Improving performance of supply chain processes by reducing variability

Dissertation

submitted to

WU
Vienna University of Economics and Business
Department of Information Systems and Operations
Institute for Production Management

to obtain the degree of a
DOCTOR IN SOCIAL AND ECONOMIC SCIENCES

by
Martin Poiger
Vienna, November 2010

Doktorat der Sozial- und Wirtschaftswissenschaften

WIRTSCHAFTS
UNIVERSITÄT
WIEN VIENNA
UNIVERSITY OF
ECONOMICS
AND BUSINESS

1. Beurteilerin/1. Beurteiler: **Univ.Prof. DI. Dr. Werner Jammernegg**

2. Beurteilerin/2. Beurteiler: **Univ.Prof. Dr. Gerald Reiner**

Eingereicht am: ________________________

WIRTSCHAFTS
UNIVERSITÄT
WIEN VIENNA
UNIVERSITY OF
ECONOMICS
AND BUSINESS

Titel der Dissertation:

Improving performance of supply chain processes by reducing variability

Dissertation zur Erlangung des akademischen Grades

einer Doktorin/eines Doktors

der Sozial- und Wirtschaftswissenschaften an der Wirtschaftsuniversität Wien

eingereicht bei

1. Beurteilerin/1. Beurteiler: **Univ.Prof. DI. Dr. Werner Jammernegg**

2. Beurteilerin/2. Beurteiler: **Univ.Prof. Dr. Gerald Reiner**

von: **Mag. Martin Poiger**

Fachgebiet: **Produktionsmanagement**

Wien, im **November 2010**

Ich versichere:

1. dass ich die Dissertation selbständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfe bedient habe.
2. dass ich diese Dissertation bisher weder im In- noch im Ausland (einer Beurteilerin/einem Beurteiler zur Begutachtung) in irgendeiner Form als Prüfungsarbeit vorgelegt habe.
3. dass dieses Exemplar mit der beurteilten Arbeit übereinstimmt.

Datum Unterschrift

Abstract

Supply chain management (SCM) has become one of the most popular and fastest growing areas in management. One major issue of SCM is the proper design of supply chains to serve customers effectively (high customer service) and efficiently (at low costs). This is particularly difficult as companies nowadays face a series of challenges like shrinking product life cycles, the proliferation of product variants (mass customization), and increasing uncertainty on both the demand and the supply side. Dealing efficiently with uncertainty is one of the most crucial points in supply chain design. According to Lovejoy (1998) a company has three generic possibilities to address uncertainty: it can either hold safety inventory, hold safety capacity, or reduce variability by using enhanced information. These three strategies constitute the so-called *Operations management (OM) triangle*. This study will analyze whether and how variability can be reduced in supply chains and thereby improve process performance of supply chains. This means that the concept of OM triangle is extended and linked to concepts from SCM, with a special focus on the analysis of the role of information and its capability for reducing variability. As one result of this study a new variability framework is presented, organizing the different types of variability in supply chains. Second, the extended OM triangle is developed, linking concepts from SCM to the OM triangle. Finally, it can be stated that handling variability within the supply chain is major challenge for every supply chain manager, as there is always some kind of uncertainty or variability. This study may help to organize this broad field of action within supply chains.

Kurzfassung

Supply Chain Management (SCM) hat sich in den vergangenen Jahren zu einem wichtigen Bereich des Managements entwickelt. Im Zentrum steht das Design von unternehmensübergreifenden Lieferprozessen um Kunden möglichst effektiv (hoher Lieferservicegrad) und effizient (bei geringen Kosten) beliefern zu können. Das ist besonders schwierig, da die Unternehmen mit Herausforderungen wie kürzeren Produktlebenszyklen, steigender Variantenvielfalt und Unsicherheit sowohl beschaffungs- als auch nachfrageseitig konfrontiert sind. Vor allem der Umgang mit Unsicherheit und Variabilität ist essentiell für den Erfolg einer Supply Chain. Nach Lovejoy (1998) können Unternehmen entweder Unsicherheit reduzieren oder sich mit Sicherheitsbestand oder Sicherheitskapazität gegen diese absichern. Diese drei Strategien bilden das sogenannte *Operations Management (OM) Dreieck*. Im Rahmen dieser Arbeit wird analysiert, ob und wie Variabilität reduziert werden kann, um die Prozessleistung der Supply Chain zu verbessern. Dafür wird das OM Dreieck erweitert und mit Konzepten des Supply Chain Management verbunden, wobei der Schwerpunkt auf der Rolle von Information liegt. Ein Ergebnis dieser Arbeit ist ein neuer Bezugsrahmen für die Organisierung der unterschiedlichen Typen von Variabilität in Supply Chains. Ein weiteres Ergebnis ist das erweiterte OM Dreieck, welches SCM-Konzepte integriert.

Acknowledgments

This dissertation would not have been possible without the contribution of many people who influenced my work throughout the years and supported me in obtaining a doctoral degree. First, I would like to thank my advisor, Prof. Werner Jammernegg, for the support and guidance he showed me during the time as a faculty member of the Institute for Production Management of WU Vienna. I could gain plenty of experience in teaching as well as in research, which will be of great value for my further professional career. Furthermore, I found perfect conditions to develop my doctoral thesis.

I would like to show my gratitude also to Prof. Gerald Reiner, who was a great colleague at the Institute for Production Management, giving me the opportunity to participate in several research projects. Thereby, I learned how the academic world is working and how a research paper is written and published. Moreover, it is my pleasure to thank all my former colleagues - it was simply a great time!

Finally, I owe sincere and earnest thankfulness to my parents Juliana and Johann for supporting me all the time, and last but not least to my wife Martina. With her love and patience she was my most important support throughout my dissertation writing.

