based on the most accurate demand information.

3.5.3. 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 constraint 3.12,

$$\sum_{i=1}^{N} r_{i,s+1}(t) \leq r_s(t), i = 1, \ldots, N, t = 1 \tag{3.12}$$

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 outsourcer 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, constraint 3.13 is 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.

$$\sum_{i=1}^{N} r_{i,s}(t) \leq C_s\,, t = L+1, \dots, T, i = 1, \dots, N \tag{3.13}$$

In the simulation study that 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 random variable.

3.6. 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 chapter, with the objective to reveal the added value of postponement and cancellation. We performed simulations where C_s (see constraint 3.13) was either infinite or a random variable following an uniform distribution, $C_s \sim U\,[0,2]$. The choice for the uniform distribution is based on data that we gathered at two particular cases that we described in Chapter 2 of this dissertation.

The simulation study is performed by simulating the discussed supply chain planning problem in a rolling horizon setting. See appendix 3.1 for a detailed description of the design of the simulation experiment and its assumptions. We consider a two-stage supply chain (as shown in Figure 3.3) with one item at stage j and three items at stage i, i.e., three variants of the product are produced out of the raw material. We assume independent non-negative (i.e., truncated) normally distributed (external) demand for items i. Table 3.1 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 outsourcer 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 4 time periods (transportation lead time plus production lead time) and $M = 2$. In the simulation runs, we considered a warming-up period of 2 periods, a run length of 300 periods, and the number of replications is 5. Longer run lengths were not possible due to computer memory constraints, but we show in Table 3.2 the 95%-confidence intervals for our results.

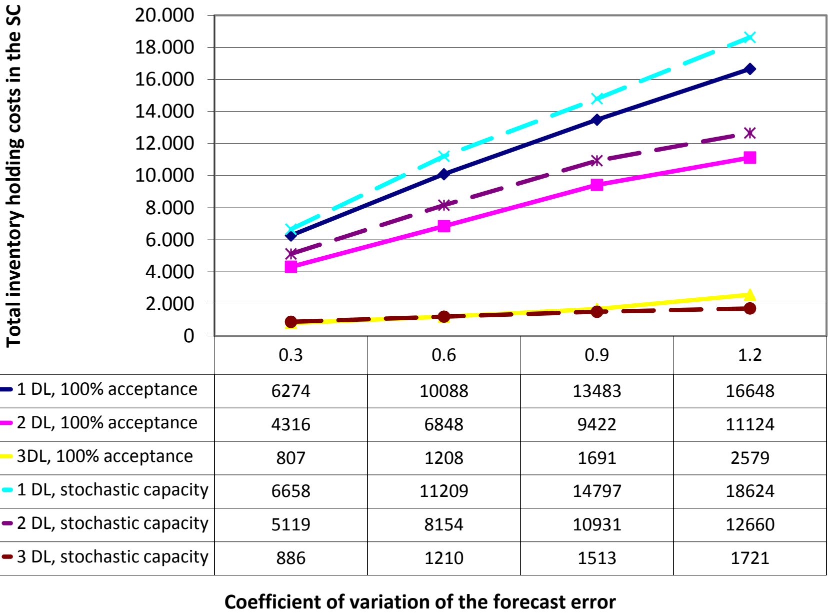
Table 3.1. Values used in the simulation study

Parameter	Possible values
Average demand variant (1,2,3)	250, 500, 100
Coefficient of variation of the demand	0.3, 0.6, 0.9, 1.2
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 3.4 shows the total inventory holding costs in the supply chain for the different scenarios that we considered in the simulation study. Equation 3.14 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).

$$TIC = \sum_{i=1}^{N}\sum_{s=1}^{S}\tau_i\big(I_{i,s}(1)+E_{i,s}(1)\big)+\sum_{s=1}^{S}\tau_j\big(I_{j,s}(1)+E_{j,s}(1)\big) \tag{3.14}$$

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 (cf. appendix 3.1). By adding the safety stocks to the inventory levels, we have one measure for the performance in the supply chain. This approach is closely related to the methodology developed in Kohler-Gudum and De Kok (2002) and applied in Boulaksil *et al*. (2009a). The x-axis of Figure 3.4 represents the scenarios we considered in the simulation study, i.e., number of considered decision levels (DL) and the coefficient of variation (CV). Table 3.2 shows the 95% confidence intervals of our results.



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

Table 3.2. 95%-confidence intervals of our simulation results

	CV = 0.3	**CV = 0.6**	**CV = 0.9**	**CV = 1.2**
1 DL, 100% acceptance	[5745 ; 6803]	[9092 ; 11083]	[12264 ; 14701]	[15491 ; 17804]
2 DL, 100% acceptance	[4262 ; 4370]	[6016 ; 7680]	[8355 ; 10489]	[10466 ; 11782]
3 DL, 100% acceptance	[792 ; 823]	[1169 ; 1246]	[1564 ; 1818]	[2422 ; 2735]
1 DL, stochastic capacity	[6342 ; 6974]	[10536 ; 11883]	[14174 ; 15421]	[18222 ; 19027]
2 DL, stochastic capacity	[4460 ; 5777]	[6959 ; 9349]	[9182 ; 12680]	[10851 ; 14470]
3 DL, stochastic capacity	[855 ; 917]	[1171 ; 1248]	[1475 ; 1551]	[1635 ; 1807]

If we consider the case where all reservations are accepted (see 100% acceptance in Figure 3.4) 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 the total inventory holding costs is obvious if we think of the relation between safety stocks and the standard deviation of demand during the lead time.

Figure 3.4 also shows the total inventory holding costs when we add another decision level to the order release process (2 DL). In this situation, the outsourcer 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 3.4, 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 sufficient 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 from the outsourcer's perspective about 80% for the studied setting. However, from a supply chain perspective, allowing for cancellation by the outsourcer means that the contract manufacturer faces more idle capacity slots, i.e., the contract manufacturer reaches a lower utilization of its production system which results in a higher cost price in the long term. Figure 3.5 shows the average number of batches cancelled by the outsourcer for the different values of CV.

Since the contract manufacturer gets the materials supplied by the outsourcer (see Figure 3.3), the cost structure of the contract manufacturer is mainly determined by fixed (labour) costs. The contract manufacturer produces on a non-dedicated production line, so when the outsourcer cancels some batches, the contract manufacturer has lost income and lost profit. Therefore, although Figure 3.4 shows a huge cost saving for the outsourcer when applying order release strategy 3, a trade-off has to be made between the cost savings the outsourcer makes and the resulting extra costs for the contract manufacturer (because of a lower utilization).

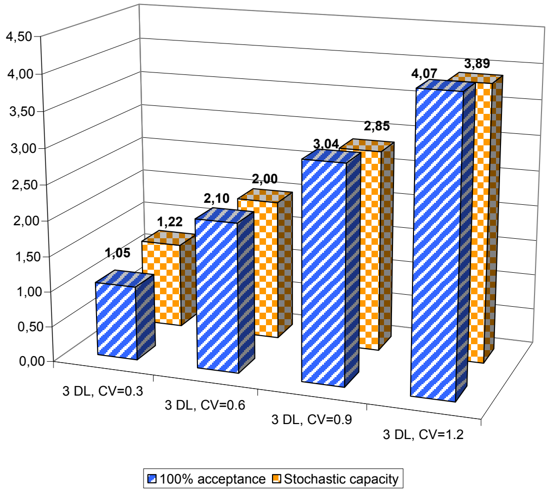


Figure 3.5. The average number of batches cancelled by the outsourcer for the situation with 3 decision levels.

This trade-off can be done as follows. Going from order release strategy 2 to 3, the outsourcer is saving a substantial amount of cost (see Figure 3.4). Say that this saving is equal to S at a certain level of demand uncertainty. Knowing that the cancellations will lead to a lower utilization at the contract manufacturer, resulting in a loss of L per cancelled batch, the contract manufacturer will only accept order release strategy 3 if he will get an extra fee of say F. Further, we know from Figure 3.5 the average number of cancellations made by the outsourcer (C).

Therefore, from a supply chain perspective, order release strategy 3 can only be successfully implemented if the following restriction holds:

$$L \cdot C \leq F \leq S \tag{3.15}$$

under the assumption that if the supply chain cost is lower, a redistribution of these costs among the supply chain members will be found that is acceptable to both parties. From Figure 3.4, we have seen that S is a big number and therefore, F has a big set of possible values, which make it attractive for the supply chain partners to implement order release strategy 3.

Figures 3.4 and 3.5 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 3.4 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 an 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.

3.7. Conclusions

In this chapter, we considered the situation where a manufacturing company outsources some production activities to a contract manufacturer that serves more customers on the same capacitated production line. Since the contract manufacturer is not willing to share all relevant information with the outsourcer, a complex situation arises for the outsourcer to control the outsourced operations properly. We proposed and discussed three alternative order release strategies that the outsourcer can implement to plan and control the outsourced operations in the supply chain. The objective was to reveal the added value of postponement and cancellation and to study the effect of stochastic capacity allocation from the contract manufacturer. 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 reveal the effect of postponement and cancellation on the supply chain performance. 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 we discussed the condition that holds to implement this order release strategy successfully. The simulation study was also performed to get insight into the effect of limited, but uncertain capacity level of the outsourced operations. Since the outsourcer 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 as more safety stocks are needed to achieve the same target service level. However, we have seen specific situations where this is not the case. When the demand is highly uncertain and cancellations are allowed, it turns out that assuming limited, but unknown capacity level leads to lower supply chain costs.

Appendix 3.1. Design of the simulation study

In Chapter 3, we study a multi-product, two-echelon system under periodic review, where the contract manufacturer's (planned) lead time L is positive. We assume that excess demand is lost, which is inevitable due to the stochasticity of demand. We design, model, and compare three different order release strategies that differ in the number of decision levels to reveal the added value of incorporating postponement and cancellation in the order release function. We conduct a numerical study by simulating the planning model, which is represented by equations (3.1) to (3.13), in a rolling horizon setting. In all simulation experiments, we aim at achieving a target service level of 99%, which is measured by the non-stock out probability. In this appendix, we discuss the design of the simulation study in more detail. More precisely, we discuss the different steps and their underlying assumptions based on which the simulation study has been conducted. To keep the explanation simple, we describe the setting for a one-echelon system, i.e., for stage i, see Figure 3.3.

Table A.3.1. *Used Symbols*

$D_i^n(t)$	Demand forecast made for item i at time period n for time period t
$d_i(t)$	Realized demand for item i at time period t
α_i	Demand forecast error of item i
$E_i(t)$	Planned emergency supply for item i in time period t
$\bar{E}_i(t)$	Real emergency supply (i.e., lost sales quantity) for item i in time period t
ε_i	Penalty cost for an emergency supply (lost sales) of one item i in time period t
$F_{\bar{E}}(x)$	Probability distribution function of $\bar{E}_i$
$I_i(t)$	Planned on hand inventory of item i at the end of time period t
$\bar{I}_i(t)$	Real on hand inventory of item i at the end of time period t
$\hat{I}_i$	Average inventory level of item i
τ_i	Inventory holding cost of one item i in time period t
$P_i(t)$	Production quantity of item i (by the contract manufacturer) available in period t
$R_i(t)$	Replenishment quantity of item i in time period t
$r_i(t)$	Release quantity towards the contract manufacturer of item i in period t
L	Planned lead time of the contract manufacturer's operations
N	Number of items i
T	Planning horizon
β	Target service level (non-stock out probability)
$\bar{\beta}$	Real service level
S_i	Safety stock level of item i
$S_i^-(t)$	Below safety stock level of item i in time period t
π_i	Cost for consuming one unit of safety stock of item i

The planning model that has been described in Chapter 3 is solved iteratively in a rolling horizon setting. We introduce the symbol n that has initially the value of 1 and increases when the iteration is repeated, i.e., after a shift of the horizon. The first step in the simulation experiment is to generate demand forecasts $D_i^1(t)$ for each (discrete) time period $t \in T$, with T is the planning horizon. This done by the demand generator that has been designed to generate both the demand forecasts $D_i^n(t)$ and the realized demand $d_i(t)$, which are input to the planning model. With the demand generator, we are able to imitate the demand process and the demand forecast behavior as we observed in real-life cases (cf. Boulaksil and Franses, 2009).

Then, we solve the supply chain planning model as presented in section 3.5. The objective function (3.1') is minimized subject to several constraints. In the event that the demand forecast $D_i^1(t)$ in a time period t exceeds the available on hand inventory $I_i(t)$, excess demand is fulfilled by a (fictitious) emergency supply $E_i(t)$ with zero lead time and we incur a penalty cost of ε_i per supplied unit. We also charge holding costs on inventory on hand at the rate of $\tau_i \ll \varepsilon_i$ per unit per time period. The emergency supplies have been modeled to enable the model to come up with a feasible solution in case of insufficient inventory.

$$Min \sum_{i=1}^{N}\sum_{t=1}^{T} \tau_i I_i(t) + \sum_{i=1}^{N}\sum_{t=1}^{T} \varepsilon_i E_i(t)\, , i = 1, \dots, N, t = 1, \dots, T \tag{3.1'}$$

The objective function (3.1') is minimized subject to several constraints. Constraint 3.2' is the balance equation that balances the goods flow from one time period to the subsequent time period. $I_i(t)$ is a state variable of the system, $D_i^1(t)$ is input from the demand generator, and $R_i(t)$ is a decision variable.

$$I_i(t) = I_i(t-1) + R_i(t) - D_i^1(t), i = 1, \dots, N, t = 1, \dots, T \tag{3.2'}$$

Constraint 3.3 ensures that item i can be either replenished by the contract manufacturer $P_i(t)$ or (if impossible) via the costly emergency supply $E_i(t)$. In section 3.5, we also discuss other constraints, such as that the production quantity has to be an integer multiple of a fixed batch size and we have some non-negativity constraints.

$$R_i(t) = P_i(t) + E_i(t), i = 1, \dots, N, t = 1, \dots, T \tag{3.3}$$

Then, the released quantity towards the contract manufacturer is determined by constraint 3.5.

$$r_i(t) = P_i(t+L), i = 1, \dots, N, t = 1, \dots, T \tag{3.5}$$

After the first solving round, $r_i(t)$ is determined for $t \in T$ and $r_i(1)$ is implemented, i.e., released towards the contract manufacturer. Then, $P_i(t)$ decisions for the interval $[t, t+L]$ are frozen, which means that they cannot be changed. Having solved the planning model, the real demand $d_i(t) = D_i^1(t) + \alpha_i$ is revealed by the demand generator, where α_i is the random demand forecast error that follows the normal distribution. As stated in section 3.6, we require that $d_i(t)$ is non-negative.

By now, we can evaluate the performance of the previously made planning decisions in terms of costs and service level. The real on hand inventory $\bar{I}_i(t)$ can be determined by equation 3.2'', where $(\cdot)^+ = max\{0,\cdot\}$. $\bar{I}_i(t)$ is stored in a database to later determine the average performance.

$$\bar{I}_i(t) = \left(\bar{I}_i(t-1) + P_i(t) - d_i(t)\right)^+, i = 1, \dots, N, t = 1 \tag{3.2''}$$

By equation 3.16, we determine $\bar{E}_i(t)$, $(\cdot)^- = min\{0,\cdot\}$, which is also stored in the database.

$$\bar{E}_i(t) = -\left(\bar{I}_i(t-1) + P_i(t) - d_i(t)\right)^-, i = 1, \dots, N, t = 1 \tag{3.16}$$

Note that $\bar{I}_i(t)$ and $\bar{E}_i(t)$ can only be determined for $t = 1$, as $I_i(t)$ and $E_i(t)$ are planned quantities that can later change after the disclosure of the real demand $d_i(t)$. Now, we can measure whether we face a stock out, which is the case if $\bar{E}_i(t) > 0$. The next step in the simulation experiment is a shift of the planning horizon by one time period, i.e., $t \coloneqq t + 1$ and $n \coloneqq n + 1$. Then, the demand generator updates the demand forecasts: $D_i^n(t) \coloneqq D_i^{n-1}(t) + \alpha_i$, which are input to the planning model. Now, a new planning problem arises with updated $D_i^n(t)$ for $t \in T$, updated $I_i(0)$, and the frozen $P_i(t)$ for $t \in [1, L-1]$ decisions. Then, the same planning model is solved with the (updated) status information and release decisions $r_i(t)$ result, of which $r_i(1)$ is implemented. This process repeats with a slight adaptation of 3.2', which should be written as:

$$I_i(t) = I_i(t-1) + R_i(t) - D_i^n(t), i = 1, \dots, N, t = 1, \dots, T \qquad (3.2''')$$

The described process of generating demand forecasts, solving the planning problem, implementing the decisions, evaluating the performance of the decisions, shifting the planning horizon, updating the status information, and so on reflects the real-life planning process the best. By repeating this iterative process very frequently, we simulate the real planning process, by which we are able to derive the (empirical) probability distribution function of $\bar{E}_i$, which we denote by $F_{\bar{E}}(x)$. We can also compute the average inventory level $\hat{I}_i$, which is derived by taking the (long-run) average of $\bar{I}_i(1)$.

The next step is to set the safety stock level S to achieve the target service level β to be able to fairly compare the performance of the different order release strategies. To do that, we use the safety stock adjustment procedure introduced by Kohler-Gudum and De Kok (2002) and further developed by Boulaksil *et al.* (2009a). This procedure has been developed for a backordering system, as one of the underlying assumptions is that the inventory process is independent of the safety stock level. That is not the case in our situation, as we consider a lost sales situation. However, the error caused by applying this procedure to a lost sales system is limited due to the high target service level ($\beta = 0.99$). Huh *et al.* (2009) show that when the lost sales penalty cost becomes large compared to the inventory holding cost (which means that a high service level is targeted), the relative cost difference between the optimal policy and the best order-up-to policy converges to zero. They state that ‘when b (= the unit penalty cost) is large, the probability of demand exceeding supply in a period is so small that the issue of whether excess demand is lost or backordered should not make a big difference’.

Hence, the safety stock level S is set equal to the smallest x that satisfies the following condition: $F_{\bar{E}}(x) \geq \beta$. The safety stock level is a parameter that is input to the planning model and is time independent. Although Huh *et al.* (2009) show that the cost difference between the two policies is limited (in case of high service level), the question remains whether this also holds for the system parameters, such as the safety stock. We test whether including the safety stock level results in achieving the target service level by simulating the planning model with the safety stock parameter included in a rolling horizon setting (equations 3.17, 3.18, 3.2’’’, 3.3, and 3.5). In this planning model, the safety stock parameter S is included and costs are incurred of π_i for the consumption of safety stock.

$$Min \sum_{i=1}^{N}\sum_{t=1}^{T} \tau_i \left(I_i(t) - \left(S_i - S_i^-(t)\right)\right) + \sum_{i=1}^{N}\sum_{t=1}^{T} \pi_i S_i^-(t) + \sum_{i=1}^{N}\sum_{t=1}^{T} \varepsilon_i E_i(t), i = 1, \dots, N, t = 1, \dots, T \qquad (3.17)$$

$$I_i(t) \geq \left(S_i - S_i^-(t)\right) \geq 0 \qquad (3.18)$$

The procedure is exactly the same as without the safety stock parameter. We again measure $\bar{I}_i(t)$ and $\bar{E}_i(t)$ by which we can determine the realized service level $\bar{\beta}$. We have seen that $\bar{\beta} - \beta$ is negligibly small. Finally, the performance of interest for each order release strategy is the total inventory holding cost 3.14’, which consists of the average inventory level and the safety stock, given that $\beta = 0.99$.

$$\sum_{i=1}^{N} \tau_i\left(\hat{I}_i + S\right) \qquad (3.14')$$

4. Dual sourcing with contract manufacturing – comparison between two different allocation strategies under rolling horizon mathematical programming models[3]

In Chapter 1, we discussed three main reasons for outsourcing in the pharmaceutical industry. One of the reasons for outsourcing is to have an external source producing the same product next to an internal source to share the supply uncertainty. Especially for strategic products, a (pharmaceutical) company is not willing to rely on a single (internal) source, which results in a dual sourcing case. In this chapter, we deal with a dual sourcing setting and the research question is: *In case a contract manufacturer exists next to an internal manufacturing source, how to allocate the production volume over the two sources in a smart way?*

In this chapter, we consider an outsourcer that faces stochastic stationary demand and low demand forecast accuracy, i.e., the realized demand deviates substantially from the forecasted quantity. The outsourcer has two different supply sources for the same product: its own manufacturing plant and a contract manufacturer. The two sources are constraining the supply quantities in different ways. Its own manufacturing plant is more rigid, cheaper and capacitated, whereas the contract manufacturer is more flexible but more expensive. Due to the intractability of the optimal policy, we propose a mathematical programming model for the considered dual sourcing setting, since APS systems, implemented at many companies to assist the supply chain planning decision, are based on this type of models. Based on extensive simulation studies and data from a real-life situation, we compare the performance of two different allocation strategies for the considered dual sourcing setting: the dynamic allocation strategy and the rigid allocation strategy. The results show that for the considered setting, the rigid allocation strategy performs substantially better than the dynamic allocation strategy if the parameters are chosen properly. This insight is helpful for managers to choose for the better performing allocation strategy when part of the production is outsourced and when poor demand forecasting is faced. Further, the insights are also helpful in negotiations on the production volumes with the contract manufacturer.

4.1. Introduction

Manufacturing companies increasingly outsource parts of their supply chains to contract manufacturers. Various benefits, reasons, risks, and theories on outsourcing have been developed, discussed, and analyzed in a wide body of literature (see e.g. Kremic *et al.*, 2006). Companies expect to benefit from outsourcing, although there are significant risks that may be realized if full outsourcing is conducted (Vining and Globerman, 1999). Therefore, many companies decide to outsource part of the production volume and to keep the other part in-house, which results in having a dual sourcing setting with a combination of internal manufacturing and outsourcing.

A variety of reasons exists for having single or dual/multiple suppliers. For example, in case of high supplier development costs, it is less attractive to have multiple suppliers. Moreover, having a single supplier limits the coordination efforts (lower ordering costs) and helps to invest more in a long-term relationship. Further, single sourcing helps to obtain price discounts as larger volumes will be ordered at a single supplier.

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[3] The results in this chapter have also been presented in Boulaksil and Fransoo (2008b).

On the other hand, many companies avoid the dependence on a single supplier for the supply of their (strategic) products. To limit the risks associated with such a situation, managers therefore generally prefer multi-sourcing. Multi-sourcing leads to less interrupted supply in case of unexpected disruptions at (one of) the suppliers, it promotes competition between the suppliers, and it reduces the lead time variability (Sculli and Wu, 1981).

Many papers have studied (single-stage) inventory systems that face stochastic demand, which can be replenished from multiple (usually two) suppliers with different lead times and costs. In the Operations Management literature, the dual sourcing strategy is mainly researched by making a trade-off between a flexible but expensive supplier and a rigid and cheap supplier. In the next section, we will discuss these papers more in depth and show our contribution to the literature.

In this chapter, we consider based on a real-life situation an outsourcer that faces stochastic demand and low demand forecast accuracy, i.e., the realized demand deviates substantially from the forecasted quantity. The outsourcer has two supply sources for the same product: its own production facility and a contract manufacturer. Having two sources implies that the outsourcer has to divide the purchase volume. The volume released towards the two sources is constrained in different ways. Compared with the contract manufacturer, the outsourcer's own manufacturing site is cheaper but less flexible, as changes in the production volume require hiring (expensive) temporal workers or firing existing workers, which are very costly measures. The other source, the contract manufacturer, is more expensive but more flexible, as he serves multiple customers and benefits from capacity pooling.