Vienna, November 2010

Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation

Supply chain management has become one of the most popular and fastest growing areas in management. Academic journals publish myriad articles on supply chain management, universities offer courses and even programs on supply chain management and companies successfully implement approaches and strategies offered by supply chain management. One major issue of SCM, among others (see *Section 2.2*), is the proper design of supply chains to serve customers effectively (high customer service) and efficiently (low costs), involving upstream and downstream partners (suppliers, customers). This is particularly difficult as companies nowadays face a series of challenges like shrinking product life cycles, the proliferation of product variants (mass customization), and increasing uncertainty on both the demand and the supply side.

To be successful in the long term it is necessary to fulfill or exceed customer's expectations. Hill (2000) has introduced the concept of *order winners* and *order qualifiers*, differentiating between the importance among the competitive priorities of cost, quality, flexibility and delivery (Schmenner and Swink, 1998). Order qualifiers are criteria that must be provided by the firm in order to enter or stay in the market. Order winners enable the company win orders in the marketplace. Clearly, in a dynamic environment, order qualifiers and winners may vary over time. In many industries, especially in Business-to-Business (B2B) relationships, process-oriented (time-related) criteria are becoming order winners. For instance, in the automotive industry the qualifiers now are often quality and costs and the order winner is delivery performance or delivery reliability. Process-oriented criteria are usually based on time, a factor which has become very important since the 1980's as a major source of competitive advantage (Stalk Jr., 1988). Generally, it is important to have processes which are able to efficiently fulfill customers expectations. Therefore, it is necessary to properly design firm's internal processes as well as the supply chain process, including upstream and downstream partners.

The most famous model dealing with supply chain design is provided by Fisher (1997), who differentiates between supply chains for functional goods and innovative goods. Functional goods are usually characterized by stable, predictable demand, long product life cycles, low product variety and low margins. Supply chains for such products mainly compete in terms of costs, which means they have to be first and foremost *efficient*. Innovative products are characterized by unpredictable demand, very short product life cycles, high product variety and high margins. Supply chains for such products mainly have to be *responsive*, which means that the supply chain should be able to react to changes in demand very quickly. Clearly, efficient and responsive supply chains have to be designed differently.

In practice, there are many hybrid forms of supply chains, combining elements from both generic forms. A very important example for such a hybrid supply chain is the *assemble-to-order process*. Such a process consists of both an order-driven part and a forecast-driven part. The border between the two parts is called *customer order decoupling point* (CODP). Upstream of the CODP the process is forecast-driven, which means economies of scale are used to produce efficiently. Downstream of the CODP the process is order-driven, which means the already finished components or parts are not assembled until a binding customer order arrives. Thereby the advantages of both process types are combined.

A crucial point in supply chain design is how to efficiently deal with uncertainty. Sources of uncertainty in supply chains are suppliers (e.g., delayed delivery), manufacturing (e.g., machine breakdown), and customers (e.g., uncertain demand) (Davis, 1993). This classification was extended by Geary et al. (2002), who added control uncertainty as a fourth source of uncertainty. Control uncertainty comes from the control system, which transforms customer demand into production plans and supplier orders (e.g., order batching). As a result of uncertainty many aspects and factors in a supply chain, like for instance customer demand or supplier delivery time, have to be treated as random variables, as they are usually not constant and not known in advance. This kind of uncertainty is also called variability and is usually measured by the standard deviation or by the coefficient of variation (see 2.1).

Addressing variability within supply chains is important because of (1) its negative impact on firm performance (due to direct costs and opportunity costs) and (2) its potential amplification within the firm and across firms (Germain et al., 2008). An empirical study of more than 900 manufacturing companies in the UK show that companies which are doing particularly well have lower process variability, high schedule stability and more reliable deliveries by suppliers (Mapes et al., 2000). Similar results were found by Field et al. (2006) analyzing financial services processes. According to Hopp and Spearman (2007) variability always deteriorates the performance of a system, as it leads to a mismatch of production (supply) and demand. To correct this misalignment additional (excess) resources are necessary. Generally, there are three types of excess resources, called buffers (Anupindi et al., 2006; Hopp and Spearman, 2007):
To maintain customer service in presence of variability a firm can ...

> ... hold additional stock (=**safety inventory**) of raw material, components and finished goods. This type of buffer is probably the most common within supply chains (Chopra and Meindl, 2007).
>
> ... hold additional capacities (=**safety capacity**). Holding safety capacities means that under average demand the firm's machines are not fully utilized. In case of increased demand (peak demand) this excess capacity can be used to fulfill customer orders still on time.
>
> ... simply tell its customers delivery times including **safety time**. For example, if the average delivery time of a particular product is four weeks, the company might communicate a possible delivery time of six weeks. By that a late delivery as compared to a initially confirmed date can be reduced considerably.

Clearly, the higher the variability of demand as well as of production and supply, the higher the necessary buffer.

Similarly, Lovejoy (1998) states that a company has three generic possibilities to maintain given customer service (fill rate, delivery time) in presence of variability: it can either hold safety inventory, hold safety capacity, or reduce variability by using enhanced information. These three strategies constitute the so-called *Operations management (OM) triangle*, consisting of the inventory point, the capacity point and the information point (see 2.1).

The position of a company's operations within this triangle depends on its strategy, the cost structure of the industry, the availability of information, and others (Schmidt, 2005). Usually, both safety capacity and safety inventory are costly. Therefore, it is particularly interesting in which cases information can substitute excess capacity or excess inventory and thereby reduce costs without reducing customer service. This conceptual model from operations management was further studied by Klassen and Menor (2007). They extended and strengthened this model by providing empirical evidence that the trade-offs between capacity (utilization), variability and inventory (CVI trade-offs) occur at multiple levels of operating and business systems and not just on the process level.

1.2 Gaps, research questions and objectives

As already mentioned, both the SCM literature and the literature on information sharing is both very heterogeneous and fragmented, and some authors even argue that SCM does not have its own "theory" (Chen and Paulraj, 2004a; Croom et al., 2000). Hence, it might be useful to contribute to the theory of SCM by trying to better organize the available concepts and approaches. Therefore, the first goal of this study is to use the OM triangle to build a conceptual model of information sharing in supply chains from existing literature. With this new model, one looks to answer the following research questions:

1. How can variability be reduced in supply chains to get "closer" to the information point?
2. Which information and information sharing concepts reduce variability in a supply

chain, and thereby also reduce the necessary amount of safety capacity or safety inventory without decreasing customer service?

In terms of methodology there is a gap between analytical research (mathematical modeling), which is often very stylized, and case study research, which is often just anecdotal. Bertrand and Fransoo (2002) suggest quantitative modeling using empirical (real-world) data. A similar suggestion is made by Silver (2004), who suggests "de-emphasizing mathematical optimization and instead seeking improvements through better representations of problems or situations of real interest to management". This is in line with a general call for more theory-driven, empirical research (Melnyk and Handfield, 1998). Therefore, the conceptual model of the extended OM triangle is tested by means of the analysis of real supply chains out of different industries. The goal is to gain further insight concerning the impact of variability reduction by information sharing on supply chain performance. Finally managerial implications should be presented, helping firms to better design their supply chains.

1.3 General supply chain model and definitions

As there are many different perspectives within supply chain management as well as plenty of different terms and definitions, it is important to clarify the basic supply chain model used to study the before mentioned research questions. Contrary to centrally managed multi-stage supply chains, this study takes the viewpoint of a manufacturing company (focal company), working together with suppliers and delivering to business customers. By that, the study is restricted to business-to-business (B2B) context. Furthermore, the analysis is done on process level and not on network level, meaning that supply chain processes of particular products are studied. *Figure 1.1* shows this general model, consisting of a manufacturer (focal company), a supplier and a customer. This model is inspired by the SCOR-Model, which mainly suggests to model a supply chain with the activities *plan*, *source*, *make*, *deliver* and *return* (SCC, 2008).

For this model two main activities are differentiated between for every involved company, namely *Make* and *Deliver*, for which flow time is defined as the key performance measure. Generally, flow time is the time a part or an order needs to go through a particular process. Therefore, production flow time is defined as the time necessary to produce an order, or in other words, the time from the arrival of components or raw material at the company until the entry of the finished order in the finished goods inventory. Delivery flow time is composed of the time products spend in the finished goods inventory and times for consignment and transportation activities until the arrival at the customer.

As can be seen in *Figure 1.1*, flow time of a company is the sum of production flow time and delivery flow time. Consequently, the supply chain flow time is the sum of flow times of all supply chain stages. As production activities as well as transportation activities are subject to variation, flow time has to be regarded as a random variable, which is usually described by mean and standard deviation (or variance) (Hopp and Spearman, 2007). Frequently, the term lead time is used instead of flow time. For this study, lead time stands for the time allowed for a particular activity. In contrast to flow time, lead time is a constant and not a random variable, and is set by management (Hopp and Spearman, 2007). Consequently, production lead time is the time allowed to produce an order, and delivery lead time the time allowed to deliver an order.

Generally, the shorter flow times the better for the company as well as for the customer, as with shorter flow times, work-in-process (WIP) is lower (Little's Law - see *Section 2.1*) and delivery is faster. From customers point of view customer lead time is relevant, as it captures the required time from placing an order until delivery. If the customer lead time is very long, i.e., longer than production flow time and delivery flow time together, make-to-order (MTO) production is possible. This means that production only starts after the arrival of an order, which completely removes demand uncertainty.

If the customer requires immediate delivery, i.e., production and delivery flow time are longer than customer lead time, production has to be executed in advance based on forecasts. This type of production is referred to as make-to-stock (MTS) production. The hybrid form of these two types is called assemble-to-order (ATO) production, meaning that early parts of the production process are done based on forecasts, as they would exceed customer lead time. Activities, which can be finished within customer lead time,

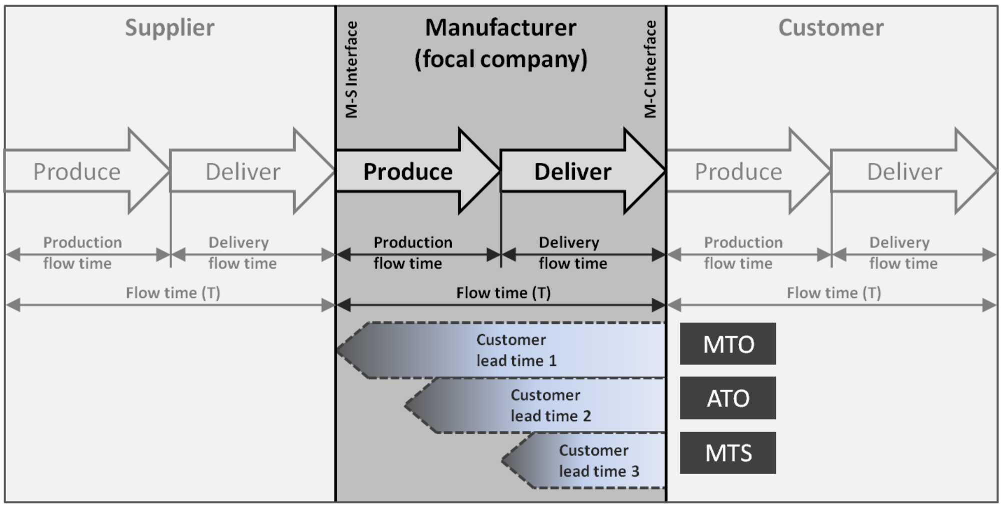

Figure 1.1: General model of a supply chain - Overview flow times

are only started after a customer order has arrived. *Figure 1.1* shows the different types of production depending on the length of customer lead time.