Nowadays, many companies have implemented an Advanced Planning and Scheduling (APS) system to plan and control their supply chain (Stadtler and Kilger, 2005). These systems are based on mathematical programming models that generate order releases. In this chapter, we introduce a mathematical programming model that models the described dual sourcing setting and determines the allocation quantities towards the two sources. Then, by extensive simulation studies, we compare the performance of two different allocation strategies within the model.

The mathematical model captures the characteristics of the described system. We conduct an extensive simulation study, i.e., by solving the model in a rolling horizon setting to get insights into the optimal dynamic allocation strategy. Next, we compare this dynamic allocation strategy with another allocation strategy that is discussed in the literature (Rosenshine and Obee, 1976; Janssen and De Kok, 1999). We refer to the latter strategy as the rigid allocation strategy. The comparative simulation study shows that if parameters are chosen properly, the rigid allocation strategy is performing substantially better than the dynamic allocation strategy.

This chapter is organized as follows. Section 4.2 gives an overview of the relevant literature and we show our contribution to the literature. Section 4.3 presents the mathematical model for the two allocation strategies. Section 4.4 shows the numerical results of the simulation studies and the experiments that we conducted. Section 4.5 discusses a case study that we performed. Section 4.5 draws some conclusions based on this study.

4.2. Literature review

Many papers have discussed the dual (or multi-) sourcing problem (Minner, 2003), mainly from the inventory control perspective. Some papers researched the problem to show the advantages or disadvantages of single- versus dual sourcing strategies or the added value of having dual sources (e.g. Du *et al.*, 2006; Burke *et al.*, 2007). Du *et al*. (2006) show that a company achieves higher profits and a better bargaining position with dual sourcing in case there is no difference in the fixed costs of the two sources. Burke *et al.* (2007) show that single sourcing is only outperforming dual sourcing when supplier capacity is relatively large compared with the demand. This part of the literature is mainly focussing on the strategic decision on whether to conduct dual sourcing, which is not relevant in our case, as we assume that dual sourcing is a given strategy.

Many papers have studied dual sourcing inventory systems, i.e., a single-stage inventory system that faces stochastic demand, which can be replenished from two suppliers with different lead times and costs. Mostly a trade-off is made between a flexible but expensive supplier and a rigid but cheap supplier. First, we will discuss some of these papers that assume deterministic lead times and the insights that follow from these papers.

Fuduka (1964) derives optimal policies for the setting where an order can be replenished from a supplier at a unit price c_k with lead time k or at a unit price c_{k+1} with lead time $k+1$. Moinzadeh and Nahmias (1988) are one of the first that deal with the basic dual sourcing problem. They consider an inventory system with two supply options, where one option has a shorter lead time than the other. They develop an (approximation) algorithm to determine the parameters (lot sizes and reorder points) for the two supply options.

Tagaras and Vlachos (2001) analyze an inventory system with two replenishment sources, a regular one and an emergent one. The regular source is used for the regular orders, whereas the emergent mode (with shorter lead time) is used in case of imminent stock-outs. They show that including the emergency mode in the system leads to substantial cost savings.

Most inventory models on dual sourcing that assume deterministic lead times consider an inventory system with two suppliers with different unit costs and (deterministic) lead times, i.e., the supplier with the shortest lead time has the highest unit cost. Due to the complexity of this problem, most models are restricted to two suppliers, zero setup costs, a lead time difference of one period, deterministic lead times, and mostly further reduced to a single-period problem (Minner, 2003).

In our modelling, we also assume two suppliers that supply with deterministic (planned) lead times, but we consider a multi-period problem. Further, our model can easily deal with non-zero setup costs, batch sizes, and an arbitrary difference in the lead times of the two sources. To our knowledge, no model has been documented that can deal with all these aspects. Further, we include costs for deviations in production volumes at the outsourcer's internal production facility, as the outsourcer is rather rigid and requires rather smooth production levels.

Another stream of papers on dual sourcing considers random lead times for the suppliers. These papers have mainly in common that they show that the mean and variance of the effective lead times in a dual source case are reduced compared with the single source case (Sculli and Wu, 1981; Lau and Zhao, 1993; Chiang and Benton, 1994). Other papers refer to dual sourcing as order splitting strategies, but these papers also show that these strategies reduce lead time uncertainties by splitting the order over more than one supplier (e.g. Sedarage *et al.*, 1999). Although we do not consider the stochastic lead time case, we briefly discuss some of the papers from this stream of the literature.

Sculli and Wu (1981) assume normally distributed lead times for the two suppliers. They compute the mean and standard deviation of the effective lead time and the interarrival time between two receipts. They show that both the reorder level and safety stocks are lower under dual sourcing.

Lau and Zhao (1993) consider a continuous review inventory system with two suppliers with stochastic demand and lead times. They present a procedure to determine the optimal order policy, i.e., the total order quantity, reorder point, and allocation quantities between the suppliers. With respect to allocation quantities, they show that the optimal proportion of order split mainly varies with the difference between the suppliers' (mean) lead time.

Chiang and Benton (1994) compare the performance of sole sourcing and dual sourcing strategies under stochastic demand and lead times. They investigate the effect of cost structures on the relative performance of sole sourcing versus dual sourcing inventory control policies. They assume normally distributed demand and shifted-exponential lead times and they conclude that dual sourcing strategy performs better than sole sourcing strategies except in cases where the ordering cost is high, the lead time variability is low, or the customer service is low.

With respect to the allocation quantities between the two sources, the papers that assume stochastic lead times show that the allocation quantity is a function of the lead time difference (Lau and Zhao, 1993) or consider the allocation quantity as an input to the model, i.e., not as a decision variable (e.g. Chiang and Benton, 1994). Sometimes, simple allocation rules are applied, as e.g. Chiang and Benton (1994), who suppose that whenever the inventory level drops to the reorder point, two orders of *equal* size are placed simultaneously at the two suppliers.

In this chapter, we approach the dual sourcing problem from a different perspective, namely from the supply chain planning perspective. The models that have been developed in the supply chain planning literature (cf. De Kok and Fransoo, 2003) do not consider multiple supply sources. 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, the type of models implemented in virtually all APS systems. This chapter contributes to the latter modelling approach, by including dual sourcing in the supply chain planning models.

We introduce a mathematical programming model for the dual sourcing case and we compare two different allocation strategies: the dynamic allocation strategy and the rigid allocation strategy. In the first strategy, the allocation quantities, i.e., the order quantities released to the two sources can vary from a time period to another. The papers that we discussed so far are in line with that strategy. The second strategy (the rigid allocation strategy) assumes that one of the two suppliers replenishes every period a fixed quantity (standing order quantity) and the replenishment quantity from the other supplier is a decision variable, i.e., the second supplier captures the uncertainties of the system. The latter type of models (that follow a rigid allocation strategy) are a combination of a constant push strategy and a dynamic pull strategy (Rosenshine and Obee, 1976; Janssen and De Kok, 1999). We briefly discuss the two papers that considered the rigid allocation strategy.

Rosenshine and Obee (1976) investigate a dual sourcing inventory system, where one supplier delivers a constant quantity in every period. If the inventory drops below the reorder level, an emergency order with zero lead time is released that increases the inventory level to a base-stock level.

Janssen and De Kok (1999) analyze a similar model. They consider an inventory system with two suppliers. One of the two suppliers delivers a fixed quantity and the replenishment decisions for the second supplier is made based on an (R, S) policy. They present an algorithm to determine the parameters such that costs are minimized at a certain service level constraint and they show that the coefficient of variation of the demand is the determining factor of the optimal value of the fixed quantity to be delivered by one of the two suppliers.

In this chapter, we compare the performance of the dynamic allocation strategy with the rigid allocation strategy, as the optimal policy for dual sourcing strategies is generally unknown due to its complexity. The model that we propose for determining the allocation quantity allows for including batch sizes, setup costs, any difference in lead times between the suppliers, and capacity constraints.

To our knowledge, this has not been studied yet in the literature. Further, we refer the reader to Minner (2003) who gives an excellent review of the literature on inventory models with multiple supply options and discusses their contribution to supply chain management.

4.3. The model

In this section, we introduce the mathematical programming model for the dual sourcing case and we discuss the two allocation strategies in more detail. The dual sourcing case has been formulated by mathematical programming principles, as these types of models are underlying Advanced Planning and Scheduling (APS) systems, which are implemented at many companies to plan and control their supply chain operations (Stadtler and Kilger, 2005).

The planning horizon of the dual sourcing problem is T time periods. A subscript t refers to a time period within T and a superscript s refers to one of the S sources. In this chapter, we consider the case where $S = 2$ (dual sourcing), but the model formulation is applicable for cases with more sources. Further, the superscript 1 ($s = 1$) refers to the own manufacturing site and the superscript 2 ($s = 2$) refers to the contract manufacturer.

For the modelling, we assume linear inventory holding costs α per unit per time period, linear lost demand costs β per unit per time period, and linear production costs of γ^s per unit for producing at source s. Further, we also assume costs for fluctuations in the production level δ per unit for the own manufacturing site.

Equation (4.1) is the objective function of the model,

$$Min \sum_{t=1}^{T} \alpha i_t + \sum_{t=1}^{T} \beta l_t + \sum_{t=1}^{T} \delta \left| q_t^1 - q_{t-1}^1 \right| + \sum_{t=1}^{T} \sum_{s=1}^{S} \gamma^s q_t^s \tag{4.1}$$

where i_t is the inventory level at time period t, l_t the lost demand quantity in t, and q_t^s the allocation quantity in time period t at source s. The objective function consists of four terms. The first term represents the inventory holding costs, the second term the lost demand costs, the third term costs for fluctuations in the production quantity (only) at the own manufacturing site, and the fourth term represents the (different) production costs at the two sources.

The objective function is minimized subject to several materials and capacity constraints, which are discussed below. Equation (4.2) is the inventory balance equation with r_t is the replenishment quantity in period t, d_t is the (exogenous) demand forecast in period t, which is input to the model, and $(\cdot)^+ = max\{0,\cdot\}$.

$$i_t = (i_{t-1} + r_t - d_t)^+ \tag{4.2}$$

In this model, d_t is inserted into the model as a point estimate for every period $t \in [1, T]$. In section 4.4.1, we describe how the demand forecast is related with the real demand.

These estimates are the output of a demand generator that generates a random series of demand forecasts from a stationary probability distribution. As we discussed in section 4.1, we assume that the demand forecast accuracy is low, i.e., the forecast error is substantial. Therefore, after solving the planning problem, the demand generator generates a random number from the same probability distribution, which represents the realized demand. Hence, the demand forecasts and the real demands are realizations from the same stochastic process. Consequently, the variance of the forecast error is equal to $\sigma^2(d_t - \hat{d}_t) = 2\sigma^2(d_t)$, with $\hat{d}_t$ is the demand forecast and $\sigma^2(d_t)$ is the variance of the demand process. Therefore, the coefficient of variation of the forecast error is: $cv_{forecast\ error} = \sqrt{2} \cdot cv(d_t)$, with $cv(d_t)$ is the coefficient of variation of the demand process.

The replenishment quantity that is available in t is equal to the sum of the allocation quantities in period q_{t-L_s} from the different sources (i.e., decisions that are taken in period $t - L_s$), where L_s is the planned lead time of the production at source s (see equation 4.3).

$$r_t = \sum_{s=1}^{S} q_{t-L_s}^s \tag{4.3}$$

Equations (4.2) and (4.3) show that the allocation quantities are replenished with a lead time of L_s time periods. The allocation quantity at source s at time period t (q_t^s) to be available at time $t + L_s$ is a decision variable in the model. The allocated quantity to source 1 (to the own manufacturing site) in t cannot exceed the capacity level c^1 of this source.

$$q_t^1 \leq c^1 \tag{4.4}$$

Further, the allocation quantities towards the two sources might be an integer multiple of fixed batch sizes (Q^s).

$$q_t^s = n \cdot Q^s, n \in \mathbb{N} \tag{4.5}$$

When quantities q_t^s are allocated and replenished after L_s periods, d_t is observed. An expression for the lost demand in t is given by equation (4.6) where $(\cdot)^- = min\{0,\cdot\}$.

$$l_t = -(i_{t-1} + r_t - d_t)^- \tag{4.6}$$

Finally, we require that the following variables and parameters are non-negative.

$$i_t, q_t^s, \alpha, \beta, \delta, \gamma \geq 0 \tag{4.7}$$

4.3.1. Dynamic allocation strategy

When the dynamic allocation strategy is applied, the order quantities to be released to each of the two sources (q_t^s) are decision variables in the model. That means that these quantities are determined given the demand forecasts, the model constraints and at minimum total cost. We call this strategy the dynamic allocation strategy, as the allocation quantities at the two sources can vary from time period to the subsequent period.

4.3.2. Rigid allocation strategy

The alternative strategy is the rigid allocation strategy, which is a combination of a constant pull and a dynamic push strategy and it is in line with the model of Janssen and De Kok (1999). In this strategy, the own manufacturing site delivers each period a fixed quantity, which is lower than the expected demand. This means that (q_t^1) becomes a parameter instead of a decision variable in the model. The choice for having the own manufacturing site delivering a fixed quantity is that the own manufacturing site is rigid and less flexible than the contract manufacturer. This strategy implies that all uncertainties are captured by the contract manufacturer.

4.4. Simulation study

In this section, we discuss the simulation studies that we performed to compare the performance of the two strategies for the dual sourcing problem. We first discuss the simulation methodology and then we show and discuss the results of several experiments.

4.4.1. Methodology

In the simulation studies, the model that we discussed in section 4.3 is solved in a rolling horizon setting, where demand forecasts and the state of the system are updated when the planning horizon is shifted. The simulation methodology is as follows. The planning horizon T is divided into a fixed number of time buckets, which are all filled by demand forecasts generated by a demand generator. This generator generates a random series of numbers from a stationary probability distribution with parameters that are derived from historical forecast data. Those numbers represent the demand forecasts. As we discussed in section 4.1, we assume that the demand forecast accuracy is low, i.e., the forecast error is substantial. Therefore, after solving the planning problem, the demand generator generates a random number from the same probability distribution, which represents the realized demand. Hence, the demand forecasts and the real demands are realizations from the same stochastic process. Consequently, the variance of the forecast error is equal to $\sigma^2\left(d_t - \hat{d}_t\right) = 2\sigma^2(d_t)$, with $\hat{d}_t$ is the demand forecast and $\sigma^2(d_t)$ is the variance of the demand process. Therefore, the coefficient of variation of the forecast error is: $cv_{forecast\ error} = \sqrt{2} \cdot cv(d_t)$, with $cv(d_t)$ is the coefficient of variation of the demand process.

We assume (discretized) Gamma distributed demand forecasts with an expected demand forecast of 100. Moreover, we assume that q_0^1=100. Then, the mixed-integer programming model that is shown in section 4.3 is solved, i.e., the objective function is minimized given the materials and capacity constraints. The allocation decisions that follow from the model are implemented. Then, at the end of the first time bucket (planning cycle), the demand generator generates a random number from the same probability distribution (Gamma distribution), which represents the realized demand. Then, the state of the system is updated (demand forecasts, inventory levels) and the cycle is repeated with the horizon shifted by one period. By repeating this process very frequently, long-run performance measures can be determined. This methodology reflects the real-life planning practice, as we have observed at companies. In the simulation runs, we consider a warming-up period of 3 periods, a run length of 300 periods and the number of replications is 15 (following the procedures suggested by Law and Kelton, 2000). Longer run lengths were not possible due to computer memory limitations.

4.4.2. Experimental design and results

Figure 4.1 shows the setting that we consider in the simulation studies. Demand for item 1 is stochastic and we assume that it is Gamma distributed with an average demand of 100 per period.

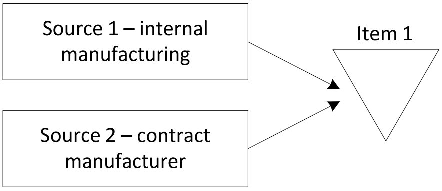

Figure 4.1. The considered dual sourcing setting

Item 1 can be supplied by the two sources, as discussed earlier and as shown in Figure 4.1. The lead time for source 2 is set equal to 1 period, whereas the lead time for source 1 is a varying parameter in the experiments. The experimental set-up is as follows. We compare the dynamic allocation strategy with the rigid allocation strategy by measuring the total costs, the sum of the cost components from equation 4.1 and the service level, which is measured as the fraction of demand that is not lost, i.e., satisfied from stock. The parameters that we vary in the experiments are shown in Table 4.1.

Table 4.1. The parameters that change in the experiments and their set of values

Parameter	**Symbol**	**Experimental values**
Coefficient of variation of demand	CV	{0.25;1}
Lead time of the internal source	L_1	{1,2,3}
Internal capacity level	c^1	{50;75}
Batch size	Q^s	{1,25}
Standing order quantity	q^1	{50;75}

As Table 4.1 shows, we vary a number of parameters to evaluate the performance of the two strategies. The coefficient of variation of the demand is set equal to 0.25 (low demand uncertainty) and 1 (high demand uncertainty). The lead time of the internal source is varied between 1, 2, and 3 periods. By doing so, the lead time difference with the contract manufacturer is increased, as the lead time for the contract manufacturer is kept equal to 1 period. The internal capacity level is varied between 50% and 75% of the expected demand. Further, we also experiment with a batch size equal to 25 and when the rigid allocation strategy is simulated, the quantity that we fix at the internal site (standing order quantity) is varied between 50 and 75. Further, based on data that we derived from a real-life case, we set the unit inventory holding costs equal to 0.20, the fluctuation costs equal to 1.00, the internal unit production costs equal to 0.50, and the unit production cost at the contract manufacturer equal to 1.50. Appendix 4.1 shows the complete simulation results, but below we will discuss the experiments in more detail.

4.4.2.1. Experiment 1: Comparison between the two strategies with low demand uncertainty

In this experiment, we compare the dynamic allocation strategy (DAS) with the rigid allocation strategy (RAS) when the demand uncertainty is low. In the dynamic allocation strategy, the allocation quantities towards the two sources are decision variables, whereas in the rigid allocation strategy the internal manufacturing site is producing each period a fixed quantity (a parameter), as it is less flexible than the contract manufacturer. In the latter case, the third term in the objective function (see equation 4.1) becomes equal to zero. The allocation decisions towards the contract manufacturer remain decision variables in the model.

Table 4.2. Results of experiment 1 (for low demand uncertainty)

	Input						Output				
Run	**Strategy**	**CV**	**L_1**	**CAP**	**q^1**	**Q**	**SL**	**TC**	**IC**	**PC**	**FC**
1	DAS	0.25	1	50	-	1	0.88	85	3	82	0
2	RAS	0.25	1	-	50	1	0.87	85	3	82	0
3	DAS	0.25	1	50	-	25	0.93	95	4	91	0
4	RAS	0.25	1	-	50	25	0.92	91	5	87	0
5	DAS	0.25	1	75	-	1	0.92	66	4	61	1
6	RAS	0.25	1	-	75	1	0.98	65	14	52	0
7	DAS	0.25	1	75	-	25	0.94	72	6	65	1
8	RAS	0.25	1	-	75	25	0.99	68	15	53	0
SL = service level TC = total costs			IC = inventory holding costs PC = production costs					FC = fluctuation costs			

Table 4.2 shows the results of experiment 1 for low demand uncertainty (CV=0.25). If we compare run 1 with run 2, we see no significant difference in the performance of the two strategies. However, if we compare run 6 with runs 1 and 2, then we see that increasing q^1 (the standing order quantity) leads to both an increase in the service level and a decrease of the total costs. The same holds for the case when a batch size is considered (see runs 4 and 8).

4.4.2.2. Experiment 2: Comparison between the two strategies with high demand uncertainty

In experiment 2, we repeat the same experiment, but now with high demand uncertainty (CV=1). In this case, we again see that the total costs and the service level are most sensitive to q^1. However, in contrast to the low demand uncertainty case, increasing q^1 leads to both an increase of the total costs and the service level, which makes it hard to compare the performance of the two strategies. Therefore, we have conducted experiment 3 in which we will study the effect of q^1 on the total costs for both levels of demand uncertainty.

Table 4.3. Results of experiment 2 (for high demand uncertainty)

	Input						Output				
Run	**Strategy**	**CV**	**L_1**	**CAP**	**q^1**	**Q**	**SL**	**TC**	**IC**	**PC**	**FC**
9	DAS	1	1	50	-	1	0.76	100	21	67	12
10	RAS	1	1	-	50	1	0.76	98	31	66	0
11	DAS	1	1	50	-	25	0.79	112	21	78	13
12	RAS	1	1	-	50	25	0.81	98	32	66	0
13	DAS	1	1	75	-	1	0.78	110	21	61	28
14	RAS	1	1	-	75	1	0.98	191	138	53	0
15	DAS	1	1	75	-	25	0.77	116	23	62	31
16	RAS	1	1	-	75	25	0.96	191	137	54	0

4.4.2.3. Experiment 3: The effect of the standing order quantity (q^1) on total costs

In this experiment, we only vary the standing order quantity (q^1) to test the effect on total costs. The experiment is conducted such that a target service level of 0.90 was maintained (Kohler-Gudum and De Kok, 2002; Boulaksil *et al.*, 2009a). Figure 4.2 shows the result of experiment 3. For both levels of demand uncertainty, an optimal q^1 (standing order quantity) exists. Obviously, for the low demand uncertainty case, the optimal q^1 is higher than in the high demand uncertainty case. Moreover, the optimal domain is broader than in the high demand uncertainty case.

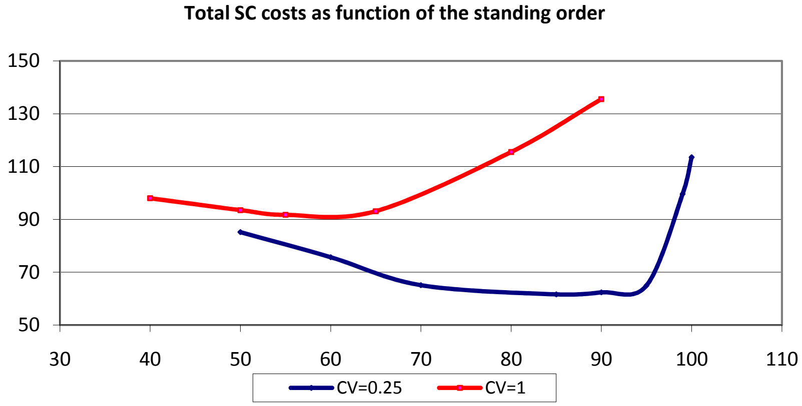

Figure 4.2. The effect of the standing order quantity on the total costs

4.4.2.4. Experiment 4: Increasing the lead time difference between the two sources

In experiments 1 and 2, we assumed that both sources supply with an equal lead time of 1 period. In this experiment, we test what the effect is of increasing the lead time difference between the two sources. We do that by increasing the lead time of the internal manufacturing source, as this source is more rigid and less flexible. Table 4.4 shows the results of this experiment where L_1 is equal to 3 periods. As one can see, increasing the lead time difference does not lead to significant changes, neither in the results nor in the insights that we gathered from experiments 1 and 2. Appendix 4.1 shows also the results for $L_1 = 2$ periods.