Consequently, short flow times are favorable for both MTS and MTO production, as according to Little's Law WIP can be reduced, which leads to better financial results (lower current assets → higher ROI). Furthermore, for MTO production, flow time reduction is crucial to fulfill customer orders within customer lead time. Therefore, flow time is used as the key performance indicator to evaluate process improvement by variability reduction.

1.4 Methodology and research design

According to Reisman and Kirschnick (1995) seven more or less distinct research strategies can be found in Operations Research and Management Science literature: the ripple process (existing models are extended incrementally), the embedding process (two or more models are embedded in a more general formulation), the bridging process (tying two or more known models into a more general theory), the transfer of technology process (transfer of a model to another context or discipline), the creative application process (a known methodology is applied directly to a problem previously unaddressed in such a way), the structuring process (intellectual structure is created to explain a new situation with new phenomena), the statistical modeling process (models are built on the basis of empirically obtained data). This list is not necessarily exclusive or complete, but still very helpful to find an appropriate way to deal with a particular research topic. For this study the bridging process is used in the same way as the OM triangle is combined with models and concepts from supply chain management.

In the empirical part of the study, two different real-world supply chains are analyzed with respect to the framework. The analysis of these supply chains is done with the rapid modeling software MPX and comprises the modeling and evaluation of the status quo of the supply chain process as well as the identification of process improvements and their impact on process performance.

Rapid modeling is a technique that is based on the idea that a process is made up of a network of queues (Enns, 1996). This software uses the node-decomposition approach, where a network is broken down in its workstations, each regarded as a G/G/m queue (Suri et al., 1995; Rabta, 2009). Compared to simulation, rapid modeling is easy to use (without any programming expertise), is not time-intensive, and generates quite good results for processes in steady state. Suri et al. (1995) underline the advantage of using open queueing networks by stating that it is better to find approximate solutions to models close to reality than finding exact solutions for models that are only rough approximations of reality (e.g., linear programming).

MPX is successfully used in academic teaching (de Treville and Van Ackere, 2006) and consulting, mainly for analyzing manufacturing systems. MPX intuitively guides the user through a complete process analysis, by requesting inputs of labor, equipment, products, lot sizes, bill of materials, demand, variability, operations and routings. When the modeling of the manufacturing process is completed performance measures like WIP and flow time can be computed almost instantaneously. Process alternatives can be evaluated by incorporating "what-if" scenarios into the validated model.

An overview of different rapid modeling software was provided by Rabta et al. (2009). Most recently, the so-called *Rapid Modeler* was developed within the project "Keeping Jobs in Europe" (European Community's Seventh Framework Program), coordinated by the University of Neuchâtel (University of Neuchâtel, 2010).

The overall goal of this study is to analyze whether and how variability can be reduced within supply chains and thereby improve the process performance of supply chains. This is done by extending the concept of OM triangle to the whole supply chain, with a special focus on the analysis of the role of information and its capability of reducing variability. By combining the OM triangle with different forms of information sharing and supply chain best practices, a framework to support supply chain design is developed, further illustrated by means of two real-world supply chains.

The remainder of this thesis is organized as follows. In *Section 2* the theoretical background is presented, discussing the OM triangle, supply chain management and information sharing. In *Section 3* definitions of uncertainty and variability are provided and a new variability framework is developed. *Section 4* shows different ways of tackling variability and clarifies the role of information for reducing variability. Furthermore, the extended version of the OM triangle is presented. In *Section 5* the analysis of real-world supply chains with respect to variability reduction is demonstrated and linked to the extended OM triangle. The thesis is concluded in *Section 6* by wrapping up the main results, providing answers to the research questions, and deriving managerial implications.

2 Theoretical Background

In the following chapter the relevant theories on the *Operations Managemet Triangle*, Supply Chain Management and Information Sharing are presented.

2.1 Operations Management Triangle

Operations management is the business function within a company responsible for "the design, operation and improvement of the systems that create and deliver the firms goods and services" (Chase and Aquilano, 2004) and deals with issues like operations strategy, process analysis, facility layout, quality management, forecasting, inventory control, scheduling, etc. One very important theory used within operations management, especially for process analysis and capacity management, is queuing theory, i.e., the management of waiting lines. Models from queuing theory offer the possibility of estimating waiting times of orders or customers in a queuing system. For instance, queuing theory can help to appropriately dimension the number of agents in a call center in order to keep waiting times at a reasonable level (Aksin et al., 2007). Besides the service industry, queuing also plays an important role in manufacturing systems (e.g., Anupindi et al., 2006; Buzacott and Shanthikumar, 1993; Hall, 1991; Hopp and Spearman, 2007; Hopp, 2008; Nahmias, 2008; Nyhuis and Wiendahl, 2009). A formal outline of queuing systems is provided by Kleinrock (1975, 1976) and a recent review by Stidham, Jr. (2002).

A queuing system usually consists of an arrival process, a production or service process, and a queue (Hopp and Spearman, 2007). The expected time spent by a job in such a system is called flow time T, defined by the sum of the mean effective process time t_e

plus the expected waiting time t_q (*2.1*).

$$T = t_\mathrm{e} + t_\mathrm{q} \tag{2.1}$$

The mean effective process time t_e is the average time required to process one job and includes setup, downtime, etc. The reciprocal value of t_e is the average flow rate r_e, also referred to as average capacity, standing for the number jobs, which can be finished per time period. The waiting time t_q depends on t_e, on the utilization ρ and on the variability of both process and interarrival time. The utilization ρ is the probability that a station is busy, and is calculated for a single machine by dividing mean arrival rate r_a by mean flow rate r_e (*2.2*). The mean arrival rate r_a is the average number of jobs coming to the station per time unit (reciprocal value of mean interarrival time t_a).

$$\rho = \frac{r_\mathrm{a}}{r_\mathrm{e}} \tag{2.2}$$

Variability in queuing systems is measured by the coefficient of variation (for a general discussion of the concept of variability see *Section 3.1.2*). The coefficients of variation of the process time (c_e) and of the interarrival time (c_a) are defined by (*2.3*), in which σ_e denotes the standard deviation of the effective process time t_e, and σ_a the standard deviation of the interarrival time t_a.

$$c_\mathrm{e} = \frac{\sigma_\mathrm{e}}{t_\mathrm{e}} \qquad c_\mathrm{a} = \frac{\sigma_\mathrm{a}}{t_\mathrm{a}} \tag{2.3}$$

Using all these factors the waiting time t_q can be computed by a simple but very powerful approximation formula introduced by Kingman (1961), called Kingman's equation (*2.4*):

$$t_\mathrm{q} = t_\mathrm{e} \times \frac{\rho}{(1-\rho)} \times \frac{(c_\mathrm{e}^2 + c_\mathrm{a}^2)}{2} \tag{2.4}$$

In general, this is a good approximation for waiting time in the so-called G/G/1 queuing model, if process and interarrival times are "generally" distributed, i.e., they are specified by mean and standard deviation without any specific information about the distribution.

Furthermore, this formula works particularly well in systems with high utilization.

This model clearly shows that waiting times rise with process time, with average utilization and with variability. First, the longer the service time, the longer the waiting time. Second, with rising average utilization, the utilization factor ($\frac{\rho}{1-\rho}$) increases in a highly nonlinear way. For instance, a utilization of 0.5 leads to a utilization factor of 1, a utilization of 0.8 to a utilization factor of 4. From this follows that a high average utilization has a huge impact on waiting time. Finally, the higher the coefficients of variation, the higher the variability factor and consequently, the higher the waiting time.

Figure 2.1 graphically shows the relationship between average utilization and waiting time for different coefficients of variation. In case of very low variability ($c_{\mathrm{a}} = c_{\mathrm{e}} = 0.5$) the system can be highly utilized, as flow time remains low also with utilization of over 0.9. In case of moderate variability ($c_{\mathrm{a}} = c_{\mathrm{e}} = 1$), reasonable waiting time already occurs with utilization of 0.8, and in systems with high variability ($c_{\mathrm{a}} = c_{\mathrm{e}} = 2$) even a utilization of 0.6 results in very long waiting times.

Processes consisting of various activities can be analyzed by breaking down the process or network into its nodes, regarding every node (activity) as a single queue (Jackson Network - Jackson, 1963). This approach is called node-decomposition, and is the basis for rapid modeling software (Suri et al., 1995). The flow time through the whole process can be calculated by more or less summing up all process times as well as all waiting times (from every node or activity).

For managers it follows that, in the case of high variability, it is not reasonable to maximize average utilization, as flow time will rise exponentially, and customers may have to wait too long. This is somehow counterintuitive and goes against standard management training, which emphasizes increasing resource utilization (de Treville and Van Ackere, 2006).

The *OM triangle*, introduced by Lovejoy (1998) (see *Section 1.1*) is based on the basic queuing model, stating that capacity, inventory and information are substitutes in providing customer service. In particular, the OM-Triangle is obtained by fixing three extreme points on the waiting time curve. *Figure 2.2* shows the three points called the inventory

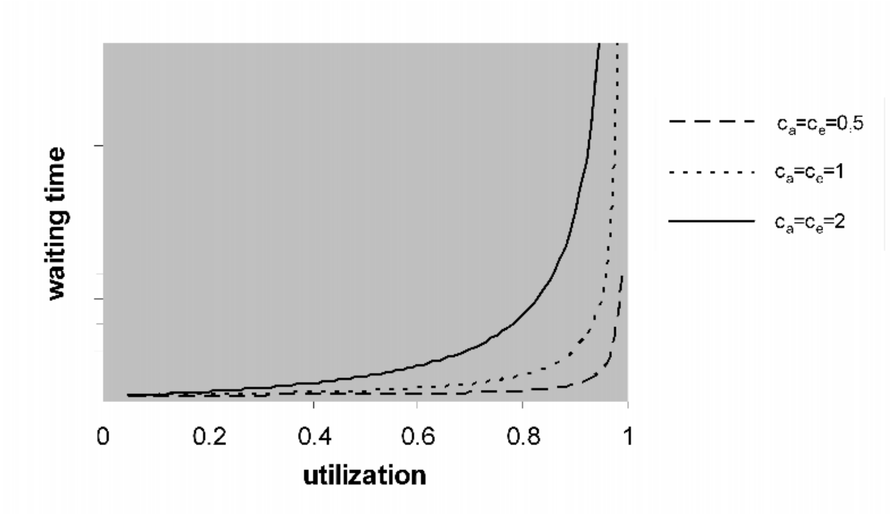

Figure 2.1: Waiting time depending on utilization

point, the capacity point and the information point. In addition to the waiting time, the y-axis displays also inventory. This can be explained by *Little's Law* (Little, 1961), which states that for a stable process (process inflow and outflow rates are identical in the long-run) the inventory (I) in a process (also called Work-in-Process - WIP) depends on the arrival rate (r_a) and on the flow time (T) (*2.5*):

$$I = r_a \times T \tag{2.5}$$

Consequently, in a stable system inventory is directly proportional to the flow time. Therefore, the vertical axis in *Figure 2.2* can both show waiting time and inventory.

These trade-offs between capacity, variability and inventory (referred to as *CVI trade-offs* by Klassen and Menor, 2007) can be captured similar to the approximation formula (*2.4*) by the modified Pollacek-Kintchine formula (Lovejoy, 1998) (*2.6*),

$$I = K \times \frac{\rho}{1-\rho} \times V \tag{2.6}$$

where I is the long-run average inventory, K is a constant, ρ is the long-run average utilization and V is the variability.