Table 4.4. Results of experiment 4

	Input						Output				
Run	**Strategy**	**CV**	**L_1**	**CAP**	**q^1**	**Q**	**SL**	**TC**	**IC**	**PC**	**FC**
17	DAS	0.25	3	50	-	1	0.87	84	3	81	0
18	DAS	0.25	3	50	-	25	0.92	92	5	87	0
19	DAS	0.25	3	75	-	1	0.91	65	4	61	0
20	DAS	0.25	3	75	-	25	0.94	73	6	66	1
21	DAS	1	3	50	-	1	0.80	109	26	72	12
22	DAS	1	3	50	-	25	0.79	105	25	70	10
23	DAS	1	3	75	-	1	0.79	122	27	66	28
24	DAS	1	3	75	-	25	0.79	132	29	74	28

4.5. Real-life case study

To further explore the insights that we gathered from the previous section, we performed a real-life case study at a pharmaceutical company to test and verify the results. This company is a research- and development based worldwide operating pharmaceutical company with a global presence in branded prescriptive medicines. This company plans and controls its global supply chain integrally and has implemented a so-called Advanced Planning and Scheduling tool (Stadtler and Kilger, 2005) to support this. In order to limit the supply risks, this company applies a dual sourcing strategy by outsourcing part of the production volumes to (expensive) contract manufacturers and by keeping the other part of the production volumes internally. In case of unexpected supply inability of one of the two sources, the company is still able to supply (part of) the market.

In this case study, we consider the supply chain of one of the strategic products of this company. This product has two different variants (with different strengths) and is supplied from stock to end-customers, which are hospitals and pharmacies. The product can be produced at an internal manufacturing site and at a contract manufacturer.

During this case study, we were positioned at this company and we have regularly visited the contract manufacturer in case. Further, several managers and planners at different hierarchical levels of the companies were regularly interviewed. To ensure reliable results, multiple sources of evidence were used. Therefore, besides the interviews, we also performed an extensive documentation study, data analyses, looked into archival data, such as the contracts, and did direct observations.

Figure 4.3 shows the structure of the supply chain that we consider. Items 1 and 2 can be both supplied from sources 1 and 2, which are the internal manufacturing source and the contract manufacturer respectively. Table 4.5 shows the relevant real-life data that we gathered from the case study and which is used in the simulation study. Moreover, we had 4 years of historical demand and forecast data, which were also used in the simulation study to imitate the real demand and forecast process as much as possible. Further, the planning horizon at this company is 12 months.

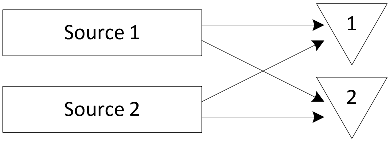

Figure 4.3. Setting for the simulation study

Table 4.5. Parameters used in the simulation study

Parameter	Item 1	Item 2	Source 1	Source 2
Average demand	600,000	110,000		
Batch size	100,000	50,000		
Coefficient of variation of the demand	0.27	0.38		
Capacity level			330,000	
Lead time			4 months	3 months
Production cost	Source 1: € 0.51 Source 2: € 1.16	Source 1: € 0.29 Source 2: € 1.46		
Inventory holding cost	€ 0.20	€ 0.20		
Fluctuation cost			€ 0.50	

Currently, this company applies a dynamic allocation strategy for this dual sourcing case. Based on the insights from section 4.4, we did again a simulation study to test whether the rigid allocation strategy would lead to an improvement of the supply chain performance, measured by the total cost and the service level. Table 4.6 shows the results of the comparative study. Run 1 is where the dynamic allocation strategy has been simulated. The simulation results of this run (total costs of €652,447 and a service level of 0.94) are close to the real performance of this supply chain. Runs 2 and 3 show the simulation results when the rigid allocation strategy is applied. At run 2, the standing order quantity is set equal to a quarter of the expected demand and at run 3, half of the expected demand is fixed.

Table 4.6. Results of the comparison between the two allocation strategies

Allocation strategy	Run	Performance measures	
		Total cost	*Service level*
DAS	1	€ 652,447	0.94
RAS	2	€ 552,460	0.72
	3	€ 616,093	0.98

The results of Table 4.6 show that run 3 is substantially better than run 1, as lower costs are achieved at a higher service level. For the supply chain we studied, the dynamic allocation strategy results in a total cost of € 652,447 and a service level of 0.94. The rigid allocation strategy results in total costs of € 616,093 and a service level of 0.98 if half of the expected demand is constantly supplied by the internal manufacturing site. This confirms the results that we gathered from the previous section.

To check whether changing the level of demand uncertainty will change the insight that follows from Table 4.6, we double and halve the demand uncertainty (compared with experiment 1) to see whether this has an effect on the gap between the results of the two allocation strategies.

Table 4.7. Results of doubling and halving the demand uncertainty

Allocation strategy	Run	Demand uncertainty	Performance measures	
			Total cost	*Service level*
DAS	4	high	€ 641,592	0.88
RAS	5	high	€ 536,799	0.72
	6	high	€ 584,942	0.92
DAS	7	low	€ 649,751	0.97
RAS	8	low	€ 561,410	0.72
	9	low	€ 637,899	0.99

When we double the demand uncertainty (runs 4 till 6), we see again that there is a situation where the rigid allocation strategy (total cost of € 584,942 at a service level of 0.92) performs better than the dynamic allocation strategy (total cost of € 641,592 at a service level of 0.88). We see that the performance gap indeed increases compared to the results of Table 4.6. Runs 7 till 9 show the results when the demand uncertainty is halved and again, we see that the rigid allocation strategy (at a certain parameter setting) performs better than the dynamic allocation strategy.

4.5. Conclusions

Inspired by a real-life case, we considered in this chapter the situation where an outsourcer faces stochastic demand and low demand forecast accuracy, i.e., the realized demand deviates substantially from the forecasted quantity. The outsourcer has partly outsourced the production activities to a contract manufacturer, which results in a dual sourcing setting with an internal manufacturing source and a contract manufacturer. The two supply sources are different. The internal manufacturing source is cheaper (lower unit production cost), but is less flexible (longer lead time and fluctuations in the production volume is costly). Since many companies have implemented Advanced Planning and Scheduling (APS) systems, which are based on mathematical programming models, we formulated a mathematical programming model for the described dual sourcing setting.

Based on extensive simulation studies and a real-life case study, we compared the performances of two different allocation strategies for the dual sourcing setting: the dynamic allocation strategy (DAS) and the rigid allocation strategy (RAS). With the DAS strategy, the allocation towards the two sources is dynamic and determined from period to period. In the RAS, the most rigid source (the internal manufacturing source) supplies each period a fixed quantity (the standing order quantity) and only the supply from the contract manufacturer remains a decision variable.

We have shown that in a stationary case, the RAS strategy performs significantly better than the DAS strategy if the standing order quantity is set optimally or close to optimal. The reason is that the DAS strategy attaches too much importance to the random demand forecasts, which are inaccurate. We have shown that the optimal standing order quantity exists and that the optimal standing order quantity decreases when the demand uncertainty increases. The fact that the RAS strategy outperforms the DAS strategy is insensitive to the lead time structure, batch sizes, capacity levels, and the level of demand uncertainty. The question is whether this conclusion also holds for cases where the demand forecasts are more accurate (i.e., lower forecast errors), which is an idea for future research (see section 7.3).

To further found our insights, we conducted a case study at a pharmaceutical company that faces the dual sourcing problem. In this case study, we used data that we gathered from real-life. We have shown that for this company, switching from the DAS to the RAS strategy leads to an increase in the supply chain performance, both in terms of total cost and service level. Therefore, managers of companies that have implemented such APS systems and face a dual sourcing setting are recommended to consider applying the RAS strategy.

Appendix 4.1. Simulation results

EXPERIMENTAL SETTING, INPUT PAR.							**EXPERIMENTAL RESULTS**									
								COSTS				**AVERAGES**				
	Strategy	**CV**	**L1**	**Cap**	**Qfix**	**Q**	**SL**	**TC**	**IC**	**PC**	**FC**	**Inv**	**S1**	**S2**	**LD**	**SH**
1	DAS	0.25	1	50	-	1	0.88	85	3	82	0	15	50	38	12	0
2	DAS	0.25	1	50	-	25	0.93	95	4	91	0	21	50	44	7	0
3	DAS	0.25	1	75	-	1	0.92	66	4	61	1	18	75	16	8	1
4	DAS	0.25	1	75	-	25	0.94	72	6	65	1	28	75	19	7	1
5	DAS	0.25	2	50	-	1	0.88	84	3	81	0	16	50	37	12	0
6	DAS	0.25	2	50	-	25	093	91	5	87	0	24	50	41	7	0
7	DAS	0.25	2	75	-	1	0.91	67	4	62	1	22	75	16	10	1
8	DAS	0.25	2	75	-	25	0.94	74	6	68	1	29	75	20	6	1
9	DAS	0.25	3	50	-	1	0.87	84	3	81	0	17	50	37	13	0
10	DAS	0.25	3	50	-	25	0.92	92	5	87	0	23	50	42	8	0
11	DAS	0.25	3	75	-	1	0.91	65	4	61	0	20	75	15	9	0
12	DAS	0.25	3	75	-	25	0.94	73	6	66	1	31	75	19	6	1
13	DAS	1	1	50	-	1	0.76	100	21	67	12	105	42	31	23	12
14	DAS	1	1	50	-	25	0.79	112	21	78	13	106	42	38	16	13
15	DAS	1	1	75	-	1	0.78	110	21	61	28	104	52	23	22	28
16	DAS	1	1	75	-	25	0.77	116	23	62	31	115	53	24	24	31
17	DAS	1	2	50	-	1	0.78	103	25	67	11	124	43	30	21	11
18	DAS	1	2	50	-	25	0.79	109	25	72	12	124	43	34	20	12
19	DAS	1	2	75	-	1	0.79	123	26	66	30	131	53	27	22	30
20	DAS	1	2	75	-	25	0.81	127	27	68	32	134	52	28	19	32
21	DAS	1	3	50	-	1	0.80	109	26	72	12	128	43	34	20	12
22	DAS	1	3	50	-	25	0.79	105	25	70	10	126	44	32	21	10
23	DAS	1	3	75	-	1	0.79	122	27	66	28	136	56	25	22	28
24	DAS	1	3	75	-	25	0.79	132	29	74	28	147	54	31	22	28
25	RAS	0.25	1	-	50	1	0.87	85	3	82	0	17	50	38	13	0
26	RAS	0.25	1	-	50	25	0.92	91	5	87	0	23	50	41	8	0
27	RAS	0.25	1	-	75	1	0.98	65	14	52	0	68	95	3	2	0
28	RAS	0.25	1	-	75	25	0.99	68	15	53	0	75	95	4	1	0
29	RAS	1	1	-	50	1	0.76	98	31	66	0	157	50	27	24	0
30	RAS	1	1	-	50	25	0.81	98	32	66	0	159	50	28	19	0
31	RAS	1	1	-	75	1	0.98	191	138	53	0	692	92	5	2	0
32	RAS	1	1	-	75	25	0.96	191	137	54	0	683	94	5	4	0

CV	Coefficient of variation of the demand
DAS	Dynamic allocation strategy
RAS	Fixed allocation strategy
L1	Lead time of source 1
Qfix	Quantity fixed and supplied by source 1
Q	Batch size
TC	Total cost
IC	Inventory cost
PC	Production cost
FC	Fluctuation cost
Inv	Average inventories
S1(2)	Average quantity allocated to source 1(2)
SL	Service level
LD	Average lost demand quantity
SH	Average shift quantity at source 1

5. Capacity reservation and utilization for a manufacturer with uncertain capacity and demand

In this chapter, we turn back to the case where the contract manufacturer is the only source of supply and the research question addressed in this chapter is: *What is the structure of the optimal reservation and order policies for the outsourcer to control the outsourced supply chain?* We consider a manufacturing company that has outsourced the production activities to a contract manufacturer. The contract manufacturer produces on a non-dedicated capacitated production line, i.e., the contract manufacturer produces for multiple outsourcers on the same production line. The contract manufacturer requires that all outsourcers reserve capacity slots before ordering and responds to these reservations by acceptance or partial rejection, based on allocation rules that are unknown to the outsourcer. Therefore, the allocated capacity for the outsourcer is not known in advance, also because the outsourcer has no information about the reservations of the other outsourcers. We study this problem from the outsourcer's perspective that faces stochastic demand and stochastic capacity allocation from the contract manufacturer. A single-item periodic review inventory system is considered and we assume linear inventory holding, backorder, and reservation costs. We develop a stochastic dynamic programming model for this problem and characterize the optimal policy. We conduct a numerical study where we also consider the case that the capacity allocation is dependent on the demand distribution. For this case, we show the structure of the optimal policy based on a numerical study. Further, the numerical results reveal several interesting managerial insights, such as that the optimal reservation policy is little sensitive to the uncertainty of capacity allocation. In that case, the optimal reservation quantities hardly increase, but the optimal policy suggests increasing the utilization of the allocated capacity. Moreover, we show that for the contract manufacturer, the desired behavior is already achieved when small reservation costs are charged.

5.1. Introduction

Outsourcing has been defined by Chase *et al*. (2004, p.372) as an 'act of moving some of a firm's internal activities and decision responsibilities to outside providers'. In the last few years, many papers appeared on the development of outsourcing in many industries (Kremic *et al.*, 2006). A survey in 1997 of more than 600 large companies by the American Management Association finds that substantial numbers of companies are now outsourcing in many areas: information systems, finance, accounting, manufacturing, maintenance, and personnel. Among manufacturing companies, more than half had outsourced at least one component of their production process (Bryce and Useem, 1998).

Due to contractual agreements and limited information transparency, outsourcing complicates the order placing process for the outsourcer, especially when the contract manufacturer serves a number of outsourcers on the same production line (see Chapter 2). It is common in practice to have a contractual agreement that obliges the outsourcers to reserve capacity prior to ordering (Zhao *et al.*, 2007). Capacity reservation offers several benefits to supply chain members such as mitigating the bullwhip effect (Lee *et al.*, 1997), providing flexibility to deal with uncertain demand and helps the contract manufacturer with its capacity planning, i.e., to secure capacity prior to receiving orders from the outsourcers (Serel *et al.*, 2001).

In this chapter, we consider an outsourcer that has outsourced the production activities for a long-term to a contract manufacturer, which is the only source of supply for that specific product. The contract manufacturer performs the production activities on a non-dedicated capacitated production line on which multiple outsourcers are served. Basically, the contract manufacturer does not have its own product portfolio, but only produces by offering outsourcing services to the outsourcers.

According to the contractual agreement, the contract manufacturer requires from the outsourcer to reserve capacity slots in advance. Once the reservations are collected, the contract manufacturer plans its capacity based on allocation rules and priorities that are unknown to the outsourcer. Therefore, the available capacity for each outsourcer is not known in advance. Later, the contract manufacturer responds to the outsourcer with the accepted reservation quantity, which is the upper bound for the order quantity, which is placed by the outsourcer to meet the uncertain demand.

From the outsourcer's perspective, it is not obvious what the optimal strategy is to control such a system. Reservation secures capacity for future orders, but also increases costs. A large body of literature deals with production planning models and inventory systems that considers capacitated supply (Federgruen and Zipkin, 1986; Ciarallo *et al.* 1994), but does not consider capacity reservation in their models. Therefore, our main contribution to this line of research is that we include the capacity reservation problem to the production planning model in case of uncertain capacity and demand.

We study this multi-period inventory system from the outsourcer's perspective that faces uncertain capacity from the contract manufacturer and uncertain customer demand. The outsourcer has to decide on the reservation and order quantities (to release to the contract manufacturer) in order to minimize the expected costs. We develop a stochastic dynamic programming model for this problem and characterize the optimal policy. We also conduct a numerical study in which we extend the problem by considering dependency between the demand and capacity distributions. The numerical results reveal several interesting managerial insights, such as that the utilization of the reservations (the order quantity divided by the accepted reservation quantity) is increased when the capacity uncertainty or the reservation costs increase, while the optimal reservation policy is little sensitive to the level of capacity uncertainty. We also show that the desired reservation and order behavior is achieved when small reservation costs are charged. Moreover, we show the structure of the optimal reservation policy in case of dependency between the distributions, which is characterized by two parameters.

This chapter is organized as follows. In section 5.2, we discuss the literature review and show our contribution to the literature. In sections 5.3 and 5.4, we present the model and some analytical results. Then, in section 5.5, we present and discuss the numerical results and the managerial insights. Finally, in section 5.6, we draw some conclusions and discuss some ideas for future research.

5.2. Literature review

Federgruen and Zipkin (1986) were one of the first to study a periodic review inventory model with a finite but certain capacity level. They proved the optimality of modified basestock policies. An extension of this work is that of Ciarallo *et al.* (1994) who study the stochastic demand and stochastic capacity setting. They show that in a single-period setting, the optimal policy is not affected by the capacity uncertainty, but in the multi-period setting, order-up-to policies that are dependent on the distribution of the capacity are optimal. Several other papers extended this problem (Güllü, 1998; Hwang and Singh, 1998; Wang and Gerchak, 1996; Iida, 2002; Jaksic *et al.*, 2008). Our main contribution to this line of research is that we add the reservation problem to the stochastic demand and stochastic capacity case.

In our model, the outsourcer makes a reservation by sharing advance demand information (Karaesmen *et al.*, 2002) without knowing exactly what the supply quantity will be, which can be considered as a form of supply uncertainty. A large stream of papers studies the supply uncertainty problem (Bassok and Akella, 1991; Parlar *et al.*, 1995; Güllü *et al.*, 1999; Pac *et al.*, 2009). Most of these papers consider completely uncertain supply quantities, whereas in our case, the supply uncertainty can be partly controlled by the reservation decisions.

Another related part of the literature is about capacity reservation, which has been studied at both the tactical and the operational level. At the tactical level, the main objective is to study contract types and the conditions under which coordination in the supply chain can be achieved. Erkoc and Wu (2005) study the so-called deductible reservation contract, which means that the buyer pays a fee in advance for each reserved unit of capacity. When the buyer places a firm order, the reservation fee is deducted from the order payment, but the fee is not refundable in case the reserved capacity is not fully utilized within the specified time.

At the operational level, many papers have studied capacity reservation (Bonser and Wu, 2001; Hazra and Mahadevan, 2009; Serel *et al*., 2001; Serel, 2007; Van Norden and Van de Velde, 2005; Mincsovics *et al.*, 2009). The main objective of these studies is to decide on getting materials supplied either at a lower price by reserving capacity in advance with the long-term supplier or at a higher price from the spot market (Hazra and Mahadevan, 2009) or making reservations to *guarantee* the delivery of (a portion of) the reserved quantity, given the existence of the more expensive spot market (Serel *et al.*, 2001) or given the uncertain availability of the item in the spot market (Serel, 2007).

Serel *et al.* (2001) show that the existence of the spot market alternative significantly reduces the capacity reservation quantity from the long-term supplier. A similar case is considered by Hazra and Mahadevan (2009), who derive the supplier's optimal capacity reservation price in such a setting. Another paper that has studied capacity reservation is that of Jain and Silver (1995). They consider a single-period setting with stochastic demand and supplier's capacity, but dedicated capacity can be ensured by paying a premium to the supplier. The paper shows that the cost function is not convex in the dedicated capacity, but an algorithm is developed for finding the best level of dedicated capacity.

The literature on capacity reservation considers a single-period (or two-period) dual sourcing setting. We contribute to this line of research by considering a multi-period setting where the reservation problem is integrated with the inventory control problem. The paper that is the closest to our work is that of Costa and Silver (1996). A multi-period inventory problem is considered where the supplier capacity and the customer demand are uncertain. In that paper, the decision maker has the option to reserve some capacity for one or more periods, but the reservations have to be made prior to the start of the planning horizon, whereas in our model, the reservations can be done in each period of the planning horizon, based on more updated information. Furthermore, we characterize the optimal policy for our setting.

5.3. Model

Table 5.1. Notation

T	number of periods in the planning horizon
h	inventory holding cost per unit per period
b	backorder cost per unit per period
s	reservation cost per unit per period
x_t	inventory position in period t before ordering
y_t	inventory position in period t after ordering
r_t	reservation quantity in period t for period $t+1$
z_t	reservation position in period t after reserving
a_t	actual accepted reservation quantity in period t
A_t	accepted reservation quantity in period t
q_t	order quantity in period t
D_t	random demand in period t
$f_t(d_t)$	probability density function of the demand in period t
d_t	actual demand in period t
C_t	random capacity in period t
c_t	actual capacity in period t
α	discount factor ($0 < \alpha \leq 1$)

As discussed earlier, we consider an outsourcer that has outsourced the production activities for a long-term to a contract manufacturer that serves a number of outsourcers on the same production line. The contract manufacturer is the only source of supply for the product. According to the contractual agreement, the outsourcer reserves capacity before ordering. The reservations are needed by the contract manufacturer for its capacity planning and the contract manufacturer responds to a reservation r_{t-1} one period later by the accepted reservation quantity a_t.

At the moment of reservation, the outsourcer does not know what the actual allocated capacity c_t will be, because the contract manufacturer decides on the capacity allocation based on rules and priorities that are unknown to the outsourcer. Further, the outsourcer also has no information about the reservations of other outsourcers. Therefore, from the outsourcer's perspective, a_t is the minimum of r_{t-1} and the uncertain allocated capacity C_t at the contract manufacturer.

Once a_t is announced, the reservation costs are charged, which are equal to sa_t with s being the unit reservation cost. These costs are introduced by the contract manufacturer to avoid that the outsourcers inflate their reservations. The outsourcer is not charged for each unit reserved r_t, as this would be 'unfair' if part of the reservation is rejected. In essence, our reservation cost structure is similar to the deductible reservation fee of Erkoc and Wu (2005), as in both cases, a premium is also paid for reservations that are not utilized.

After knowing a_t, the outsourcer decides on the order quantity q_t to meet the uncertain demand D_t. The order quantity q_t cannot exceed a_t and is delivered by the contract manufacturer just before the real demand d_t is observed.

To model this finite-horizon planning problem, we use a stochastic dynamic programming approach with two state variables: the inventory position before ordering x_t and a_t, which forms an upper bound on q_t. These state variables are needed to make decisions on r_t and q_t. We assume a periodic review inventory system with stochastic demand and stochastic capacity. As far as the model is concerned, we do not need to make any assumptions on the probability distributions of D_t and C_t. However, to show some optimality results in section 5.4, we have to assume that the two distributions are independent of each other. In section 5.5.2, we relax this assumption and investigate the effects of dependency between the distributions.

We consider the following sequence of events. At the start of period t, the decision maker reviews x_t and a_t, where $a_t = min\{r_{t-1}, c_t\}$. Then, the reservation costs are incurred: sa_t. Based on the current state of the system (x_t, a_t), the decision maker decides on $r_t \geq 0$. The decision maker also decides on q_t, which raises the inventory position to $y_t = x_t + q_t$, where $0 \leq q_t \leq a_t$. Then at the end of period t, q_t that was ordered at the beginning of period t arrives and d_t is observed and satisfied as much as possible from inventory; unsatisfied demand is backordered. Then, inventory holding and backorder costs are incurred.