Companies running their operations at the capacity point operate at low average utilization to be able to quickly respond to volatile demand. This is especially necessary in

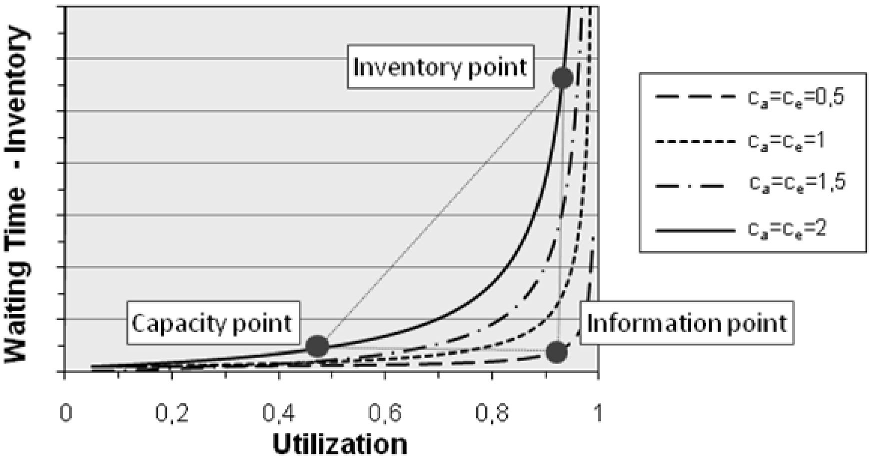

Figure 2.2: OM triangle

service industries like emergency service, where waiting times are critical. Companies with high fixed costs of capacity try to run their operations at nearly 100% utilization, and demand variability is buffered by high inventory. This makes sense for industries with durable products, meaning commodities such as paper, steel or petrochemicals. Finally, companies capable of reducing variability in their operations operate at the information point. The assumption behind this proposition is that by having better information it might be possible to significantly decrease variability, which means that the process can be run at higher utilization without increasing flow time (inventory). The most famous example for this point is Toyota with the lean production approach.

The OM triangle is very useful as a framework to illustrate the different possibilities for designing and managing firm's processes. Clearly, there is no absolutely perfect point. A firm has to decide *where* to operate on the triangle - in other words, *where* on the waiting curve or on which curve (depending on the level of variability). This decision has to take into account customer's expectations, overall corporate strategy, industry, cost structure, and so forth. Anyhow, the less variability in the processes the better the performance. Possibilities for reducing variability in order to improve process efficiency and effectiveness within supply chains are discussed in in the following chapters of this thesis.

The OM triangle is not the only framework in that sense. For instance, Bitran and Morabito (1999) investigate trade-off curves, illustrating the trade-off between Work-in-process (WIP) and capacity investments. They underline the usefulness of such trade-off curves for the evaluation of strategic options as a function of resources required to provide customer service. Similarly, Schwarz (1998) suggests the information/control/buffer (I/C/B) portfolio, linking operations management, technology management, and information system management. Later, this portfolio was extended to the Information/Decision-Making/Implementation/Buffer (IDIB) portfolio (Schwarz, 2005). Empirical evidence for the existence of the trade-offs between capacity, inventory and variability was provided by Klassen and Menor (2007) by examining archival economic data on the industry level.

2.2 Supply Chain Management

The term *Supply Chain Management* (SCM) was initially coined in the early 1980s by consultants (Oliver and Webber, 1992). There is nevertheless no consensus as to the exact meaning of SCM, as there are many different definitions of *supply chain* and *supply chain management*. For the purpose of this study, the definition of Mentzer et al. (2001) has been chosen, who define SCM as “the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole”. Discussions on defining SCM are for instance provided by Croom et al. (2000); Cooper et al. (1997) and Gibson et al. (2005).

Probably one reason for this plethora of definitions is that so many different disciplines have contributed to SCM such as logistics and transportation, operations management, materials and distribution management, marketing, purchasing and information technology (Giunipero et al., 2008). In any case, the relevance and importance for both academics and practitioners is evident (Burgess et al., 2006; Storey et al., 2006; Melnyk et al., 2009; Giunipero et al., 2008).

SCM thinking has been influenced by theories like systems theory, transaction cost economics, game theory, interorganizational relationships and industrial network theories as well as by the virtual organization (Giannakis et al., 2004), and has become now a very rich but still heterogeneous academic field. Recent literature reviews try to address the heterogeneity by suggesting frameworks to better organize all the different approaches and concepts. Such reviews are provided by Burgess et al. (2006); Carter and Ellram (2003); Chen and Paulraj (2004b); Croom et al. (2000); Ganeshan et al. (1999); Giunipero et al. (2008); Kouvelis et al. (2006); Storey et al. (2006) and Tan (2001).

Analyzing these reviews and looking at the popular textbooks of SCM (e.g., Chopra and Meindl, 2007; Simchi-Levi et al., 2008; Fawcett et al., 2007), usually the following topics are covered within SCM: supply chain strategy, supply chain performance, supply chain design, network planning, supply chain contracts, information sharing, demand forecasting, supply chain planning, inventory management, transportation, information technology in supply chains, supply chain risk management, sourcing, and revenue management.

Outsourcing and advances in information technology have been among the reasons for the emergence and development of SCM (Kok and Graves, 2003). The focus on core competencies and the outsourcing of non-core activities (Prahalad and Hamel, 1990) has led to reduced vertical integration, meaning that more companies are involved in producing and delivering a product. Advances in information technology (e.g., Enterprise Resource Planning (ERP) systems, Advanced Planning Systems (APS), etc.) and the internet are also important as necessary data can be better provided and the exchange of information between companies is facilitated (Kok and Graves, 2003).

Another very important driver of the development of SCM was the so-called *Bullwhip Effect*, referring to the phenomenon that order variability increases upstream in the supply chain. This phenomenon, initially described by Forrester (1958, 1961), got really popular with the Beer Game (Sterman, 1989), which is played now in nearly every SCM course. A seminal analysis of the bullwhip effect was provided by Lee et al. (1997a,b, 2004), who identified four different causes for the bullwhip effect: demand signal processing, order batching, prize variations and the rationing game.