The state variables of the dynamic programming model (x_t, a_t) are updated at the start of period $t + 1$ in the following way:

$$x_{t+1} = x_t + q_t - d_t \tag{5.1}$$

$$a_{t+1} = min\{r_t, c_{t+1}\} \tag{5.2}$$

We assume linear inventory holding, backorder and reservation costs. Let $g_t(x_t, a_t)$ denote the minimum expected cost function, optimizing the cost over the finite planning horizon T from t onward and starting in the initial state (x_t, a_t). Then, we have the following DP recursion:

$$g_t(x_t, a_t) = sa_t + \min_{\substack{r_t \geq 0 \\ x_t \leq y_t \leq x_t + a_t}} \{\mathcal{L}(y_t) + \alpha E_{D_t, C_{t+1}}[g_{t+1}(y_t - D_t, A_{t+1})]\}, 1 \leq t \leq T \tag{5.3}$$

where

$$\mathcal{L}(y_t) = h \int_0^{y_t} (y_t - d_t) f_t(d_t) dd_t + b \int_{y_t}^{\infty} (d_t - y_t) f_t(d_t) dd_t \tag{5.4}$$

and

$$A_{t+1} = min\{r_t, C_{t+1}\} \tag{5.2'}$$

The last part of (5.3) is the expected future cost, which is derived by taking the expectation over D_t and C_{t+1}. Further, the stopping condition is $g_{T+1}(\cdot) = 0$.

5.4. The optimal order and reservation policy

In this section, we characterize the optimal solution of (5.3) by assuming that the demand (D_t) and capacity (C_t) are identically and independently distributed across periods and are independent of each other. We prove the optimality of a state-dependent reservation policy and a modified basestock policy.

Let $h_t(y_t, a_t) = \mathcal{L}(y_t) + \alpha E_{D_t, C_{t+1}}[g_{t+1}(y_t - D_t, A_{t+1})]$ denote the cost-to-go function in period t. Accordingly, the minimum expected cost function $g_t(.)$ can be rewritten as

$$g_t(x_t, a_t) = \ sa_t + \min_{\substack{r_t \geq 0 \\ x_t \leq y_t \leq x_{t+} a_t}} h_t(y_t, a_t), \qquad 1 \leq t \leq T \tag{5.3'}$$

In order to describe the optimal reservation policy, we introduce the ”reservation position”: $z_t = x_t + r_t$. Let $(\hat{y}_t, \hat{z}_t)$ be the unconstrained minimizers of $h_t(y_t, a_t)$ for given state variables (x_t, a_t). We first show the convexity results that allow us to find the structure of the optimal policy. Note that the loss function $\mathcal{L}(y_t)$ is convex in y_t (Porteus, 2002). The optimal decisions at any period t (y_t, z_t) are made by minimizing $h_t(\cdot)$ over the feasible region.

Theorem 1:

a. For any period $1 \leq t \leq T$, $g_t(x_t, a_t)$ and $h_t(y_t, a_t)$ are (jointly) convex functions.

b. For any period $1 \leq t \leq T$, the optimal order policy is given by:

$$y_t^* = \begin{cases} x_t + a_t & if \quad x_t < \hat{y}_t - a_t \\ \hat{y}_t & if \quad \hat{y}_t - a_t \leq x_t \leq \hat{y}_t \\ x_t & if \quad x_t > \hat{y}_t \end{cases} \tag{5.5}$$

c. For any period $1 \leq t \leq T$, the optimal reservation policy is given by:

$$z_t^*(a_t) = \begin{cases} \hat{z}_t(a_t) & if \quad x_t \leq \hat{z}_t(a_t) \\ x_t & if \quad x_t > \hat{z}_t(a_t) \end{cases} \tag{5.6}$$

See appendix 5.1 for the proof.

The optimal order policy (5.5) is a modified basestock policy, as the order quantity is bounded by a_t if $x_t < \hat{y}_t - a_t$. The optimal reservation policy (5.6) is a state-dependent reservation-up-to policy. This policy implies that at a given a_t, the reservation quantity should bring the reservation position $z_t = x_t + r_t$ to the optimal reservation position $\hat{z}_t(a_t)$ if $x_t \leq \hat{z}_t(a_t)$. Otherwise, $z_t^*(a_t) = x_t$, which means to reserve nothing.

To summarize, the inventory system can be optimally controlled by two critical parameters: the optimal order-up-to level $\hat{y}_t$ and the optimal reservation-up-to level $\hat{z}_t(a_t)$ according to policies (5.5) and (5.6).

5.5. Numerical study

In this section, we present and discuss a numerical study that we conducted by solving the stochastic dynamic programming formulation given in (5.3). We construct a number of experiments and we are mainly interested in the effects of:

- different levels of demand and capacity uncertainty and different reservation costs in case of stationary distributions (section 5.5.1), and
- dependency between the demand and capacity distributions (section 5.5.2)

on the optimal decisions and the system performance.

The following parameters are set at fixed values: T=12, α=0.99, h=1, and b=10. Furthermore, we assume a Gamma distribution for the demand and a Uniform distribution for the capacity (Burgin, 1975).

5.5.1. Stationary demand and capacity availability

In this section, we consider different levels of demand and capacity uncertainty and we vary the unit reservation cost. In experiments 1-24 (see Table 5.2), $E[D_t] = E[C_t]$ = 5, but we vary:

- the coefficient of variation of the demand $CV(D_t)$ between 0.5 (low), 1 (medium), and 1.5 (high);
- the coefficient of variation of the capacity $CV(C_t)$ between 0.28 (low) and 0.52 (high);
- the unit reservation cost between 0, 2, 5, and 10.

Table 5.2 shows the results of these experiments, where $\hat{z}_1(a_1)$ is shown as a vector in $\overrightarrow{a_1}$. Moreover, the expected costs are shown for $(x_t, a_t) = (0,6)$, as this is a feasible state for all experiments.

Table 5.2. Results with varying demand uncertainty, capacity uncertainty, and reservation cost

Exp	$\boldsymbol{E[D_t]}$	$\boldsymbol{CV(D_t)}$	$\boldsymbol{E[C_t]}$	$\boldsymbol{CV(C_t)}$	$\boldsymbol{s}$	$\boldsymbol{\hat{y}_1}$	$\boldsymbol{\hat{z}_1(a_1)}$	***E[Cost]***
1	5	low	5	low	0	19	36	306.32
2	5	low	5	low	2	22	{20,…,16}	425.00
3	5	low	5	low	5	25	{19,…,15}	598.52
4	5	low	5	low	10	28	{18,…,14}	882.65
5	5	medium	5	low	0	30	59	573.06
6	5	medium	5	low	2	33	{30,..,26}	690.27
7	5	medium	5	low	5	35	{27,…,23}	860.26
8	5	medium	5	low	10	38	{24,…,20}	1136.68
9	5	high	5	low	0	37	77	704.83
10	5	high	5	low	2	39	{36,…,32}	820.01
11	5	high	5	low	5	41	{31,…,27}	985.60
12	5	high	5	low	10	43	{27,…,23}	1250.49
13	5	low	5	high	0	22	39	379.69
14	5	low	5	high	2	28	{25,…,17}	495.67
15	5	low	5	high	5	36	{25,…,17}	663.92
16	5	low	5	high	10	45	{24,…,16}	937.70
17	5	medium	5	high	0	32	60	614.62
18	5	medium	5	high	2	38	{34,…,26}	729.24
19	5	medium	5	high	5	43	{33,…,25}	892.21
20	5	medium	5	high	10	49	{32,…,24}	1154.19
21	5	high	5	high	0	38	78	735.05
22	5	high	5	high	2	43	{40,…,32}	847.08
23	5	high	5	high	5	47	{37,…,29}	1003.41
24	5	high	5	high	10	51	{34,…,26}	1251.89

The results from Table 5.2 show that higher demand uncertainty increases $\hat{y}_1$, $\hat{z}_1(a_1)$ and leads to higher costs. However, the higher the unit reservation cost s, the lower the effect of an increase of the demand uncertainty, because the incremental increase of the optimal reservation quantities decreases. Figure 5.1 shows the optimal order-up-to and reservation-up-to levels for different unit reservation cost and different levels of demand uncertainty. From the results, we see that when s increases, the optimal order-up-to level increases much more than the reservation quantities. In other words, when the unit reservation costs increases, it is optimal to increase the order quantity (much more than the reservation quantity) such that a larger part of the accepted reservation is utilized, instead of increasing the reservation quantities. See Figure 5.2 that confirms this insight by showing the optimal ratio $\frac{z_t}{y_t}$.

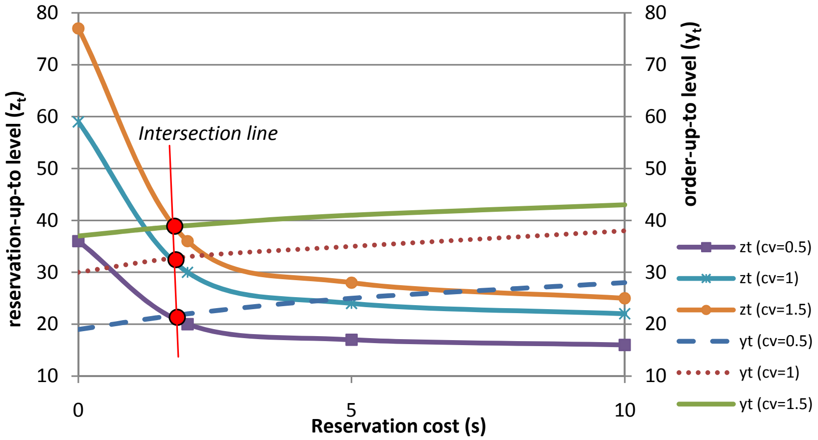

Figure 5.1. Order-up-to ($\hat{y}_t$) and reservation-up-to ($\hat{z}_t$) levels for different levels of demand uncertainty and reservation cost and the intersection line

From the other side, the contract manufacturer would prefer a situation where the difference between the reservation and order quantities is minimal, ideally zero. In Figure 5.1, we show that these ideal situations are reached at small unit reservation cost. The intersection line that connects the intersection points is almost vertical, which means that the optimal s is very robust to the level of demand uncertainty. This means that the contract manufacturer should incorporate just small unit reservation cost, but greater than zero, in the contract to avoid large discrepancies between the reservation and order behavior.

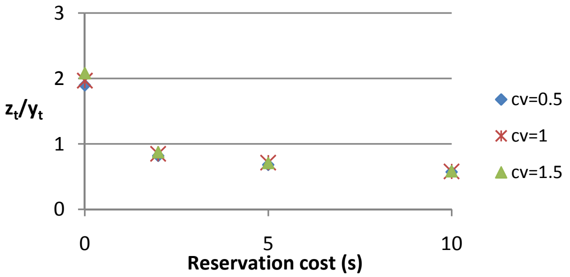

Figure 5.2. The optimal ratio z_t/y_t at different unit reservation cost and different levels of demand uncertainty

Another insight from Table 5.2 is that the higher the demand uncertainty, the lower the effect of an increase of capacity uncertainty on the optimal cost (see Figure 5.3, where *ΔCost* is given by (5.7)).

$$\Delta Cost = \frac{E[Cost|CV(C_t) = high] - E[Cost|CV(C_t) = low]}{E[Cost|CV(C_t) = low]} \tag{5.7}$$

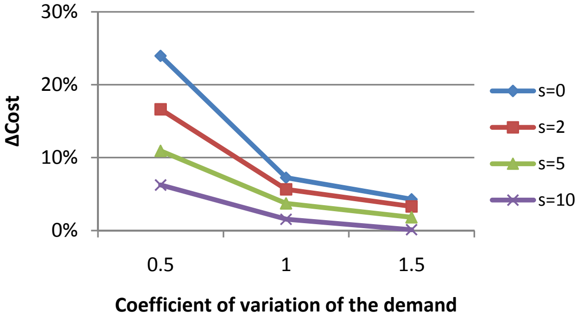

Figure 5.3. Relative cost increase due to increased capacity uncertainty

The explanation for this effect is that when the capacity uncertainty increases, $\hat{z}_1(a_1)$ increases little compared with $\hat{y}_1$, i.e., the order quantity increases much more than the reservation quantity (see Figure 5.4). Therefore, when the capacity uncertainty increases, it is optimal to increase the order-up-to level much more than the reservation-up-to level. Therefore, when the capacity uncertainty increases, the optimal ratio $\frac{z_t}{y_t}$ decreases.

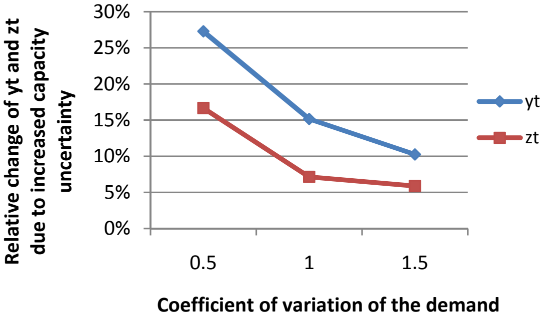

Figure 5.4. Relative change in y_t and z_t due to increased capacity uncertainty (when s=2)

5.5.2. Dependency between the distributions

In this section, we show the results of a numerical study in which we consider dependency between the demand and capacity distributions. In this study, we assume that the capacity allocation C_t of the contract manufacturer is dependent on the outsourcer's demand D_t and therefore, the results of section 5.4 do not hold anymore. We consider both the situations where the dependency is positive (section 5.5.2.1.) and negative (section 5.5.2.2.). We also show the structure of the optimal policy for these two situations. In appendix 5.2, we show how the conditional probability distributions are determined.

5.5.2.1. Positive dependency

In this numerical study, we consider the case where the contract manufacturer is allocating more capacity when the outsourcer's demand is higher. The idea is that when the outsourcer's demand is higher, the outsourcer will request more (in terms of reservations and orders) and the contract manufacturer is then willing to allocate more capacity to the outsourcer to avoid the outsourcer searching for another source of supply. This situation is also possible when the outsourcers' demand quantities are negatively correlated, which means that the more the outsourcer reserves and orders the less the other outsourcers reserve and order, the more capacity is available for the outsourcer.

First, we show the structure of the optimal policy as we observed during the numerical studies. Then, we discuss the numerical results and compare them with non-correlated case. Based on the numerical studies, we observed that the optimal order policy remains a modified basestock policy with the same structure as (5.5). However, the reservation policy does not remain the same. Figure 5.5 shows the structure of the optimal reservation policy in case of positive dependency, as we observed in our numerical study. The policy can be characterized by two optimal reservation-up-to levels, where the second level is lower than the first one. When the inventory position exceeds some point, it is optimal to target for a lower reservation-up-to level, as less capacity is needed, which is the result of positive dependency.

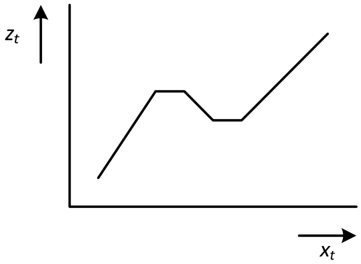

Figure 5.5. The structure of the optimal reservation policy in case of positive dependency

Table 5.3 shows the numerical results for 9 experiments that we conducted with positive dependency between the demand and capacity distributions. The results show that for all experiments, the expected cost is lower than in case with no dependency (on average 20.6 %). Due to the positive dependency, less has to be reserved with lower risk of getting too high accepted reservations, which results in lower (reservation) costs.

This result suggests that it is worthwhile to collect market information of the competitors (that produce at the same contract manufacturer) and to assess the dependency between the own demand and that of the competitors. In case of a negative dependency (which means there is a positive dependency between the own demand and the available capacity at the contract manufacturer), which is for example the case when the competitors operate in different market sectors, it is wise to adapt the reservation policy towards the contract manufacturer.

Table 5.3. Results with positive dependency

Exp	$E[D_t]$	$CV(D_t)$	$E[C_t]$	$CV(C_t)$	s	$\hat{y}_1$	E[Cost]
25	5	low	5	low	0	17	234.74
26	5	low	5	low	2	20	358.88
27	5	low	5	low	5	24	538.13
28	5	low	5	low	10	28	830.40
29	5	medium	5	low	2	31	598.66
30	5	high	5	low	2	38	717.91
31	5	low	5	high	2	25	370.53
32	5	medium	5	high	2	35	554.45
33	5	high	5	high	2	40	684.23

5.5.2.2. Negative dependency

In this numerical study, we consider the negative dependency case. Such a situation is likely when the different outsourcers that all reserve and order at the same contract manufacturer operate in the same market, which results in a positive correlation between the demand D_t of the different outsourcers. That means that all outsourcers will increase their reservations and orders in case of a demand increase and vice versa. In such a situation, the contract manufacturer faces increased demand from all outsourcers simultaneously, which results in a smaller capacity allocation for each outsourcer. Based on the results of the numerical studies, we observe that the optimal order policy remains the same as (5.5), but the structure of the reservation policy changes and is shown in Figure 5.6.

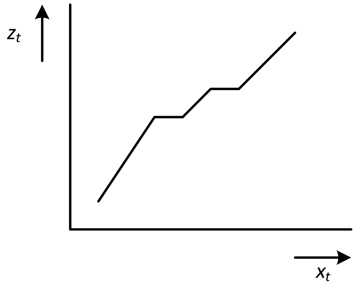

Figure 5.6. The structure of the optimal reservation policy in case of negative dependency

Like in the positive dependency case, the optimal policy can be characterized by two optimal reservation-up-to levels, but the second one is now higher than the first one. Due to the negative dependency, the model compensates the little allocation of capacity by increasing the reservation-up-to level. Table 5.4 shows the numerical results of the experiments that we conducted with negative dependency between the demand and capacity distributions. The results show that for all experiments, the costs are higher than in case with no dependency. Due to the negative dependency, the probability of not getting enough supplied to meet the demand increases, which increases the backorder costs.

Like in the positive dependency case, it is worthwhile to assess whether there is dependency between the own demand and that of the competitors, by which the dependency between the own demand and the contract manufacturer's available capacity level can be estimated. If the latter dependency appears to be negative, it is recommended to take measures to eliminate the negative dependency, as this leads to higher costs. The elimination can be done by keeping some safety stock to avoid backorders or by agreeing (contractually) on paying slightly more to make an appeal to (in case needed) a fixed amount of the contract manufacturer's production capacity.

Table 5.4. Results with negative dependency

Exp	$E[D_t]$	$CV(D_t)$	$E[C_t]$	$CV(C_t)$	s	$\hat{y}_1$	***E[Cost]***
34	5	low	5	low	0	20	395.51
35	5	low	5	low	2	22	507.63
36	5	low	5	low	5	25	673.77
37	5	low	5	low	10	28	947.42
38	5	medium	5	low	0	32	719.15
39	5	medium	5	low	2	35	825.08
40	5	high	5	low	2	41	953.94
41	5	low	5	high	0	24	575.52
42	5	low	5	high	2	29	681.81
43	5	medium	5	high	2	40	983.23
44	5	high	5	high	2	46	1116.38

5.6. Conclusions

In this chapter, we consider the case where a manufacturing company has outsourced the production activities to a contract manufacturer. The contract manufacturer produces on a non-dedicated production line on which multiple outsourcers are served. For capacity planning purposes, the contract manufacturer requires that the outsourcer reserves capacity before ordering and responds to the reservations by acceptance or partial rejection based on rules that are unknown to the outsourcer. Therefore, the allocated capacity to the outsourcer is not known in advance.

We study this problem from the outsourcer's perspective that faces stochastic customer demand and stochastic capacity allocation from the contract manufacturer and that has to decide on the reservation and order quantities under uncertainty. We develop a stochastic dynamic programming model for this problem and we characterize the optimal reservation and order policies. The optimal reservation policy is a state-dependent policy, as the optimal target reservation-up-to level is dependent on the accepted reservation quantity. The optimal order policy is a modified basestock policy; the order quantity is bounded by the accepted reservation quantity.

We conduct a numerical study which reveals several interesting (managerial) insights. First, in case the unit reservation cost or the capacity uncertainty increases, it is optimal to increase the order quantity (much more than the reservation quantity) and so, the utilization of the accepted reservation quantity. This might be counterintuitive, as one would expect to mainly increase the reservation quantities in case the capacity uncertainty increases to hedge against the uncertainty faced from the contract manufacturer. Another insight is that the effect of an increase of the capacity uncertainty decreases substantially when the demand uncertainty increases. When the demand uncertainty increases, the optimal order quantities increase, by which the order will be (closely) equal to the accepted reservation quantity. The action of increasing the order quantity is also required when the capacity uncertainty increases, and therefore, we see that the effect of an increase of the capacity uncertainty is little when the demand uncertainty increases.

Another managerial insight follows from the fact that from the contract manufacturer's perspective, it is desired to have the reservation equal to the order quantity. We have seen that this can be achieved when little reservation costs are charged. This optimal unit reservation cost is more or less independent of the level of demand uncertainty. Charging no reservation costs leads to over reservation and charging higher reservation costs leads to under reservation. This managerial insight is helpful when having contract negotiations with the outsourcers on setting the reservation cost, which is a contract parameter.

Finally, we studied the case where the capacity allocation of the contract manufacturer depends on the outsourcer's demand distribution. When the distributions are dependent, the structure of the optimal order policy is the same as in the independent case, but the optimal reservation policy changes to a policy with two optimal target reservation-up-to levels. Dependent on whether the dependency is positive (or negative), the second optimal reservation-up-to level is lower (or higher) than the first one by which the model adapts its reservation quantities to the higher (or lower) capacity allocation. We have seen that the expected cost decreases when the dependency is positive and increases when the dependency is negative. These results suggest that it is worthwhile to collect market information of the competitors (that produce at the same contract manufacturer) to assess the dependency between the own demand and the available capacity at the contract manufacturer. In case the dependency is positive, it is wise to adapt the reservation policy towards the contract manufacturer to save costs. In case of negative dependency, one can think of measures like keeping safety stocks to hedge against the little capacity allocation of the contract manufacturer or agreeing on paying an additional premium to ensure (in case needed) a fixed amount of capacity from the contract manufacturer. Of course, these measures should be cheaper than the extra cost due to the negative dependency.

Appendix 5.1. Proof of theorem 1

Let

$$g_t(x_t, a_t) = \min_{\substack{r_t \geq 0 \\ x_t \leq y_t \leq x_t a_t}} \{sa_t + \mathcal{L}(y_t) + \alpha E_{D_t, C_{t+1}}[g_{t+1}(y_t - D_t, A_t)]\}$$
$$= \min_{\substack{r_t \geq 0 \\ x_t \leq y_t \leq x_t a_t}} \{sa_t + h_t(y_t, a_t)\} = sa_t + i_t(x_t, a_t)$$

- The functions $g_t(x_t, a_t)$ and $h_t(y_t, a_t)$ are jointly convex functions for any $t \in [1, T]$. We prove this by induction. $g_{T+1}(\cdot) = 0$ and is convex. Assume that $h_{t+1}(\cdot)$ is also convex. Then, the function $h_t(y_t, a_t) = \mathcal{L}(y_t) + \alpha E_{D_t, C_{t+1}}[g_{t+1}(y_t - D_t, A_t)]$ is also convex, because:
    - $\mathcal{L}(y_t)$ is a convex funtion;
    - $E[g_{t+1}(y_t - D_t, A_t)]$ is convex due to the convexity of the expected value operator. Rule: If $f: \mathbb{R}^n \to \mathbb{R}$ is convex, then the function $g(x) = E_w\{f(x + w)\}$ is also a convex function, where w is a random vector in $\mathbb{R}^n$, provided that the expected value is finite for every $x \in \mathbb{R}^n$ (Bertsekas, 2005);
    - the linear combination of two convex functions remains convex. Rule: Let K be a non-empty index set, X a convex set, and for each $k \in K$ let $f_k(\cdot)$ be a convex function on X and let $p_k \geq 0$. Then $\sum_{k \in K} p_k f_k(x)$, $x \in X$ is a convex function on any convex subset of X, where the sum takes finite values (Heyman and Sobel, 2004).

- $i_t(x_t, a_t) = \min_{\substack{r_t \geq 0 \\ x_t \leq y_t \leq x_t a_t}} \{h_t(y_t, a_t)\}$ is also convex when $h_t(y_t, a_t)$ is convex. Rule: Let X be a non-empty set with A_x a non-empty set for each $x \in X$. Let $C = \{(x, y): y \in A_x, x \in X\}$, let J be a real-valued function on C, and define $f(x) = \inf\{J(x, y): y \in A_x\}, x \in X$. If C is a convex set and J is a convex function on C, then f is a convex function on any convex subset of $X^* = \{x: x \in X, f(x) > -\infty\}$ (Heyman and Sobel, 2004).

- The function $g_t(x_t, a_t) = sa_t + i_t(x_t, a_t)$ is then also convex.

Appendix 5.2. Conditional probability distribution

In part of the numerical studies, we consider the case where the capacity allocation C_t by the contract manufacturer is positively or negatively dependent on the outsourcer's demand D_t. Therefore, we adapt the probability mass function of C_t to a conditional probability mass function in which C_t is conditioned on D_t: $P\{C_t = c | D_t = d\}$. This function is basically a matrix *F* of size $m \times n$, where $m = d_{max}$ (the maximum demand) and $n = b - a + 1$ (where *a* and *b* are the bounds of the capacity distribution).

In case of positive dependency, elements $F_{m,1} = F_{1,n}$ = 0 and $F_{1,1} = F_{m,n} =$ 0.5, see the matrix below. Then, the rows and columns are filled by a *linear* decrease/increase from 0 to 0.5. Finally, the probabilities are rescaled, such that capacity distribution sums up to 1.

$$F = \begin{bmatrix} 0.50 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0.50 \end{bmatrix}$$

In case of negative dependency, the same procedure is applied, but now $F_{1,1} = F_{m,n} =$ 0 and $F_{m,1} = F_{1,n}$ = 0.5, see the matrix below.

$$F = \begin{bmatrix} 0 & \cdots & 0.50 \\ \vdots & \ddots & \vdots \\ 0.50 & \cdots & 0 \end{bmatrix}$$

6. Capacity flexibility allocation in an outsourced supply chain with reservation[4]

In the previous chapters, we studied the outsourced supply chain mainly from the outsourcer's perspective. We discussed the implications of outsourced supply chains on the operations planning (Chapter 2), the value of a more advanced order release strategy (Chapter 3), the optimal policies (Chapter 5), but all these chapters consider the perspective of the outsourcer. In this chapter, we study the outsourced supply chain from the contract manufacturer's perspective. The research question addressed in this chapter is: *How should the contract manufacturer allocate its capacity flexibility to the different outsourcers?*

In this chapter, we consider a contract manufacturer that serves a limited number of outsourcers (customers) on a single capacitated production line. The outsourcers have different levels of demand uncertainty and the contract manufacturer faces the question how to allocate the contractual capacity flexibility in an optimal way. The contractual capacity flexibility is a contract parameter that sets the amount of demand the contract manufacturer is obliged to accept from the outsourcers. We develop a hierarchical model that consists of two decision levels. At the tactical level, the contract manufacturer allocates the capacity flexibility to the different outsourcers by maximizing the expected profit. Offering more flexibility to the more uncertain outsourcer generates higher expected revenue, but also increases the expected penalty costs. The allocated capacity flexibilities (determined at the tactical level) are input parameters to the lower decision level, where the operational planning decisions are made and actual demands are observed. We perform a numerical study by solving the two-level hierarchical planning problem iteratively. We first solve the higher level problem, which has been formulated as an integer program, and then perform a simulation study, where we solve a mathematical programming model in a rolling horizon setting to measure the operational performance of the system. The simulation results reveal that when the acceptance decision is made (given the allocated capacity flexibility decision), priority is given to the less uncertain outsourcer, whereas when the orders are placed, priority is given to the most uncertain outsourcer. Our insights are helpful for contract manufacturers when having contract negotiations with the outsourcers. Moreover, we show that hierarchical integration and anticipation are required, especially for cases with high penalty cost and tight capacities.

6.1. Introduction

In the last few years, outsourcing is increasingly developing in many industries (e.g. Liston *et al.*, 2007). The rise of contract manufacturers that often serve a number of competing outsourcers, results in new challenges and complexities. Due to shorter life cycles, need for innovation, and increased competition between the outsourcers, the contract manufacturers are challenged to increase the level of reactivity, responsiveness and to act more proactively. Therefore, contract manufacturers are more under the pressure to redesign the contractual decisions to deal with new and increased level of (demand) uncertainties.

These capabilities are often referred to as *flexibility*, which has been widely discussed among researchers and practitioners (Sethi and Sethi, 1990; D'Souza and Williams, 2000; Bertrand, 2003; Slack, 2005). Flexibility is also increasingly recognized by researchers and practitioners as an important performance measure of a company (De Toni and Tonchia, 2001) and of a supply chain (Duclos *et al.*, 2003; Sanchez and Perez, 2005). This literature also addresses the limited academic research with respect to the performance impact of supply chain flexibility (Beamon, 1999).

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[4] The results in this chapter have also been presented in Boulaksil *et al.* (2009b).

This chapter deals with the determination of contractual flexibilities from a contract manufacturer's perspective that has a long-term relationship with a number of outsourcers with different levels of demand uncertainty. The contract manufacturer negotiates with the outsourcers individually on the flexibilities, assuming that the outsourcer is willing to pay more for additional allocation of capacity flexibility. We model the contractual flexibilities explicitly, provide an approach to quantify the performance potentials, and optimize the allocation of contractual flexibilities by formulating and optimizing an integer programming problem, which anticipates on the operational performance.

Figure 6.1 shows the supply chain structure that we are considering in this chapter. The contract manufacturer produces for all outsourcers on the same capacitated production line and does not have its own product portfolio, nor does it have inventory ownership. The contract manufacturer produces by offering outsourcing services to the outsourcers, based on orders from the outsourcers and contractual obligations. We study this make-to-order system from the contract manufacturer's perspective that faces the task of controlling its capacity in an optimal way. The outsourcers have different levels of demand uncertainty and the more uncertain an outsourcer, the more he is willing to pay the contract manufacturer for an additional unit of capacity flexibility. On the other hand, the more flexibility offered, the higher the probability that the contract manufacturer will not be able to produce all future orders, which results in (high) penalty costs, as defined in the contract.

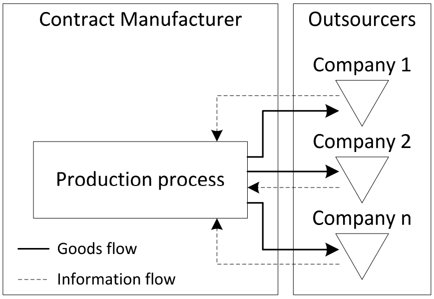

Figure 6.1. The supply chain structure under study

The allocation of capacity flexibility is a medium-term tactical decision that the contract manufacturer makes (e.g. once a year) when having contract negotiations. This allocation decision results in a parameter setting that is input to the short-term periodic operational planning model and which anticipates on the operational planning process. The operational planning process is as follows. The contract manufacturer requires that all outsourcers share their advance demand information prior to ordering, which is considered as capacity reservation. Based on the contract manufacturer's capacity planning and the allocated capacity flexibilities, the reservations are either accepted or (partly) rejected. The accepted quantities are an upper bound for the order quantities that follow afterwards. Basically, the more flexibility allocated to an outsourcer, the more reservations will be accepted from that outsourcer.

We develop a hierarchical model (see Figure 6.2) with two decision levels, which reflects current industry practice. At the higher decision level, the contract manufacturer decides on the allocation of capacity flexibility. At this level, the capacity level and the number of outsourcers are given as a result of a higher-level strategic decision that is beyond the scope of this study. Besides the capacity level and the number of outsourcers, some other parameters are also input to the capacity flexibility allocation decision: the levels of demand uncertainty of the outsourcers and the revenue and cost structure. We assume that this information is available at the contract negotiations.

At this decision level, the expected profit function is maximized by making a trade-off between the extra revenue that is generated by increasing the allocation of capacity flexibility and the penalty costs, which result when the contract manufacturer is not able to produce all (future) orders. Moreover, the higher level model anticipates on the performance at the operational planning level.

The output of the higher decision level is the allocation of capacity flexibility for each outsourcer which is an input parameter for the lower decision level. At the lower decision level, short-term (say monthly) acceptance and production decisions are made. The acceptance decision is crucial and it should anticipate the uncertainties from the outsourcers. The allocated capacity flexibilities from the higher decision level are meant to help in the anticipation of the operational planning decisions. When the acceptance and production decisions are made, the operational performance of the system can be measured and compared with the higher level (expected) performance. We will see that there are some inconsistencies between the two decision levels. Therefore, feedback is given from the lower decision level to the higher decision level, which helps the higher decision level to anticipate on the performance at the lower decision level. In section 6.3.3, we discuss how this feedback is modeled and in section 6.5, we will see that ignoring this feedback results in large errors.

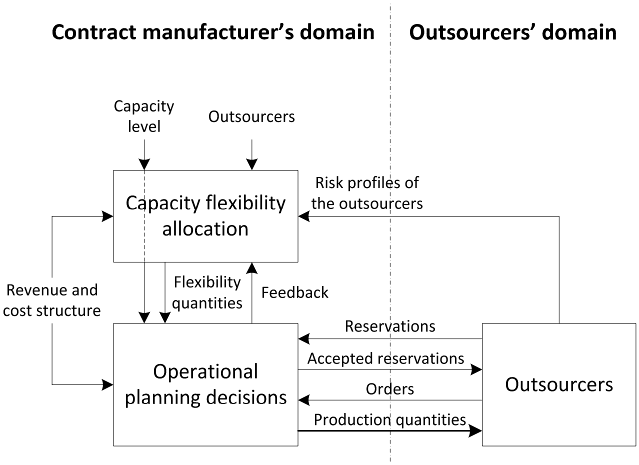

Figure 6.2. Two-stage hierarchical model

This chapter is organized as follows. The next section discusses the literature review. In section 6.3, we develop the formal model for the hierarchical planning problem. Then, in section 6.4, we present the results of the numerical study. In section 6.5, we discuss the inconsistency between the two decision levels. Finally, in section 6.6, we draw the conclusions and discuss some managerial insights.

6.2. Literature review

In the last two decades, a large number of papers appeared on production flexibility in the Operations Management literature (cf. Bertrand, 2003). We do not intend to provide a complete review of this literature, but we shortly review some related work and discuss our contribution to the literature. From a supply chain perspective, flexibility has mainly been studied by addressing the question whether and to what extent a certain contract coordinates the supply chain (Tsay, 1999; Cachon and Lariviere, 2005). In this stream of the literature, no explicit evaluation of the flexibilities is done and mainly a single product or a single customer is considered, which means that the implication of different customers competing for a joint capacity has not been considered.

From a more operational perspective, the measurement of production flexibility has been studied intensively. Production flexibility has a lot of measures and dimensions (D'Souza and Williams, 2000; Bertrand, 2003) and has been studied in the literature as a strategy to deal with innovation, uncertainties, short life cycles, and increased competition (Frazelle, 1986; Gupta and Goyal, 1989; Sethi and Sethi, 1990; Beach *et al.*, 2000; Bish *et al.*, 2005; Slack, 2005). This literature characterizes different types and measures of flexibilities, but does not model it formally to decide on the optimal level of flexibility.

Van Mieghem (1998) focuses on determining the optimal investment decisions on flexible capacity at the strategic or tactical level, under the assumption of a single production period. In Bish *et al.* (2005), the management of flexible capacity in a dynamic make-to-order environment is studied, where the focus is on the allocation of products to the different production plants. This line of research does not consider the operational implications of the flexibility decisions taken at higher level for a joint production capacity. Therefore, the question remains how to optimally use the production flexibility to deal with short-term demand uncertainty in a make-to-order environment.

Finally, most approaches in the literature on production flexibility consider the demand side as given, either deterministic or stochastic. In our case, we also consider the demand distributions as given, but the demand can be 'controlled' by the flexibility allocation decisions and the contractual design with the outsourcers.

6.3. Model formulation

In this section, we discuss the formulation of the two-level hierarchical planning model (see Figure 6.2). For the higher decision level, we develop an integer programming model which solves the flexibility allocation problem under uncertainty to optimality. This level also anticipates on the lower decision level. The output of this level is input to the lower level, where the acceptance and production decisions are made after observing the reservations and orders from the outsourcers. Based on these observations, we can measure the performance of the system. At both levels, we assume penalty costs for lost demand, as defined in the contract between the outsourcers and the contract manufacturer. Moreover, we also discuss the consistency between the two decision levels.

6.3.1. Capacity flexibility allocation

In this section, we present the mathematical model for the higher decision level of the hierarchical planning model (see Figure 6.2) at which the contract manufacturer decides on the optimal allocation of capacity flexibilities. Capacity flexibility is a contract parameter that sets the amount of demand the contract manufacturer is obliged to accept from the outsourcers. This is considered as a tactical decision, made for the medium-term (e.g. one year).

Table 6.1. Used symbols

C	capacity level (of the contract manufacturer)
D_j	demand from outsourcer *j* (discrete random variable)
D_s	demand from all outsourcers (discrete random variable)
θ_j	guaranteed demand to be accepted from outsourcer *j*
θ_s	guaranteed demand to be accepted from all outsourcers
μ_j	expected demand from outsourcer *j*
μ_j'	updated expected demand from outsourcer *j*
μ_s	expected demand from all outsourcers
μ_s'	updated expected demand from all outsourcers
$f_j(x)$	probability mass function of demand from outsourcer *j*
$f_j'(x\|\varepsilon_j)$	updated probability mass function of demand from outsourcer *j* given ε_j
$f_s(x)$	probability mass function of demand from all outsourcers
$f_s'(x\|\vec{\varepsilon})$	updated probability mass function of demand from all outsourcers given $\vec{\varepsilon}_j$
J	number of outsourcers served by the contract manufacturer
ε_j	capacity flexibility allocated to outsourcer *j*
$\vec{\varepsilon}$	allocation of capacity flexibility to all outsourcers
σ_j	standard deviation of demand from outsourcer *j*
τ_j	unit revenue generated from outsourcer *j*
τ_s	total revenue generated from all outsourcers
β	unit penalty cost
$\pi(\vec{\varepsilon})$	expected profit function
t	time period
j	outsourcer (subscript)
$r_j(t)$	reservation from outsourcer *j* in time period t
$a_j(t)$	accepted reservation for outsourcer *j* in time period t
$q_j(t)$	order quantity from outsourcer *j* in time period t
$p_j(t)$	production quantity for outsourcer *j* in time period t
ρ_t	capacity utilization in time period t
ρ	expected capacity utilization
$\alpha_j(t)$	acceptance rate in time period t
α_j	expected acceptance rate
$\gamma_j(t)$	service level in time period t
γ_j	expected service level
M	a big number
δ	consistency factor
$\mathbb{Z}^+$	non-negative integer number
$\xi(t)$	amount of demand that can be still accepted from the outsourcers in time period t
$\psi_j(t)$	not (yet) accepted reservation quantity from outsourcer *j* in time period t

The contract manufacturer has a fixed production capacity C and serves J outsourcers with different levels of demand uncertainty, i.e., with different probability functions of the demand $f_j(x)$. The ideal situation is to have the capacity C fully utilized when orders are placed.

However, before orders are placed, outsourcers reserve capacity at the contract manufacturer which is responded to with the acceptance decision. The order quantity that follows after the acceptance decision cannot exceed the acceptance quantity. Therefore, the acceptance decision is crucial and should anticipate and incorporate the risk that the order quantity can be lower than the accepted reservation quantity, knowing that that risk is different for the different outsourcers. Therefore, at the tactical level, the capacity flexibility (ε_j) is determined for each outsourcer j, such that the profit of the production line is maximized, and which is an input parameter to the operational planning level. Below, we discuss how the allocation of capacity flexibility is determined and optimized.

The demand D_j from outsourcer j is discrete and a random variable and has the probability mass function $f_j(x)$, which is assumed to be known to the contract manufacturer, based on e.g. historical data. Demand reflects the reservation and order quantities. We assume that each unit of demand corresponds to one unit of capacity consumption and that the demands from the different outsourcers j are independently distributed. Therefore, the total demand from all outsourcers D_s has the probability mass function $f_s(x)$ with $\mu_s = \sum_{j=1}^{J} \mu_j$ and $\sigma^2(D_s) = \sum_{j=1}^{J} \sigma^2(D_j)$.

The idea is that the contract manufacturer will accept only a limited part of the demand uncertainties from the outsourcers, which is expressed by the acceptance decision at the operational level. In the long-run, the average demand accepted from outsourcer j should be at least equal to the expected demand μ_j from that outsourcer. Therefore, we introduce $\theta_j = \mu_j + \varepsilon_j$, which is the guaranteed demand the contract manufacturer will accept from outsourcer j, with $\varepsilon_j \in \mathbb{Z}^+$ is the flexibility allocated and offered to outsourcer j. The guaranteed demand is the part of the demand the contract manufacturer will always accept. The contract manufacturer is not obliged to accept demand larger than θ_j.

The flexibility ε_j offered to outsourcer j (with σ_j) is appreciated by the outsourcers and we assume that the outsourcers are willing to pay an additional amount for each unit ε_j. We consider a unit revenue function $\tau_j(\varepsilon_j, \sigma_j)$ that is increasing in ε_j and σ_j, i.e., the more uncertain outsourcer is willing to pay more for an additional ε_j. The outsourcers are willing to pay additionally for the allocated capacity flexibilities, because otherwise, they would have to keep more inventories at the more downstream stages to buffer against the limited capacity availability.

By introducing ε_j, we truncate the demand distribution by updating $P\{D_j = \theta_j\} := 1 - \sum_{i=0}^{\theta_j - 1} P\{D_j = i\}$ and $P\{D_j > \theta_j\} = 0$. Hence, we get an updated probability mass function $f_j'(x|\varepsilon_j)$ for the demand (see Figure 6.3 for an example). All demand larger than θ_j is not necessarily accepted and therefore the distribution is truncated at θ_j, resulting in a probability mass function $f_j'(x|\varepsilon_j)$ with an updated $\mu_j' = \sum_{i=0}^{\theta_j} i \cdot P\{D_j = i\}$.

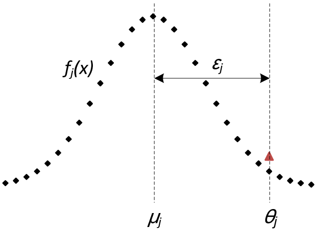

Figure 6.3. The original and updated probability functions for the demand

Hence, the total expected revenue τ_s the contract manufacturer generates is given by (1).

$$\tau_s = \sum_{j=1}^{J} \tau_j(\varepsilon_j, \sigma_j) \cdot \mu'_j \tag{6.1}$$

By updating the individual demand distributions of the different outsourcers, we also get an updated probability function of the total demand $f'_s(x|\vec{\varepsilon})$ and an updated $\theta_s = \sum_j \theta_j$. By offering more capacity flexibility to the outsourcers, the probability that not all demand can be fulfilled, i.e., not all orders can be produced increases, which results in penalty costs. If the unit penalty cost is β, the expected penalty costs are given by (6.2).

$$\beta \sum_{x=C+1}^{\theta_s} x f'_s(x|\vec{\varepsilon}) \tag{6.2}$$

Both the revenue and the cost side are a function of $\vec{\varepsilon_j}$, which are the decision variables of the integer programming model. Therefore, a trade-off has to be made between the extra revenue that is generated by offering more flexibility ε_j and the increased penalty costs. The objective of the model is to maximize the (non-linear) expected profit function $\pi(\vec{\varepsilon})$ and to determine the optimal $\vec{\varepsilon} = \{\varepsilon_j\} \in \mathbb{Z}^+,\ \forall\, j \in J$.

$$Max\ \pi(\vec{\varepsilon}) = \left(\sum_{j=1}^{J} \tau_j(\varepsilon_j, \sigma_j)\mu'_j - \beta \sum_{x=C+1}^{\theta_s} x f'_s(x|\vec{\varepsilon}) \right) \tag{6.3}$$

Equation (6.3) is the objective function, which maximizes the expected profit by choosing the optimal $\vec{\varepsilon} = \{\varepsilon_1, \dots, \varepsilon_J\}$. The expected profit is equal to the expected revenue generated by the contract manufacturer (6.1) minus the expected penalty costs (6.2). We solve this model by a full search of the decision space $\vec{\varepsilon}$.

6.3.2. Operational planning model

In this section, we discuss the lower decision level, where the short-term (say monthly) acceptance and production decisions are made based on the operational planning model. The optimal $\vec{\varepsilon}$, θ_j, and θ_s that have been determined at the higher decision level are input to the operational planning model.

The operational planning process is as follows. At time period t, the contract manufacturer receives from all outsourcers the capacity reservations $r_j(t)$. In the same period t, the contract manufacturer decides on the quantity to accept $a_j(t)$ based on the following procedure:

1. Accept from all outsourcers j: $a_j^1(t) = min\{r_j(t), \theta_j\}$.
2. Determine $\xi(t) = \theta_s - \sum_{j=1}^{J} a_j^1(t)$ and $\psi_j(t) = r_j(t) - a_j^1(t)$ for all j.

   If $\xi(t) > 0$ and $\psi_j(t) > 0$, then go to step 3. Otherwise $a_j(t) = a_j^1(t)$.
3. Distribute $\xi(t)$ over $\psi_j(t)$ by giving priority to outsourcer j with the highest expected profit.

Note that $a_j(t)$ can be higher than θ_j, dependent on the reservation quantities of the other outsourcers. After having determined $a_j(t)$, this is communicated to outsourcer j. One period later, the orders follow, which cannot exceed the accepted quantity from the previous period: $q_j(t) \leq a_j(t-1)$. Knowing the order quantities $q_j(t)$, the contract manufacturer decides on the production quantity $p_j(t)$ based on the following optimization model (6.4)-(6.6), where $(\cdot)^+ = max\{\cdot\,,0\}$.

$$Max\left(\sum_{j=1}^{J}\tau_j(\varepsilon_j,\sigma_j)q_j(t) - \beta\sum_{j=1}^{J}\left(q_j(t)-p_j(t)\right)^+\right) \tag{6.4}$$

$$\sum_{j=1}^{J}p_j(t) \leq C \tag{6.5}$$

$$0 \leq p_j(t) \leq q_j(t)\left(\leq a_j(t-1)\right) \tag{6.6}$$

The operational planning model (6.4)-(6.6) is solved after observing $r_j(t)$ and $q_j(t)$. Then, the performance of the system can be measured by: the capacity utilization: $\rho_t = \frac{1}{C}\sum_{j=1}^{J}p_j(t)$, the acceptance rate: $\alpha_j(t) = \frac{a_j(t)}{r_j(t)}$, and the service level: $\gamma_j(t) = \frac{p_j(t)}{q_j(t)}$.