The bullwhip effect is the main motivation for collaborating within a supply chain. Many of the collaboration practices in SCM have been developed to reduce the bull-

	Control	
Information	Centralized	Decentralized
Global	e.g., VMI	Base stock policy with full information sharing
Local	Doesn‘t make sense	Classical replenishment policies without information sharing SC contracts

Table 2.1: Information and control (Silver et al., 1998)

whip effect. Popular examples are *Vendor-managed inventory* (VMI) (Disney and Towill, 2003a; Waller et al., 1999; Aviv and Federgruen, 1998) or *Collaborative Planning, Forecasting and Replenishment* (CPFR) (Chopra and Meindl, 2007; Holmstrom et al., 2002; VICS, 2004). Most of these concepts heavily rely on improved exchange (flow) of information, compared to the traditional buyer-supplier interface, where only orders are sent by the buyer and the supplier “simply” has to deliver without any further information.

A convenient way to organize different inventory replenishment strategies according to information and to the type of control is provided by Silver et al. (1998) (see Table 2.1). In terms of control they differentiate between centrally controlled supply chains and supply chains consisting of individual members deciding independently. In terms of information they contrast the cases in which all necessary information (e.g., end-consumer demand, inventory levels) are visible for all members in the supply chain (global information), and in which members do not know anything from other members except the orders of the direct downstream customer (local information). The decentralized case with local information is the traditional buyer-supplier interface where classical replenishment policies are used (e.g., base stock policy). In the case of a decentralized supply chain with global information, all members decide independently but with better results because they know about end-consumer demand, inventory levels, etc. An example for a centrally controlled supply chain with global information is VMI. Clearly, a centrally controlled supply chain with only local information does not make any sense.

2.3 Information Sharing within Supply Chains

Usually, SCM deals with three types of flows, moving upstream and downstream the supply chain: products, funds and information (Chopra and Meindl, 2007). For many concepts and best practices in SCM, the flow (exchange) of information is crucial (e.g., for VMI). In a very general statement Simchi-Levi et al. (2008) notes that abundant information reduces variability, facilitates forecasting, enables coordination, enables retailers to react and adapt to supply problems more rapidly, and enables lead time reduction. As information plays such an important role within supply chain management, information flows and the concept of information sharing are investigated in plenty of studies. Useful frameworks to organize the knowledge of that manner are provided by Huang et al. (2003) and Sahin and Robinson (2002).

Huang et al. (2003) review the literature on sharing production information using a framework consisting of the following dimensions: (1) supply chain structure (serial, divergent, dyadic, convergent or network), (2) level of decision (strategic, tactical or operational), (3) production information (product, process, resource, inventory, order and planning), (4) sharing modes (full/no), (5) dynamics performance index model (metrics to measure the dynamic performance of a supply chain like total cycle time or fill rate), and (6) supply chain dynamics model (mapping between (3) and (5)).

Sahin and Robinson (2002) suggest the following classification schemes to organize the research on information sharing: (1) channel structure (breadth and depth of the supply chain), (2) channel focus (the scope of the integration effort including either the supply side or the distribution side of the manufacturer, or both), (3) research methodology (analytical models, simulation, case study, mathematical programming, empirical analysis), (4) performance metrics (total system costs or profit, individual members' costs, demand variance, and capacity requirements), (5) number of products, (6) demand pattern (stationary, stochastic, and identically distributed among retailers), (7) degree of information sharing (the timing and specific data ranged from only sharing immediate replenishment order to sharing all POS, inventory, and cost data), (8) degree of decision-making coordination (from independent decision-making to fully centralized) and (9) planning horizon

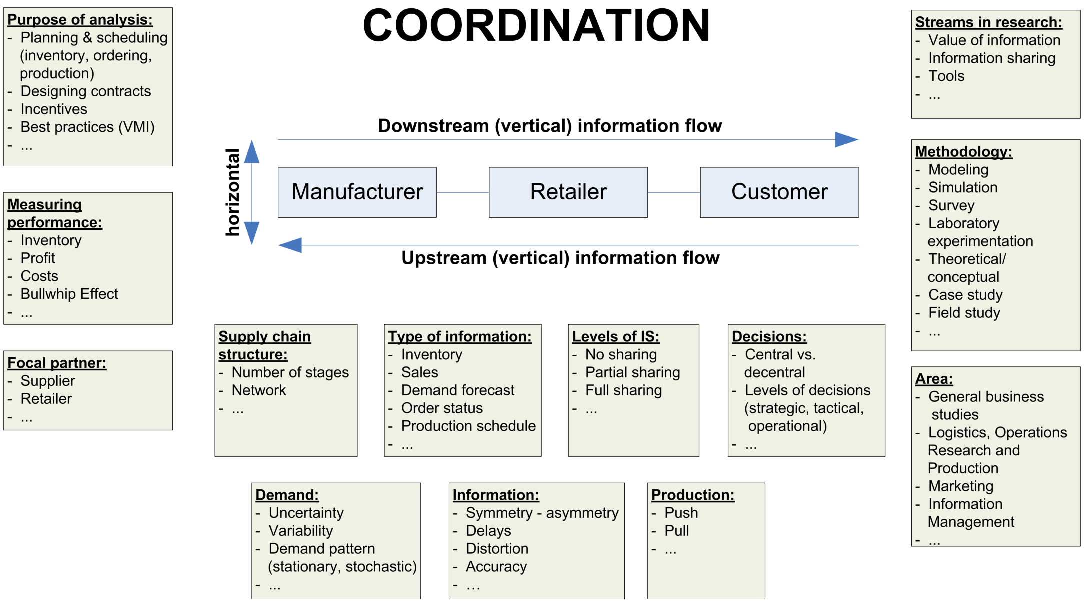

Figure 2.3: Important aspects of information sharing and coordination in supply chains

(infinite and short sales season planning horizon).