By solving the operational planning model for a large number of periods, the expected performance measures can be determined (6.7)-(6.9).

$$\rho = \lim_{M\to\infty}\frac{1}{M}\sum_{t=1}^{M}\left(\frac{1}{C}\sum_{j=1}^{J}p_j(t)\right) \tag{6.7}$$

$$\alpha_j = \lim_{M\to\infty}\frac{1}{M}\sum_{t=1}^{M}\left(\frac{a_j(t)}{r_j(t)}\right) \tag{6.8}$$

$$\gamma_j = \lim_{M\to\infty}\frac{1}{M}\sum_{t=1}^{M}\left(\frac{p_j(t)}{q_j(t)}\right) \tag{6.9}$$

6.3.3. Consistency between the two decision levels

In this section, we discuss the consistency between the two decision levels. At the higher level, we determine the optimal capacity flexibility allocation by assuming that all demand larger than θ_j will be rejected. Indeed, the contract manufacturer is not obliged to accept demand larger than θ_j, but at the operational planning level (see section 6.3.2), it is possible that the contract manufacturer accepts from outsourcer j demands larger than θ_j if $\xi(t)$ and $\psi_j(t)$ are both positive. Consequently, there is some inconsistency between the two decision levels. The decisions taken at the higher level are 'conservative', as they do not incorporate the possibility of accepting demand larger than θ_j, i.e., the higher decision level overestimates the rejected quantities. Therefore, we adapt the objective function of the higher decision level by introducing δ which takes initially the value of 1 (see equation 6.3'). Then, after solving the operational planning model, we adapt δ iteratively till the inconsistency is negligible. In section 4.5, we show some numerical results for the level of δ.

$$Max\ \pi(\vec{\varepsilon}) = \left(\sum_{j=1}^{J} \tau_j(\varepsilon_j, \sigma_j)\mu'_j - \beta\delta \sum_{x=C+1}^{\theta_s} x f'_s(x|\vec{\varepsilon}) \right) \tag{6.3)'}$$

6.4. Numerical results

In this section, we discuss the numerical results that we gathered by solving the two-level hierarchical planning model that is presented in the previous section. We consider the case with 3 outsourcers (J=3) with μ_j=10. However, they have different levels of demand uncertainty: $\sigma_3 > \sigma_2 > \sigma_1$. We consider the unit revenue function as given in 6.10. This unit revenue function has been developed, based on the following criteria:

- the unit revenue function τ_j should be an increasing function in ε_j and σ_j and it takes a non-zero value when ε_j = 0;
- the incremental increase of the unit revenue should be decreasing in ε_j. In other words, the outsourcers pay less extra for additional allocation of capacity flexibility.

$$\tau_j(\varepsilon_j, \sigma_j) = \tau_j^{max}(\sigma_j) - \frac{\sigma_j}{\varepsilon_j + 1} \tag{6.10}$$

Figure 6.4 shows the structure of the unit revenue function (6.10) for the less uncertain outsourcer (the solid line) and for the more uncertain outsourcer (dotted line). Both outsourcers pay a higher unit price when ε_j increases, but the more uncertain outsourcer pays even more for an additional ε_j. Table 6.2 shows the parameters that we vary in the numerical study and their possible values.

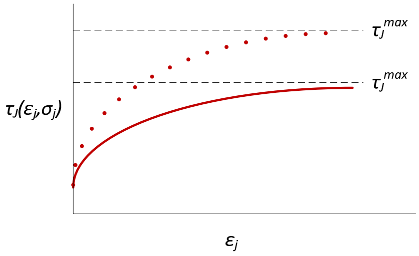

Figure 6.4. The structure of the unit revenue function for the less uncertain outsourcer (solid line) and the more uncertain outsourcer (dotted line).

Table 6.2. Set of possible values in the experimental study

Parameter	Possible values
$\{\sigma_1, \sigma_2, \sigma_3\}$	{1,2,3} ; {1,3,5}
$\tau_j^{max}(\sigma_j)$	{5,6.25,7.5,10} if σ_j={1,2,3,5}
C	{28;…;40}
β	{1;2;5;10;∞}

In the numerical study, we construct a number of experiments and we are specifically interested in the effects of:

1. different capacity levels on the optimal allocation of flexibility quantities in case of very high penalty cost (section 6.4.1);
2. different penalty costs on the optimal allocation of flexibility quantities (section 6.4.2);
3. the allocation of capacity flexibility on the operational performance of the system (section 6.4.3);

In section 6.5, we discuss the numerical results of the inconsistency between the two decision levels.

6.4.1. Varying the capacity level

In this experiment, we consider the case where $\beta >> \tau_j^{max}(\sigma_j)$, i.e., the extra revenue generated by allocating more flexibility is always lower than the penalty costs (see revenue function 6.10). It is obvious that in this case, the allocation of capacity flexibility will cumulatively never exceed the capacity level. Still, the question remains how the allocation of the optimal flexibility quantities will be divided over the outsourcers for different capacity levels. Figures 6.5 and 6.6 show the optimal allocation quantities $\vec{\varepsilon}$ for C =28,…,40 and $\beta = \infty$. Figure 6.5 shows the results in case {σ_1,σ_2,σ_3}={1,2,3} and Figure 6.6 in case {σ_1,σ_2,σ_3}={1,3,5}.

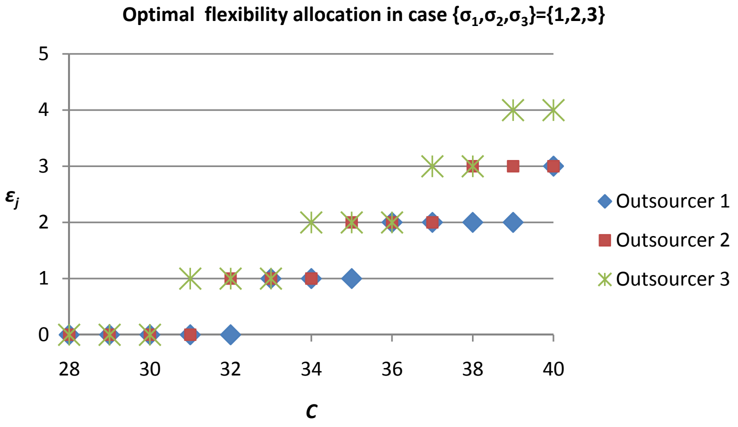

Figure 6.5. Optimal capacity flexibility allocation in case $\beta = \infty$ and {σ_1,σ_2,σ_3}={1,2,3}.

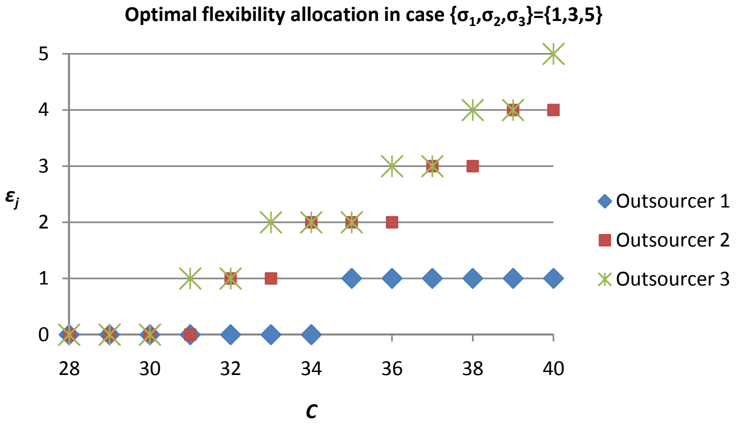

Figure 6.6. Optimal capacity flexibility allocation in case $\beta = \infty$ and {σ_1,σ_2,σ_3}={1,3,5}.

In case $C \leq 30$ (=expected total demand), the optimal capacity allocation is zero, as offering capacity flexibility is not profitable due to the high penalty costs. When $C = 30 + x$ with $x > 0$, exactly x capacity flexibility is allocated as shown in Figures 6.5 and 6.6. The allocation is done to the outsourcer that generates the highest additional expected profit when the capacity level increases with x. We see that when the capacity level increases, the more uncertain outsourcer gets at least as much capacity flexibility allocated as the less uncertain one: $\varepsilon_3 \geq \varepsilon_2 \geq \varepsilon_1$. That is because the most uncertain outsourcer is willing to pay the most for the additional capacity flexibility, which turns out to be the most profitable option for the contract manufacturer.

6.4.2. Varying the unit penalty cost

In this experiment, we vary the unit penalty cost β at different capacity levels C to study the effect on the optimal allocation of capacity flexibility, given the revenue function of (6.10). We consider two cases with respect to the level of demand uncertainty: $\{\sigma_1,\sigma_2,\sigma_3\}=\{1,2,3\}$ and $\{\sigma_1,\sigma_2,\sigma_3\}=\{1,3,5\}$. See Table 6.3 for the results of this experiment.

Table 6.3. Optimal capacity flexibility allocation for different values of β and C

$\{\sigma_1,\sigma_2,\sigma_3\}=\{1,2,3\}$						$\{\sigma_1,\sigma_2,\sigma_3\}=\{1,3,5\}$					
C	β	ε_1	ε_2	ε_3	$\pi(\vec{\varepsilon})$	C	β	ε_1	ε_2	ε_3	$\pi(\vec{\varepsilon})$
28	1	0	0	1	79.71	28	1	0	1	2	101.62
	2	0	0	1	70.51		2	0	1	1	94.56
	5	0	0	0	45.59		5	0	0	1	75.09
	10	0	0	0	8.35		10	0	0	0	47.68
29	1	0	1	1	96.13	29	1	0	1	3	113.51
	2	0	0	1	91.66		2	0	1	2	108.30
	5	0	0	0	81.19		5	0	1	1	92.68
	10	0	0	0	63.74		10	0	0	0	75.25
30	1	0	1	1	112.61	30	1	1	1	3	122.91
	2	0	0	1	108.67		2	0	1	3	119.45
	5	0	0	0	106.98		5	0	1	1	117.05
	10	0	0	0	105.91		10	0	0	0	114.98
31	1	0	1	1	126.03	31	1	1	1	3	131.65
	2	0	0	1	122.88		2	0	1	3	128.69
	5	0	0	1	121.67		5	0	1	1	126.74
	10	0	0	1	121.06		10	0	0	1	125.79
32	1	0	1	2	137.45	32	1	1	2	3	143.09
	2	0	1	1	135.41		2	0	2	3	140.25
	5	0	1	1	134.39		5	0	1	2	139.06
	10	0	1	1	134.01		10	0	1	1	138.98

The results show a number of insights. First, the optimal allocation of capacity flexibility is rather sensitive to β. The higher the β, the lower the optimal capacity flexibility quantities. Moreover, when the level of demand uncertainties is higher ($\{\sigma_1,\sigma_2,\sigma_3\}=\{1,3,5\}$), the optimal capacity flexibility quantities are higher, as the increased risk is then compensated by an increased allocation of capacity flexibility, which generates higher revenue. Furthermore, when the capacity level is higher, the expected profit increases, but also the optimal capacity flexibility quantities increases, as it is less risky to allocate more capacity flexibility.

6.4.3. The operational performance

In this section, we focus on the lower decision level that has been introduced and discussed in section 6.3.2. The optimal capacity flexibility quantities that we determined at the higher decision level are input to the lower decision level, the operational planning model. We simulate the operational planning model to measure the performance of the production line in terms of capacity utilization ρ (equation 6.7), the acceptance rate α_j (eq. 6.8), and the service level γ_j (eq. 6.9). The simulation length is 1000 periods and the number of replications is 3. The simulation results showed negligible variance in the performance measures. In this simulation study, we consider the unit revenue function as given in (6.10). Table 6.4 shows the simulation results for C ={28,…,32} and β ={1;2;5;10} in case {σ_1,σ_2,σ_3}={1,3,5}. The table shows the average capacity utilization, the average acceptance rates for the 3 outsourcers, and their service levels.

Table 6.4. Simulation results in case {σ_1,σ_2,σ_3}={1,3,5}

C	β	$\vec{\varepsilon}$	$\pi(\vec{\varepsilon})$	ρ	α_1	α_2	α_3	γ_1	γ_2	γ_3
28	1	(0,1,2)	103.79	0.90	1.00	1.00	1.00	0.78	0.98	1.00
	2	(0,1,1)	97.59	0.90	0.99	0.98	0.96	0.83	0.99	1.00
	5	(0,0,1)	81.19	0.90	0.99	0.95	0.93	0.86	1.00	1.00
	10	(0,0,0)	61.49	0.89	0.97	0.91	0.87	0.92	1.00	1.00
29	1	(0,1,3)	114.82	0.88	1.00	1.00	1.00	0.85	0.99	1.00
	2	(0,1,2)	110.56	0.88	1.00	0.98	0.97	0.86	1.00	1.00
	5	(0,1,1)	97.12	0.87	0.99	0.96	0.94	0.87	1.00	1.00
	10	(0,0,0)	91.06	0.87	0.98	0.92	0.90	1.00	1.00	1.00
30	1	(1,1,3)	123.61	0.86	1.00	1.00	1.00	0.99	1.00	1.00
	2	(0,1,3)	120.76	0.86	1.00	0.98	0.98	1.00	1.00	1.00
	5	(0,1,1)	120.61	0.85	0.99	0.97	0.96	1.00	1.00	1.00
	10	(0,0,0)	119.92	0.84	0.99	0.94	0.92	1.00	1.00	1.00
31	1	(1,1,3)	132.04	0.83	1.00	1.00	1.00	1.00	1.00	1.00
	2	(0,1,3)	129.41	0.83	1.00	0.99	0.98	1.00	1.00	1.00
	5	(0,1,1)	129.17	0.82	1.00	0.97	0.96	1.00	1.00	1.00
	10	(0,0,1)	128.63	0.82	0.99	0.96	0.94	1.00	1.00	1.00
32	1	(1,2,3)	143.24	0.81	1.00	1.00	1.00	1.00	1.00	1.00
	2	(0,2,3)	140.59	0.81	1.00	1.00	1.00	1.00	1.00	1.00
	5	(0,1,2)	140.38	0.80	1.00	1.00	0.98	1.00	1.00	1.00
	10	(0,1,1)	139.42	0.80	1.00	0.97	0.94	1.00	1.00	1.00

The results show that the higher the unit penalty cost β, the lower the acceptance rate, but the higher the service level. In other words, when the penalty cost increases, less reservations are accepted (so less risk is taken), but a larger fraction of the order is produced. This result holds for all considered capacity levels. The results also show that $\alpha_1 \geq \alpha_2 \geq \alpha_3$, i.e., priority is given to the less uncertain outsourcer when the acceptance decision is taken, whereas we see the opposite effect with the service levels, namely $\gamma_1 \leq \gamma_2 \leq \gamma_3$. The latter is because the most uncertain outsourcer generates the highest unit revenue (see eq. 6.4), which explains the priority to the most uncertain outsourcer. Thus, when orders are placed, it is optimal to give priority to the most uncertain (and most paying) outsourcer, whereas when reservations are placed, priority should be given to the most certain outsourcer. We conducted the same experiment in case {σ_1,σ_2,σ_3}={1,2,3} and the insights are the same as in case {σ_1,σ_2,σ_3}={1,3,5}.

6.5. Consistency between the two decision levels

In the previous section, we discussed the numerical results of the two decision levels separately. As discussed in section 6.3.3, there is some inconsistency between the two decision levels. The inconsistency is due to the overestimation of the rejected quantities at the higher decision level. Therefore, we adapt the objective function of the higher decision level model by introducing the parameter δ in the objective function (see eq. 6.3’). In this numerical study, we determine δ by reducing its value iteratively from 1 until consistency is achieved between the two levels, i.e., the estimated rejected quantities are equal. Figure 6.7 shows the values of δ for different β and C. We see that the higher β, the lower δ, i.e., the higher the inconsistency. That means that more correction is needed to compensate for the effect of rejecting all demand larger than θ_j. For the same reason, the opposite effect holds for C, i.e., the higher C, the higher δ.

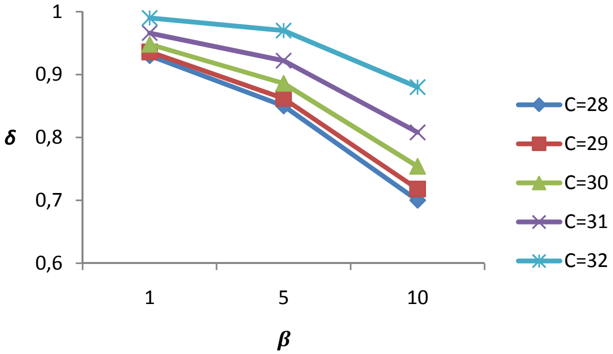

Figure 6.7. The value of δ for different β and C, and $\{\sigma_1,\sigma_2,\sigma_3\}=\{1,3,5\}$

Since the inconsistency is the highest in case of high β and small C, we show in Table 6.5 the consequence of the inconsistency on the optimal capacity flexibility quantities and on the expected profit. Moreover, we also show in Table 6.5 the initially and updated expected rejected rate $\sum_{j=1}^{J}(1-\alpha_j)$. We see that indeed for low levels of C and high levels of β, the updated $\vec{\varepsilon}$ changes the most, whereas when the capacity is sufficient, the optimal capacity flexibility allocation hardly changes. Table 6.5 also shows the initial and updated profit levels. We see that the inconsistency is the highest when β is high and C is small.

Table 6.5. The effect of inconsistency on the optimal capacity flexibility allocation in case $\{\sigma_1,\sigma_2,\sigma_3\}=\{1,3,5\}$

C	β	$\vec{\varepsilon}$ **initial**	$\sum(1-\alpha_j)$ **initial**	$\pi(\vec{\varepsilon})$ **initial**	$\vec{\varepsilon}$ **update**	$\sum(1-\alpha_j)$ **update**	$\pi(\vec{\varepsilon})$ **update**
28	5	(0,0,1)	0.13	75.09	(0,1,1)	0.10	80.69
	10	(0,0,0)	0.25	47.68	(0,1,1)	0.16	60.85
29	5	(0,1,1)	0.11	92.68	(0,1,1)	0.09	96.59
	10	(0,0,0)	0.20	75.25	(0,0,1)	0.15	90.89
30	5	(0,1,1)	0.08	117.05	(0,1,1)	0.08	120.23
	10	(0,0,0)	0.15	114.98	(0,0,0)	0.13	119.81

6.6. Conclusions

In this chapter, we study the case where a contract manufacturer serves a number of outsourcers with different levels of demand uncertainty on the same capacitated production line. For capacity planning purposes, the contract manufacturer requires that all outsourcers reserve capacity before placing orders. The contract manufacturer collects the reservations and decides on the accepted reservation quantity, which bounds the order quantity that follows later on. The contract manufacturer is not willing to accept all uncertainty from the outsourcers and therefore, the contract manufacturer wants to offer each outsourcer a contract that describes how much capacity flexibility is allocated to that outsourcer, which is the amount of demand that the contract manufacturer will always accept from the outsourcers. We assume that the more capacity flexibility offered (to more uncertain outsourcer), the higher the unit revenue for the contract manufacturer.

We developed a hierarchical model that consists of two decision levels. At the higher level, the optimal capacity flexibility allocation is determined (which is a contract parameter) by maximizing the expected profit function and by anticipating on the performance at the operational level. The capacity flexibility quantities are input to the lower decision level where the operational planning decisions are made and demands (reservations and orders) are observed. We perform a numerical study, which reveals several interesting managerial insights. First, the allocation of capacity flexibility is very sensitive to the unit penalty cost. The higher the unit penalty cost, the lower the capacity flexibility allocation. For an outsourcer, this implies that by setting the penalty cost very high, he can secure his commitment, but – on the contrary – will get less flexibility, as the contract manufacturer would want to limit his risk that is caused by providing flexibility. Consequently, for an outsourcer facing uncertain demand, it may not be a good strategy to set high penalty cost, as he will get little flexibility. Second, for a wide range of capacity levels and unit penalty costs, the more uncertain outsourcer gets at least the same and often more capacity flexibility allocated than the less uncertain outsourcer. In practice, managers often give priority and rewards to the least uncertain outsourcer, but our study gives the opposite insight, provided that the more uncertain outsourcer is willing to pay extra for additional allocation of capacity flexibility. So, paying a little extra for flexibility appears to pay-off in terms of getting flexibility guarantees. For the outsourcer, this may result into lower inventory levels (cf. Chapter 3).

The third insight comes from simulating the operational planning process. We have seen that when making the acceptance decision (given the allocated capacity flexibility decision), priority is given to the less uncertain outsourcer, because allocating capacity flexibility to that outsourcer generates the highest expected profit. The information from the less uncertain outsourcer seems to be the most valuable, whereas accepting more from the more uncertain outsourcer is risky due to the uncertainty of its demand. However, we see the opposite effect when placing orders (after the acceptance decision has been made), namely that priority is given to the more uncertain outsourcer. Now the order is placed, no risk is involved anymore and priority is given the outsourcer that generates the highest unit revenue, which is the most uncertain outsourcer.

The last part of the numerical study deals with the inconsistency between the two decision levels. At the higher decision level, we assume that all demand larger than contractually agreed upon is rejected, whereas at the operational level, more demand can be accepted, dependent on the other outsourcers. Therefore, we propose a feedback loop from the lower decision level to the higher decision level to eliminate the inconsistency between the two decision levels. Without this feedback, i.e., without the hierarchical integration, the capacity flexibility quantities are too conservative, especially when the unit penalty cost is high and the capacity is tight. Therefore, the hierarchical integration and anticipation approach is required.

7. Conclusions, implications and future research

In this dissertation, we study the planning and control of outsourced supply chains, which are supply chains where part(s) of the supply chain is outsourced to a contract manufacturer. Outsourced supply chains are increasingly developing in many industries, but we focus in this dissertation on the pharmaceutical industry, where the outsourcing relationship is typically long-term. The planning and control of outsourced supply chains is complicated due to limited information transparency, contractual obligations, and limited control over the detailed planning and priorities at the contract manufacturer.

This concluding chapter is organized as follows. In section 7.1, we summarize the results, insights, and conclusions of the research studies that we conducted in the various chapters of this dissertation. In that section, we also give answers to the research questions that were posed in section 1.4. In section 7.2, we discuss the implications of our research for the industrial practice. We believe that our models and the insights that we obtained from the different studies are helpful for applications and implementations in real-life. In section 7.3, we discuss some ideas for future research.

7.1. Conclusions

In the introductory chapter, we raised a number of research questions that are related to the planning and control of outsourced supply chains. In this section, we answer these questions one by one by summarizing the results, insights and conclusions of the research studies that we conducted in this dissertation.

1. What are the main implications of outsourcing on the supply chain operations planning models?

This first research question was addressed to understand the implications of outsourcing on the supply chain operations planning. We dealt with this question in two ways. We first conducted an extensive literature study on outsourcing research to investigate what has been documented on the implications of outsourcing. We found that the research on outsourcing that addresses outsourcing from a strategic perspective is rich, whereas the literature that studies outsourcing from the operational point of view is limited. Studying outsourcing from an operational point of view means that (operational) issues are studied that follow after having made the outsourcing decision. Those few papers that study outsourcing from an operational point of view are quantitative studies that consider outsourcing purely as a second source in addition to the internal manufacturing source to achieve certain objectives, such as the target customer delivery reliability. Therefore, we also identified that the literature lacks empirical studies on the effects of outsourcing at the operational planning and control level, where the contract manufacturer is the only source of supply.

Consequently, we conducted two extensive case studies at pharmaceutical companies that have an outsourcing relationship, where the contract manufacturer is the only source of supply for one of the outsourcer’s strategic products. The case studies involved a number of essential processes that are closely related to the supply chain operations planning process, namely: contracting, performance measurement, information sharing and availability, and the distribution of planning authority between the outsourcer and the contract manufacturer.

The case studies have shown that in an outsourced supply chain, the outsourcer (the company that outsourced part of its supply chain) is partly in control, but may not have access to all status information of the entire supply chain. Furthermore, based on the cases studies, we also found that outsourcing is complicating the supply chain operations planning in different ways. The most important one from the planning point of view is that the order release function when controlling an outsourced supply chain is different from the order release function when controlling an internal manufacturing plant. When controlling an outsourced supply chain, the order release process consists of different connected decisions in time and therefore, the order release mechanism requires a richer and more developed communication and ordering pattern than commonly assumed. The main reason for that is that the contract manufacturer requires contractually that the outsourcers reserve capacity prior to ordering, because the contract manufacturer produces for multiple outsourcers on the same production line. The reservation information is needed for capacity and materials planning purposes. The contract manufacturer responds to the reservations by acceptance or (partial) rejection based on rules and priorities that are unknown to the outsourcer. The outsourcer is not able to change or influence the decisions made by the contract manufacturer. Because of this limited information transparency, the outsourcer faces an uncertain allocation of production capacity on the short term, which should be incorporated in the order release function. The outsourcer should also incorporate the different connected decisions in its order release function and consider the uncertain capacity allocation by the contract manufacturer. We have seen in the case studies that by not doing so, a nervous ordering (and reservation) behavior results, which deteriorates the supply chain performance.

In section 2.4, we discuss some other implications of outsourcing on the outsourcer’s supply chain operations planning. We have seen that the outsourcer might face delays and asymmetries of crucial status information from the outsourcer. Moreover, the outsourcing relationship is typically a buyer-supplier-buyer relationship, which results in a stronger focus on capacity management rather than materials management. These insights from the case studies were a source of inspirations for the studies that we conducted in the remainder of this dissertation.

2. How should the supply chain operations planning models be adapted to incorporate outsourcing in the planning models? And what is the impact of adding these aspects on the performance of the supply chain operations planning models?

This research question was addressed to study one of the main implications of outsourcing on the supply chain operations planning, namely the fact that the order release function is different and more complicated when controlling an outsourced supply chain. In Chapter 3, we developed three different order release strategies that incorporate some aspects of outsourcing that followed from the case studies of Chapter 2, namely: postponement, cancellation, and stochastic capacity allocation from the contract manufacturer. The objective of this study is to reveal the effect and the added value of including these aspects on the supply chain performance. The order release strategies differ in the number of decision levels and they are organized hierarchically such that the output of each decision level forms a constraint for the lower decision level.

Based on a simulation study in which the supply chain operations planning model is solved in a rolling horizon setting, we show that increasing the number of decision levels in the order release strategy leads to substantial lower total supply chain costs. In other words, a more advanced order release strategy that incorporates postponement and cancellation performs significantly better than an order release strategy that is commonly used in practice. When the order release strategy is applied that incorporates cancellation (order release strategy 3), lower utilization results due to the cancellations. Therefore, we discussed the condition that holds to implement this order release strategy successfully.

The simulation study was also conducted to get insights into the effect of limited, but uncertain capacity level at the contract manufacturer. Since the outsourcer has no information about the capacity restrictions at the contract manufacturer, we compared the situation where we assume unlimited capacity level and limited, but uncertain capacity level. It turns out that assuming limited, but uncertain capacity level increases the total supply chain costs as more safety stocks are needed to achieve the same target service level. However, we have seen that for high levels of demand uncertainty, facing stochastic capacity levels leads to even lower supply chain costs. Because of the very high demand uncertainty, i.e., low forecast accuracy, it is likely that orders that were placed earlier are not needed anymore and therefore, it is beneficial that some orders were cancelled by the contract manufacturer.

3. In case a contract manufacturer exists next to an internal manufacturing source, how to allocate the production volume over the two sources in a smart way?

This research question was addressed to study a dual sourcing case where the contract manufacturer is a second supply source next the outsourcer's internal manufacturing source. The two sources have different levels of reactivity, flexibility, cost structure, and constraints. The internal manufacturing source is cheaper, but more rigid and the contract manufacturer is the opposite. The outsourcer faces stochastic, but stationary demand and inaccurate demand forecasts. From the literature, we know that the optimal policy is generally not known for such systems and therefore, we propose two different allocation strategies by which the system can be controlled: the dynamic allocation strategy (DAS) and the rigid allocation strategy (RAS). In the DAS strategy, the allocation quantities are dynamic and determined from period to period, whereas in the RAS strategy, the source with the lower unit production cost supplies each period a constant quantity. This constant quantity is also called the standing order quantity.

We performed a simulation study to compare the performance of the two strategies. The results show that the RAS strategy performs significantly better than the DAS strategy if the standing order quantity has been set properly. Moreover, we have shown that the optimal standing order exists and that the higher the demand uncertainty, the lower the optimal standing order quantity. For the low demand uncertainty case, the cost curve is rather flat around the optimal standing order quantity. To further found our insights, we performed a case study at a pharmaceutical company that faces the same dual sourcing problem and which is currently applying the DAS strategy. We conducted the same comparative study, based on data from this real-life case study at the pharmaceutical company. We have shown that for this company, switching from the DAS strategy to the RAS strategy leads to an improvement of the supply chain performance, both in terms of total costs and the service level.

4. What is the structure of the optimal reservation and order policies for the outsourcer to control the outsourced supply chain?

As we discussed earlier, the order release function is different and more complicated when controlling an outsourced supply chain compared with controlling an internal manufacturing plant. In this study, we consider the setting where the outsourcer reserves capacity at the contract manufacturer before ordering. The contract manufacturer collects all reservations (as he serves multiple outsourcers on the same production line), conducts its 'secret' capacity planning, and announces the accepted part of the reservation. The order that follows afterwards cannot exceed the accepted reservation. For this inventory system, we addressed the research question above to study the outsourcer's optimal reservation and order policy when uncertain demand and uncertain capacity allocation from the contract manufacturer is faced.

In the modeling, we consider (next to inventory holding and backorder costs) reservation costs that are linear in the accepted reservation quantity.

The structure of the optimal reservation policy is a state-dependent basestock policy, as the optimal reservation-up-to level (current inventory position plus the reservation quantity) is dependent on the accepted reservation quantity, which is dependent on the reservation decision of the previous period. The optimal order policy is a modified basestock level, as there is an optimal basestock level (current inventory position plus the order quantity), which is bounded by the accepted reservation quantity. Therefore, the inventory system can be optimally controlled by two critical parameters: the reservation-up-to level and the order-up-to level.

Next to characterizing the optimal reservation and order policies, we conducted a numerical study, which reveals several interesting managerial insights. In case the unit reservation cost or the capacity uncertainty increases, it is optimal to increase the utilization of the accepted reservation by increasing the order quantity much more than the reservation quantity. This might be counterintuitive, as one would expect to mainly increase the reservation quantities in case the capacity uncertainty increases to hedge against the increased uncertainty. Another insight is that the effect of an increase of the capacity uncertainty decreases substantially when the demand uncertainty increases. When the demand uncertainty increases, the optimal order quantities increase, by which the utilization of the accepted reservation increases. This effect is also required when the capacity uncertainty increases, and therefore, we see that the effect of an increase of the capacity uncertainty is limited when the demand uncertainty increases. Another insight from the numerical study is that from the contract manufacturer’s perspective, the optimal reservation cost is small, as the optimal reservation and order quantities are then equal. The optimal unit reservation cost is rather independent of the level of demand uncertainty.

Finally, we studied the case where the capacity allocation of the contract manufacturer depends on the outsourcer’s demand distribution. When the distributions are dependent, the structure of the optimal order policy is the same as in the independent case, but the optimal reservation policy changes to a policy with two optimal target reservation-up-to levels. Dependent on whether the dependency is positive (or negative), the second optimal reservation-up-to level is lower (or higher) than the first one by which the model adapts its reservation quantities to the higher (or lower) capacity allocation. This result suggests that it is wise to collect market information of the competitors, to assess the level of dependency, and to take measures accordingly. In case the dependency is positive, it is wise to adapt the reservation policy towards the contract manufacturer to save costs. In case of negative dependency, one can think of measures like keeping safety stocks to hedge against the little capacity allocation of the contract manufacturer or agreeing on paying an additional premium to ensure (in case needed) a fixed amount of capacity from the contract manufacturer. Of course, these measures should be cheaper than the extra cost due to the negative dependency.

5. How should the contract manufacturer allocate its capacity flexibility to the different outsourcers?

In this study, we study the outsourced supply chain from the contract manufacturer's perspective that serves a number of different outsourcers with different levels of demand uncertainty on the same capacitated production line. As we discussed earlier, the contract manufacturer requires from all outsourcers (for planning purposes) to reserve capacity before ordering. Based on its capacity planning, the contract manufacturer decides on the accepted reservation quantity, which is done under uncertainty. The contract manufacturer wants to offer each outsourcer a contract that describes the amount of flexibility offered to that outsourcer, which is the amount of demand (reservation) the contract manufacturer is obliged to accept from that outsourcer. Offering more flexibility to the more risky outsourcer generates higher revenue, but also increases penalty costs for lost demand. The objective is to determine the optimal allocation of capacity flexibility to the outsourcers such that the expected profit is maximized. The allocated capacity flexibility quantities are input to the lower decision level, where the operational (acceptance and production) decisions are made and actual reservations and orders are observed.

We developed a hierarchical model that consists of two decision levels: the higher decision level decides on the optimal capacity flexibility allocation and the lower decision level that makes the operational acceptance and production decisions, given the capacity flexibility quantities that are determined at the higher level. We also conducted a numerical study that reveals several interesting insights. First, the allocation of capacity flexibility is sensitive to the unit penalty cost. The higher the unit penalty cost, the lower the capacity flexibility allocation. Second, for a range of capacity levels and unit revenue and penalty costs, the more uncertain outsourcer gets at least the same and often more capacity flexibility allocated than the less uncertain outsourcer. In practice, managers often give priority and rewards to the least uncertain outsourcer, but our study gives the opposite insight.

The third insight comes from simulating the operational planning process. We have shown that when the acceptance is made (given the allocated capacity flexibility decision from the higher decision level), priority is given to the less uncertain outsourcer, because allocating capacity flexibility to that outsourcer generates the highest expected profit. The information from the less uncertain outsourcer seems to be the most valuable, whereas accepting more from the more uncertain outsourcer is risky due to the uncertainty of its demand. However, we see the opposite effect when orders are placed (after the acceptance decision is made), namely that priority is given to the more uncertain outsourcer. Now the order is placed, no risk is involved anymore and priority is given to the outsourcer that generates the highest unit revenue, which is the most uncertain outsourcer.

The last part of the numerical study deals with the inconsistency between the two decision levels. At the higher decision level, we assume that all demand larger than the allocated capacity flexibility is rejected, whereas at the operational level, more demand can be accepted, dependent on the other outsourcers. Therefore, we propose a feedback loop from the lower decision level to the higher decision level to eliminate the inconsistency between the two decision levels. Without this feedback, i.e., without the hierarchical integration, the capacity flexibility quantities are too conservative, especially when the unit penalty cost is high and the capacity is tight. Therefore, the hierarchical integration approach is required.

7.2. Managerial implications

In this dissertation, the emphasis has been on understanding the implications of outsourced supply chains on supply chain operations planning. More specifically, we focused on operational decision making in the outsourced supply chain. We provided insights from an empirical study, analytical models, and from simulation experiments to better understand the performance consequences of outsourced supply chains and to find effective ways of improving it. In practice, many other issues also play a role than those we studied in this dissertation, such as for example the negotiation power between the outsourcer and contract manufacturer. However, we believe that the results and insights that we obtained in the various research studies of this dissertation can contribute to solving the broader real-life problems related to the planning and control of outsourced supply chains. In this section, we will discuss potential managerial implications of our findings explicitly addressing the management decisions that may be affected by using the insights from our studies. Obviously, our experimental findings do not provide conclusive evidence for these insights and more empirical research may be needed. However, we believe our research does provide strong suggestions for managers to follow up on the ideas and recommendations outlined below. We distinguish between the implications at the strategic, tactical, and the operational level.

Strategic level

In the literature, strategic outsourcing decisions have been mainly motivated by the transaction cost theory, resource based view theory, and the focus on core competences (see Chapter 2). Based on our research, in which we have shown some operational implications of outsourcing, we think that one should also consider these issues when taking the strategic outsourcing decision. Considering the operational implications of outsourcing when taking the strategic outsourcing decision will lead to a different and better estimate of the transaction costs and probably to a different strategic outsourcing decision. Based on our research, we think that the transaction cost estimate will be higher if the outsourcer and the contract manufacturer do not agree on operational issues, such as the multi-level order release mechanism. We have shown that the benefits of such an order release mechanism is substantial and not considering it leads to a nervous ordering behaviour, which means that if the two parties do not agree on such an order release mechanism, the transaction cost will be substantially higher. We believe that this has not been addressed (both in the literature and in industrial practice) when taking the strategic outsourcing decision.

Tactical level

Our research has also developed some insights that might result in a different contractual agreement between the outsourcer and the contract manufacturer. First, the outsourcer may include the options of postponement and cancellation in the contract, even if the contract manufacturer would charge (little) extra for these options. The results show that the benefits of including these options are substantial and it is worthwhile to include a multi-level decision process in the contract that considers the postponement and cancellation options. We have also shown some conditions for a successful implementation of the more advanced order release strategy, as the contract manufacturer will only accept a more advanced order release strategy if he gets at least a compensation for the extra costs. It turns out that there is a big set of possible profit distributions that are acceptable to both parties.

Second, if a company faces a dual sourcing case where the contract manufacturer is the second source next to an internal manufacturing source and the company faces substantial forecast errors, it might be worthwhile to consider applying the rigid allocation strategy. By this strategy, the internal manufacturing source produces each period a fixed quantity and the contract manufacturer (the more expensive source) a variable quantity. When applying this strategy, the outsourcer should set contractual terms that the contract manufacturer accepts some variability in the order pattern. It is likely that the contract manufacturer will accept this variability, as the contract manufacturer produces for multiple outsourcers and will benefit from capacity pooling effects. The model that we developed in Chapter 4 in combination with the simulation experiment can be used to show the value of this flexibility and can thus be used in the contract negotiations with the contract manufacturer.

Third, our research shows that is worthwhile to gather market information of the competitors that produce at the same contract manufacturer to assess the dependency between the own demand and that of the available capacity at the contract manufacturer. We have seen that in case of negative dependency, which means that the competitors operate in the same market, it is wise to set contractually a fixed amount of capacity that can be claimed in case needed. By not doing so, the outsourcer will face more backorders, i.e., poorer service level. Based on the market information, the company can also assess or estimate the own demand uncertainty level related to the competitors'. In case the own demand uncertainty level is higher than that of the competitors', it might be wise to pay additionally to ensure enough capacity flexibility at the contract manufacturer. If the own demand uncertainty is lower, than our results suggest to emphasize the price when having contract negotiations.

From the contract manufacturer's perspective, it is wise to include the reservation cost as a parameter in the contract. We have seen that including little reservation costs leads to the desired behaviour from the outsourcers, because in that case, the reservation information will be consistent with the order information. When having contract negotiations with the outsourcers, the contract manufacturer might also negotiate on the allocation of capacity flexibilities. First, an estimate should be made of the penalty cost, as the optimal capacity flexibility is sensitive to the penalty cost. The estimation can be done by assessing whether the outsourcer is willing to keep safety stocks, safety time, and whether the outsourcer has a second supply source for its product(s). We developed an approach, by which the optimal capacity flexibility quantities can be determined, given that the outsourcers are willing to pay for additional allocation of capacity flexibility. We expect that outsourcers are willing to pay the additional amount; as otherwise, the little allocation of capacity flexibility has to be compensated by keeping safety stocks.

Combining the insights from the previous two paragraphs, one can conclude that including little reservation cost (in the contract) is beneficial to both parties; it leads to a win-win situation. The outsourcer with a high level of demand uncertainty secures sufficient capacity allocation from the contract manufacturer and avoids more expensive penalty costs. For the outsourcer with less demand uncertainty, it is wise to set the contract such that the reservation costs are subtracted from the total paid amount. Moreover, this outsourcer may gain competitive advantage if its competitors operate in the same market by securing sufficient capacity allocation (by paying little reservation costs). For the contract manufacturer, including reservation cost is beneficial, as it leads to a better match between the reservation and order behaviour.

Operational level

In the case studies (Chapter 2), we showed that controlling a contract manufacturer operationally in the same way as an internal manufacturing source leads to a nervous ordering behaviour with a lot of changes and a lot of panicky communication between the outsourcer and the contract manufacturer. It is essential to develop a more advanced order release mechanism that includes the various aspects of outsourcing, such as: capacity reservation, postponement (level of aggregation of shared information in time), cancellation option, and the uncertain capacity allocation from the contract manufacturer. The results have shown that the benefits of having a more complex operational order release function are substantial and that it is worthwhile for an outsourcer to invest in building up capabilities to deal with such more complex release strategies. For example, in case a company has implemented an Advanced Planning System, it is wise to adapt the order release function of the planning system to incorporate the different connected decisions in time to avoid a nervous ordering behaviour, as we have seen in the case studies.

Our research provides additional insights that contribute to the design of an order release function to control outsourced operations with respect to capacity reservation under uncertain capacity availability from the contract manufacturer. We have shown the structure of the optimal policies to apply in an outsourced supply chain, where the outsourcer faces uncertain capacity allocation and where the outsourcer has to decide on the reservation and order quantities. The results show that if reservations become more expensive or the capacity allocation from the contract manufacturer becomes more uncertain, it is optimal to increase the order quantities much more than the reservation quantities, rather than dramatically increasing the reservation quantities, which is a measure that one would expect to take in such a situation.

Applying the rigid allocation strategy (in a dual sourcing setting) results also in an interesting advantage at the operational level. The internal manufacturing source produces every period a fixed quantity (the standing order quantity) and that means that planning efforts decrease substantially. The only planning effort is to periodically revise the optimal standing order quantity.

From the contract manufacturer’s perspective, our research shows some insights that a contract manufacturer can benefit from serving a number of different outsourcers with different levels of demand uncertainty. We discussed earlier that we assume that the more uncertain outsourcer is willing to pay extra for an additional allocation of capacity flexibility. We also discussed that the contract manufacturer requires (contractually) that the outsourcers share their advance demand information with the contract manufacturer, which is considered as capacity reservation. The results of our research show that when the outsourcers reserve capacity, it is wise to give priority to the least uncertain outsourcer in the acceptance process. The reason is that the value of information of the least uncertain outsourcer is the highest; accepting its reservations is more likely to result in future revenue than accepting from the more uncertain outsourcer and leads to the highest expected (future) profit. When the orders follow later on, priority should be given to the outsourcer with the highest demand uncertainty, i.e., the most paying outsourcer. At this stage, there is no uncertainty anymore and producing for the most paying outsourcer is most profitable.

7.3. Future research

In this section, we discuss some ideas for future research. In the remainder of this section, we go through the different chapters of this dissertation and discuss some possible extensions.

In Chapter 2, we conducted two case studies and we used the insights from those case studies to understand the implications of outsourcing on the operational planning and control in the pharmaceutical industry. Like in any empirical study, one possible extension is to consider more cases (within the pharmaceutical industry) where different companies have an outsourcing relationship to strengthen the insights and to validate the conclusions of that chapter. One could also consider studying the implications of outsourcing on the operational planning in other industries, such the electronics industry, to test whether the insights also hold for those other industries.

In Chapter 3, the supply chain that we used in the simulation study is a simplified case with only one (capacitated) contract manufacturer and one outsourcer. It will be useful to study the impact of the order release strategies on a supply chain with more stages. In the capacitated case, we assumed that the capacity of the contract manufacturer is identical and independently distributed, whereas one can think of dependency between the available capacity from one time period to another. For example, the less the available capacity in the previous time periods, the more it will be in the current time period. Another extension would be to assume dependency between the reservation quantity and the available capacity. The higher the reservation quantity, the more likely it is that other outsourcers also reserve more, the less the available capacity of the contract manufacturer for each outsourcer. At last, we do not explicitly model the interaction between the several outsourcers. An idea for future research is to extend this work by modelling the other outsourcers as well.

The comparative study in Chapter 4 showed that the rigid allocation strategy outperforms the dynamic allocation strategy. This conclusion has been drawn, given that the demand distribution is stationary and the demand forecasts are highly inaccurate. It would be interesting to test whether this conclusion also holds when the demand forecasts are more accurate or in the non-stationary case. Moreover, we think that when the demand is deterministic, the dynamic allocation strategy will outperform the rigid allocation strategy. When the demand uncertainty increases, a point will be reached where the rigid allocation strategy will outperform the dynamic allocation strategy. An idea for future research is to find this turn over point and its characteristics.

Several interesting directions for extending the research study of Chapter 5 exist. The model can be extended by considering longer lead times between reservation and acceptance and between the order and delivery. Next, the model can be extended by considering non-stationary demand and capacity distributions. Moreover, in this chapter, we did not include batch sizes, which is also an interesting direction for future research.

In Chapter 6, we assume a make-to-order system for the contract manufacturer with no possibility of producing on stock. An extension would be to allow the contract manufacturer to produce on stock, based on forecasts from the outsourcers. This might be interesting, as the contract manufacturer does not fully utilize its production capacity. Another extension would be to consider the case where the demands from the different outsourcers are correlated, which reflects the real-life situation better, as the outsourcers are likely to operate in the same market.

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Summary

In this dissertation, we focus on the planning and control of supply chains where part of the supply chain is outsourced to a contract manufacturer. Supply Chain Management deals with the integration of business processes from end-customers through original suppliers that provide products, services and information that add value for customers (Cooper *et al.*, 1997). In a narrow sense, a supply chain can be 'owned' by one large company with several sites, often located in different countries. Planning and coordinating the materials and information flows within such a worldwide operating company can be a challenging task. However, the decision making is easier than in case more companies are involved in a supply chain, since the sites are part of one organization with one board and it is likely that the decision makers have full access to information needed for the supply chain planning.

Outsourcing is an 'act of moving some of a firm's *internal activities* and *decision responsibilities* to outside providers' (Chase *et al.*, 2004) and it has been studied extensively in the literature. Outsourcing is developing in many industries, but in this dissertation, we focus on outsourcing in the pharmaceutical industry, where outsourced supply chain structures are rapidly developing. Recent studies show that the global pharmaceutical outsourcing market has doubled from 2001 to 2007 and it is expected to further increase in the upcoming years.

In the pharmaceutical industry, the outsourcing relationship is typically long-term and customers often require high service levels. Due to high setup costs, production is conducted in fixed large batch sizes and campaign sizes. The cumulative lead time within the supply chain is more than one year, whereas the customer lead time is about two months. In this industry, production activities are outsourced for three main reasons. First, intellectual property legislation requires outsourcing the production activities to a contract manufacturer that owns the patent for specific technologies that are needed to perform the production activities. Second, expensive technologies or tight (internal) capacity restrictions also result in outsourcing. Third, to limit the supply uncertainty, companies outsource to have an external source producing the same product next to an internal source.

This dissertation deals with the planning and control of *outsourced supply chains*, which are supply chains where part of the supply chain is outsourced to a contract manufacturer. Most supply chain operations planning models from the literature assume that the supply chain is planned at some level of aggregation and that further coordination is conducted at a more detailed level by lower planning levels. These concepts implicitly assume that the lower planning level and the operations are conducted within the same company with full information availability and full control over the operations, which is not case when part of the supply chain is outsourced.

Hence, the objective of this dissertation is to obtain insights into the implications of outsourcing on the supply chain planning models. First, we review the literature on outsourcing research and we find that little is known on the operational planning decisions in an outsourced supply chain and on the implications of outsourcing on the operations planning. The literature on outsourcing at the operational level uses outsourcing purely as a second source to control performances such as the delivery reliability. Consequently, we discuss two case studies that we conducted into outsourced supply chains to understand the implications of outsourcing on the supply chain operations planning function, where the contract manufacturer is the only source of supply. The main implications of the planning and control of outsourced supply chains can be summarized in three categories: *limited information transparency*, *limited control over the detailed planning and priorities at the contract manufacturer*, and *contractual obligations.* Below, we discuss these in more detail.

In order to decide on the release of materials and resources in a supply chain, it is required that the decision maker is able to frequently monitor the status of the supply chain. In an outsourced supply chain, the outsourcer does not have access to all relevant information of the entire supply chain, especially not to the available capacity in each period, also because the contract manufacturer serves a number of different (and sometimes even competing) outsourcers on the same production line. Moreover, the contract manufacturer plans and controls its part of the supply chain based on rules and priorities that are unknown to the outsourcer. This results in facing an uncertain capacity allocation by the outsourcer. Another implication is that the contract manufacturer requires by contract to reserve capacity slots prior to ordering. These reservations are subject to an acceptance decision, which means that part of the reservation quantity can be rejected. The accepted reservation quantity bounds the order quantity that follows later on.

Therefore, another main insight from the case study is that in an outsourcing relationship, the order process consists of different (hierarchically connected) decisions in time. In the ordering process, the uncertain capacity allocation of the contract manufacturer should be incorporated. Hence, the order release mechanism requires a richer and more developed communication and ordering pattern than commonly assumed in practice. In a subsequent study, we build on this insight and we design three different order release mechanisms to investigate to what extent a more complicated order release function improves (or deteriorates) the performance of the supply chain operations planning models. The order release mechanisms differ in the number of decision levels and they incorporate the probabilistic behaviour of the contract manufacturer. Based on a simulation study, we show that a more advanced order release strategy that captures the characteristics of outsourcing performs significantly better than a simple order release strategy that is commonly used in practice. We also discuss the conditions for a successful implementation of the more advanced order release strategy.

In another study, we study the case where the contract manufacturer is a second source next to an internal manufacturing source for the same product and where the outsourcer faces inaccurate demand forecasts. The two sources are constraining the supply quantities in different ways. Its own manufacturing source is more rigid, cheaper and tightly capacitated, whereas the contract manufacturer is more flexible but more expensive. In that study, we compare the performance of two different allocation strategies by a simulation study in which we solve the model in a rolling horizon setting. The results show that the rigid allocation strategy (the cheaper source supplies each period a constant quantity) performs substantially better than the dynamic allocation strategy (each period the allocation quantities are dynamic) if the parameters are chosen properly.

In another study, we study the outsourcer's problem of deciding on the optimal reservation quantity under capacity uncertainty, i.e., without knowing what part of the reservation will be accepted. In that study, we develop a stochastic dynamic programming model for the problem and we characterize the optimal reservation and order policies. We conduct a numerical study where we also consider the case where the capacity allocation is dependent on the demand distribution. For that case, we show the structure of the optimal policies based on the numerical study. Further, the numerical results reveal several interesting managerial insights, such as that the optimal reservation policy is little sensitive to the uncertainty of the capacity allocation from the contract manufacturer. In that case, the optimal reservation quantities hardly increase, but the optimal policy suggests increasing the utilization of the allocated capacity.

We also study the outsourced supply chain from the contract manufacturer's perspective. In that study, we consider the case where the contract manufacturer serves a number of outsourcers with different levels of uncertainty. The contract manufacturer faces the question of how to allocate the contractual capacity flexibility in an optimal way. More precisely, we focus on the contract manufacturer's decision to make the acceptance decision under uncertainty. The more the contract manufacturer accepts from an outsourcer, the more risk is taken by the contract manufacturer, as the outsourcer might not fully utilize the accepted reservation quantity. However, we assume that the outsourcer is willing to pay an additional amount to compensate the contract manufacturer for that risk.

We develop a mixed-integer programming model, which optimizes the allocation of capacity flexibility by maximizing the expected profit. Offering more flexibility to the more risky outsourcer generates higher revenue, but also increases the penalty costs. The allocated capacity flexibilities are input (parameters) to the lower decision level, where the operational planning decisions are made and demands are observed. The simulation results reveal interesting managerial insights, such that the more uncertain outsourcer gets at least the same capacity flexibility allocated as the less uncertain outsourcer. Moreover, we have seen that when the acceptance decision is made, priority is given to the less uncertain outsourcer, because that information is the most valuable. However, we see the opposite effect when orders are placed, namely that priority is given to the more uncertain outsourcer, i.e., the most paying outsourcer, as no uncertainty is involved anymore. These insights are helpful for managers of contract manufacturers when having contract negotiations with the outsourcers.

We believe that the results and insights that we obtained in the various research studies of this dissertation can contribute to solving the broader real-life problems related to the planning and control of outsourced supply chains. We also discuss potential managerial implications of our findings explicitly addressing the management decisions that may be affected by using the insights from our studies. Considering the operational implications of outsourcing when taking the strategic outsourcing decision will lead to a different and a better estimate of the transaction costs and probably to a different strategic outsourcing decision. Based on our research, we think that the transaction cost estimate will be higher if the outsourcer and the contract manufacturer do not agree on operational issues, such as the multi-level order release mechanism. From a tactical point of view, the outsourcer may include the options of postponement and cancellation in the contract, even if the contract manufacturer would charge little extra for these options. The results show that the benefits of including these options are substantial. Moreover, we showed that controlling a contract manufacturer operationally in the same way as an internal manufacturing source leads to a nervous ordering behaviour with a lot of changes and a lot of panicky communication between the outsourcer and the contract manufacturer.

Combining the insights from different studies, one can also conclude that including little reservation cost is beneficial to both parties; it leads to a win-win situation. The outsourcer with a high level of demand uncertainty secures sufficient capacity allocation from the contract manufacturer and avoids more expensive penalty costs. For the outsourcer with less demand uncertainty, it is wise to set the contract such that the reservation costs are subtracted from the total paid amount. Moreover, this outsourcer may gain competitive advantage if its competitors operate in the same market by securing sufficient capacity allocation (by paying little reservation costs). For the contract manufacturer, including reservation cost is also beneficial, as it leads to a better match between the outsourcer's reservation and ordering behaviour.

Samenvatting

In dit proefschrift richten we ons op de planning en besturing van *logistieke ketens* (supply chains) waarvan een deel is uitbesteed aan een contractproducent, die op basis van (contractuele) afspraken produceert voor uitbesteders. Supply Chain Management gaat over het integreren van bedrijfsprocessen van eindklant tot de initiële leveranciers die producten, diensten en informatie verschaffen die waarde toevoegen voor de klant (Coopers *et al.*, 1997). Een logistieke keten kan in het bezit zijn van één groot bedrijf met meerdere vestigingen in verschillende landen. De planning en coördinatie van materialen en informatiestromen in een dergelijk wereldwijd opererend bedrijf kan een uitdagende taak zijn. Echter, het nemen van beslissingen is makkelijker dan wanneer meerdere bedrijven in een logistieke keten betrokken zijn, omdat de verschillende vestigingen onderdeel vormen van één organisatie met één bestuur en het is waarschijnlijker dat de beslissers volledige toegang hebben tot alle informatie die benodigd is voor de ketenplanning.

Uitbesteding is een handeling waarbij een bedrijf haar *interne activiteiten* en *beslissingsverantwoordelijkheden* verplaatst naar derde partijen. Uitbesteding is uitgebreid bestudeerd in de literatuur en ontwikkelt zich in vele industrieën. In dit proefschrift richten we ons op uitbesteding in de farmaceutische industrie, waar *uitbestede logistieke ketens* (outsourced supply chains) zich snel ontwikkelen. Recente studies laten zien dat de wereldwijde farmaceutische uitbestedingmarkt is verdubbeld tussen 2001 en 2007 en de verwachting is dat deze zich verder zal toenemen in de komende jaren.

Kenmerkend aan de farmaceutische industrie is dat de uitbestedingrelatie langlopend is en dat de klanten vaak een hoge servicegraad eisen. Daarnaast wordt, door de hoge opstartkosten, de productie vaak uitgevoerd in vaste grote seriegrootten. De cumulatieve doorlooptijd binnen de logistieke keten is vaak langer dan één jaar, terwijl de levertijd naar de klanten toe ongeveer twee maanden is. In deze industrie worden productieactiviteiten uitbesteed om voornamelijk de volgende drie redenen. Ten eerste vereist het intellectueel eigendomsrecht het uitbesteden van de productieactiviteiten naar een (contract)producent die de eigenaar is van het patent van de specifieke technologie die benodigd is voor de productie. Ten tweede resulteren ook dure technologieën of krappe (interne) capaciteitsbeperkingen in uitbesteding. Tenslotte besteden bedrijven uit om een tweede (externe) leverancier te hebben die hetzelfde product produceert als een interne vestiging om zo de aanvoeronzekerheid te beperken.

Dit proefschrift gaat over de planning en de besturing van *uitbestede logistieke ketens* (outsourced supply chains). Dat zijn logistieke ketens waarvan een deel is uitbesteed naar een contractproducent. De meeste *operationele planningmodellen voor logistieke ketens* (supply chain operations planning models) uit de literatuur nemen aan dat de logistieke keten wordt gepland op een bepaald aggregatieniveau en dat verder de coördinatie wordt uitgevoerd op een meer gedetailleerd niveau door lagere planningniveaus. Deze modellen nemen impliciet aan dat het lager planningsniveau en de operaties worden uitgevoerd binnen hetzelfde bedrijf met volledige informatiebeschikbaarheid en volledige beheersing over de operaties, wat niet het geval is wanneer een deel van de logistieke keten is uitbesteed.

Daarom is het doel van dit proefschrift om inzichten te verkrijgen in de gevolgen van uitbesteding voor de planningmodellen voor logistieke ketens. Om dat te bereiken bestuderen we eerst de literatuur over uitbesteding en we stellen vast dat er weinig bekend is over de operationele planningsbeslissingen in een uitbestede logistieke keten. Ook is er weinig bekend over de implicaties van uitbesteding op de operationele planning. De literatuur over uitbesteding op operationeel niveau beschouwt uitbesteding uitsluitend als een tweede leverancier om prestaties te beheersen, zoals de leverbetrouwbaarheid.

Daarnaast bespreken we twee case studies die we hebben uitgevoerd binnen uitbestede logistieke ketens om de gevolgen van uitbesteding voor de planningmodellen voor logistieke ketens te begrijpen, waarbij de contractproducent de enige leverancier is. De voornaamste gevolgen voor de planning en besturing van uitbestede logistieke ketens kunnen worden samengevat in drie categorieën:

1. *beperkte informatietransparantie en zichtbaarheid*,
2. *beperkte zeggenschap over de detailplanning en prioriteiten bij de contractproducent* en
3. *contractuele afspraken.*

Hieronder bespreken we deze in meer detail.

Om te beslissen over de vrijgave van materialen en middelen in een logistieke keten is het vereist dat de beslisser in staat is om regelmatig de status van de logistieke keten te monitoren. Echter, in een uitbestede logistieke keten heeft de uitbesteder geen toegang tot alle relevante informatie over de gehele logistieke keten, voornamelijk niet tot de beschikbare capaciteit in elke periode. Dat komt omdat de contractproducent voor een aantal verschillende (en soms concurrerende) uitbesteders op dezelfde productielijn produceert. Bovendien plant en beheerst de contractproducent zijn deel van de logistieke keten op basis van regels en prioriteiten die onbekend zijn voor de uitbesteder. Dit heeft tot gevolg dat de uitbesteder te maken heeft met een onzekere capaciteitsallocatie door de contractproducent. Een andere implicatie is dat de contractproducent contractueel vereist om capaciteit te reserveren voorafgaand aan het bestellen. Deze reserveringen zijn onderhevig aan een acceptatiebeslissing, wat betekent dat een deel van de reserveringen geweigerd kunnen worden. De werkelijke bestelling die later volgt mag dan niet groter zijn dan wat er aan reservering is geaccepteerd.

Gegeven het voorgaande komen we tot een ander belangrijk inzicht uit de case studies, namelijk dat in een uitbestedingrelatie het bestelproces uit verschillende (hiërarchisch verbonden) beslissingen bestaat. Bovendien moet in het bestelproces de onzekere capaciteitsallocatie van de contractproducent meegenomen worden. Vandaar dat het ordervrijgavemechanisme een rijkere en meer ontwikkelde communicatiepatroon vereist dan veelal in de praktijk wordt aangenomen. In een vervolgstudie bouwen we voort op dit inzicht en ontwerpen we drie verschillende ordervrijgavemechanismen om te onderzoeken in welke mate een meer gecompliceerde ordervrijgavefunctie de prestatie van de planningmodellen voor logistieke ketens verbetert of verslechtert. De ontworpen ordervrijgavemechanismen verschillen in het aantal beslissingsniveaus en ze omvatten het probabilistisch gedrag van de contractproducent. Op basis van een simulatiestudie laten we zien dat een meer geavanceerd ordervrijgavemechanisme die de karakteristieken van uitbesteding meeneemt substantieel beter presteert dan een eenvoudig ordervrijgavemechanisme dat veelal in de praktijk wordt gebruikt. We bespreken ook de voorwaarden voor een succesvolle implementatie van de meer geavanceerde ordervrijgavestrategie.

In een andere studie bestuderen we de situatie waarbij de contractproducent een tweede leverancier is naast een interne productievestiging. Beide bronnen kunnen hetzelfde product produceren en de uitbesteder kan de klantenvraag lastig voorspellen. De twee bronnen beperken de aanvoerhoeveelheden op verschillende manieren. De interne productievestiging is meer rigide, goedkoper en strak gelimiteerd in capaciteit, terwijl de contractproducent meer flexibel, maar duurder is. In deze studie vergelijken we middels een simulatiestudie de prestatie van twee verschillende allocatiestrategieën, waarbij we het wiskundig model in een rollende horizon setting oplossen. De resultaten laten zien dat indien de parameters correct worden ingesteld, de rigide allocatie strategie, waarbij de goedkopere bron elke periode een constante hoeveelheid produceert, substantieel beter presteert dan de dynamische allocatiestrategie, waarbij de allocatiehoeveelheden dynamisch zijn.

In een andere studie bestuderen we het probleem van de uitbesteder betreffende het beslissen over de optimale hoeveelheid reservering onder capaciteitsonzekerheid, d.w.z. zonder precies te weten welk deel van de reservering geaccepteerd zal worden. In deze studie ontwikkelen we een stochastisch dynamisch programmeringsmodel voor het probleem en we karakteriseren de optimale reserverings- en bestelstrategieën. We voeren een numerieke studie uit waarbij we ook kijken naar de situatie dat de (onzekere) capaciteitsallocatie afhankelijk is van de vraagverdeling. Voor die situatie laten we op basis van een numerieke studie zien wat de structuur van de optimale strategieën is. Verder verschaffen de numerieke resultaten een aantal interessante management inzichten, zoals dat de optimale reserveringsstrategie beperkt gevoelig is voor de onzekerheid van de capaciteitsallocatie van de contractproducent. In dat geval neemt de optimale hoeveelheid reserveringen nauwelijks toe en wijst de optimale strategie juist op het beter benutten van de toegewezen capaciteit.

We bestuderen ook de uitbestede logistieke keten vanuit het perspectief van de contractproducent. In deze studie beschouwen we de situatie waarbij de contractproducent voor een aantal uitbesteders produceert die verschillende niveaus van vraagonzekerheid hebben. De contractproducent heeft de vraag hoe de contractuele capaciteitsflexibiliteit optimaal toe te wijzen. We richten ons dus op de beslissing van de contractproducent over het nemen van de acceptatiebeslissing onder onzekerheid. Hoe meer de contractproducent accepteert van een uitbesteder, hoe meer risico de contractproducent neemt, omdat de uitbesteder wellicht niet de volledige geaccepteerde reservering zal benutten. Hierbij nemen we aan dat de uitbesteder bereid is om extra te betalen om de contractproducent te compenseren voor dat risico.

Voor dit probleem ontwikkelen we een mixed-integer programmeringsmodel dat de allocatie van capaciteitsflexibiliteit optimaliseert door de verwachte winst te maximaliseren. Het toewijzen van meer flexibiliteit aan de meer risicovolle uitbesteder genereert meer inkomsten, maar leidt ook tot hogere boetekosten. De toegewezen hoeveelheden capaciteitsflexibiliteit zijn invoerparameters voor het lagere beslissingsniveau, waar de operationele planningsbeslissingen worden genomen en de werkelijke bestellingen worden waargenomen. De simulatieresultaten tonen een aantal interessante management inzichten, zoals dat de meer onzekere uitbesteder minstens evenveel capaciteitsflexibiliteit toegewezen krijgt als de minder onzekere uitbesteder. Bovendien blijkt uit de resultaten dat wanneer de acceptatiebeslissing genomen wordt, er prioriteit wordt gegeven aan de minder onzekere uitbesteder, omdat die informatie kennelijk het meest waardevol is. Echter, we zien het tegenovergestelde wanneer de bestellingen worden geplaatst, namelijk dat er prioriteit wordt gegeven aan de meer onzekere uitbesteder, d.w.z., de meeste betalende uitbesteder, omdat er geen onzekerheid meer is. Deze inzichten zijn bruikbaar voor managers van contractproducenten wanneer zij contractonderhandelingen aangaan met de uitbesteders.

De resultaten en inzichten die we verkregen hebben in de verschillende onderzoeksstudies uit dit proefschrift kunnen een bijdrage leveren aan het oplossen van problemen in de bedrijfspraktijk die gerelateerd zijn aan de planning en besturing van uitbestede logistieke ketens. We bespreken ook expliciet enkele potentiële gevolgen van onze bevindingen, waarbij we ook de managementbeslissingen aan de orde stellen die mogelijk beïnvloed worden door het gebruikmaken van de inzichten uit onze studies. Wanneer er bijvoorbeeld rekening wordt gehouden met de operationele gevolgen van uitbesteding bij het nemen van de strategische uitbestedingsbeslissing, zal dit leiden tot een andere en betere schatting van de transactiekosten en wellicht ook tot een andere strategische beslissing. Op basis van ons onderzoek verwachten wij dat de schatting van de transactiekosten hoger zal zijn wanneer de uitbesteder en de contractproducent geen overeenstemming bereiken over operationele kwesties, zoals het meerniveau-ordervrijgavemechanisme.

Vanuit een tactisch oogpunt is het de uitbesteder aan te raden de opties van uitstellen en annuleren in het contract op te nemen, zelfs wanneer de contractproducent hiervoor extra kosten in rekening zou brengen. De onderzoeksresultaten tonen namelijk aan dat de winst van het opnemen van deze opties substantieel is. Bovendien hebben we laten zien dat het operationeel besturen van een contractproducent op dezelfde manier als een interne productievestiging leidt tot een nerveus bestelgedrag met veel wijzigingen en een paniekerige communicatie tussen de uitbesteder en de contractproducent.

Als we de inzichten van de verschillende studies combineren kunnen we ook concluderen dat het opnemen van beperkte reserveringskosten in het voordeel is van beide partijen; het leidt tot een win-win-win situatie. De uitbesteder met een hoge mate van vraagonzekerheid stelt daarmee namelijk een voldoende hoeveelheid capaciteitstoewijzing veilig en vermijdt daarmee hogere boetekosten. Voor de uitbesteder met minder vraagonzekerheid is het verstandig om het contract zodanig op te stellen dat de reserveringskosten in mindering gebracht worden van het totaalbedrag. Bovendien kan de uitbesteder concurrentievoordeel behalen door voldoende capaciteitsallocatie veilig te stellen (door een beetje reserveringskosten te betalen) indien de concurrenten in hetzelfde marktsegment opereren. Voor de contractproducent is het opnemen van reserveringskosten ook voordelig, omdat het leidt tot een betere match tussen het reservering- en bestelgedrag van de uitbesteders.

About the author

Youssef Boulaksil was born in Temsaman, Morocco, on 8 October 1982. In July 1983, he moved with his parents and brother to the Netherlands. After completing his pre-university education (in Dutch: VWO) at the Thorbecke College in Utrecht in 2000 (cum laude), he started his study in Industrial Engineering and Management Science at the Eindhoven University of Technology. In November 2005, he received his M.Sc. degree after completing a Master's degree project on the development and implementation of a procedure to set safety stock levels in the supply chains of Organon, a global operating biopharmaceutical company.

Subsequently, he started his PhD project in the School of Industrial Engineering of the Eindhoven University of Technology on the planning and control of outsourced operations in pharmaceutical supply chains, under the supervision of Professor Jan Fransoo. Within this project, the cooperation with Organon continued. Organon also funded part of the PhD research project. Part of the research project has been conducted at the Technical University of Denmark (DTU) in cooperation with Professor Martin Grunow.

As a PhD student, Boulaksil was involved in teaching the Bachelor course *Basics of inventory control and demand forecasting.* Moreover, he was a member of BETA (Research school for operations management and logistics) and the LNMB (Dutch network on the mathematics of operations research). For both institutes, he successfully completed the educational requirements for PhD students. As a PhD student, Boulaksil was also a board member of the PhD association PromoVE and the Student Supply Chain Forum.

During the PhD project, Boulaksil worked in total on 7 research papers, from which 3 have appeared in the scientific journals *International Journal of Production Economics, OR Spectrum,* and *Interfaces.* The remaining papers are currently still under review.

On 10 February 2010, Boulaksil defends his PhD dissertation at the Eindhoven University of Technology.

$$Min \sum_{t=1}^{T} \alpha i_t + \sum_{t=1}^{T} \beta l_t + \sum_{t=1}^{T} \delta |q_t^1 - q_{t-1}^1| +$$

The global pharmaceutical manufacturing outsourcing market has doubled in the last five years and a similar growth is expected over the next decade. Despite this huge reliance on outsourced manufacturing, remarkably little is known on how to manage the operational relationships with these key suppliers.

In this monograph, both detailed models and managerial insights are presented that assist managers to better manage the orders that they place at contract manufacturers. The work is heavily grounded in the pharmaceutical industry, as models are presented that have been implemented at one of the larger players in the industry. Moreover, a number of case studies are presented that describe the delicate relationship between outsourcer and contract manufacturer.

All studies are carefully and scientifically documented, thus providing a sound basis for any researcher interested in this topic. While the models presented are fairly specific to a setting where Advanced Planning Systems are used, the insights can assist managers across the pharmaceutical industry and any other manager dealing with long-term contract manufacturing relationships in better understanding the process that elevates performance.

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