Figure 2.3 is inspired by the aforementioned frameworks and shows the main aspects, necessary for the discussion of information sharing. Just in SCM, the literature on information sharing too, is very heterogeneous, as many different fields and areas have contributed. Relevant studies can be found in the areas of general business studies, logistics, operations research and production, marketing, and information management. In terms of research methodology all of the main approaches can be found: modeling, simulation, survey, laboratory experimentation, theoretical/conceptual modeling, case study, and field study (classification according to Pannirselvam et al. (1999)). Furthermore, it is very important for any supply chain analysis to clarify the relevant performance dimensions and the associated performance metrics. These dimensions should be defined through a strategy development process starting from the customer expectations. As mentioned in the introduction (see *Section 1.1*) not only costs are relevant, but also process-related criteria like service level or customer lead time.

Probably the most important aspect within information sharing is the identification of the different types of information, exchanged among supply chain partners. *Table 2.2* shows the types of information shared within supply chains according to Lee and Whang (2000).

Inventory level	...	to avoid holding duplicate safety stock.
Sales	...	to reduce the bullwhip effect.
Order status for tracking/tracing	...	help the customer finding out the status of his order no matter at which stage of the supply chain the order is.
Sales forecast (upstream)	...	to reduce safety inventory as downstream partners have better market knowledge.
Production or delivery schedule	...	to quote more accurate due dates to the customer.
Performance metrics	...	to identify bottlenecks within the supply chain, metrics like product quality, lead times or queuing delays can be shared.
Capacity	...	to avoid shortage gaming (see *Section 2.2*).

Table 2.2: Types of information shared within supply chains (Lee and Whang, 2000)

Another possibility for organizing the different types of information, shared within supply chains, is provided by Li et al. (2006). They differentiate between three levels of information sharing between organizations: transactional, operational and strategic. Transactional information comprises order quantities, prices, sales, product specifications, quality and delivery specifications, among others. Sharing operational information means exchanging data on inventory levels, costs and schedules, production and transportation capacities, lead times, and shipments. Finally, under strategic information they understand point-of-sale (POS) information, real-time demand, understanding of market trends, the things customers value most, and product designs.

Some of this information is more useful when moved upstream in the supply chain and other information when moved downstream. For instance, companies at a stage far downstream of the supply chain have better understanding of end consumer demand and should share this knowledge (forecasts, POS-data) with upstream partners. On the other hand, upstream partners can inform downstream partners about order status, capacity utilization, production schedules or inventory levels. The downstream partner can use this information to quote better due dates and to better organize inventory replenishment. In addition to the more common vertical information sharing (upstream and downstream), horizontal information sharing is also possible between companies at the same stage in the supply chain.

When talking about types of information, quality also plays an important role. According to Forslund (2007) information quality can be captured by the constructs, summarized in *Table 2.3*.

Timeliness	Orders or forecasts arrive in the agreed time - before lead time is frozen or within the planning horizon
Accuracy	Free from obvious mistakes
Convenience	Easy access without further processing
Reliability	The probability that an order or a forecast remains unchanged

Table 2.3: Constructs for measuring information quality (Forslund, 2007)

A more comprehensive overview of information quality is suggested by Miller (1996), listing the following dimensions: relevance, accuracy, timeliness, completeness, coherence, format, accessibility, compatibility, security and validity. Empirical results underlining the importance of information quality are provided by Malhotra et al. (2005) and Wiengarten et al. (2010).

Besides the type and the quality of information also the mode of information sharing is relevant. There are several possibilities between no information sharing (the traditional situation, when just orders are sent without any further information) and full information sharing. Lee and Whang (2000) describe three models of information sharing: the information transfer model (e.g., EDI), the third party model, and the information hub model. In the information transfer model a partner transfers information to the other partner, who maintains the database for decision making. In the third-party model a third party maintains the database and collects information. In the information hub model the third-party is a system.

The greatest challenge of information sharing is the alignment of the incentives of different partners. Trust and cooperation, along with confidentiality, are critical components in a supply chain partnership. The technology is always important for information sharing activities. However, the implementation of a cross-organizational information system is costly, time consuming, and risky. They conclude that information sharing only enables better coordination and planning. Organizations have to develop capabilities to effectively use information. Information becomes the basis for supply chain integration. Nevertheless, full value of information sharing cannot be achieved because of the existing challenges (Lee and Whang, 2000).

Due to the importance of information within SCM, plenty of studies have been published dealing with the value of information and information sharing. A very comprehensive overview of collaboration and information sharing is provided by Chen (2003). He classifies the model-oriented literature into two parts. First, he reviews papers dealing with the value of information within supply chains from the perspective of a central planner trying to "optimize" the whole supply chain. Second, he discusses the papers addressing incentives issues in supply chains consisting of independent firms with private information. Another review provided by Li et al. (2005) compares several models on the value of information. The authors conclude that "information sharing in supply chains is valuable. However, the value and affecting factors are dependent on analytical methods. It would be meaningless simply to compare the numerical values." This means the value or impact of information sharing is not easy to quantify in terms of costs or other performance dimensions.

Ketzenberg et al. (2007) focus their review on information sharing and the value of information in inventory replenishment. Like Li et al. (2005), they also recognize the heterogeneity of results concerning the value of information and come up with a research framework to better explain differences in the literature. They classify and compare the various models on the value of information sharing according to sources of uncertainty and other modeling assumptions like the type of review (periodic or continuous), decision-making (centralized or decentralized), and supply chain structure (serial or distribution). They conclude that their framework represents a starting point for conceptualizing a theory behind the value of information in supply chain management, as it still does not capture the full complexity of relationships between the factors influencing the value of information.

Further reviews are provided by Fiala (2005); Koller (2008); Kulp et al. (2003) and Gunasekaran and Ngai (2004). Further empirical results showing different aspects of information sharing are given by Bailey and Francis (2008); Childerhouse et al. (2003); Kaipia and Hartiala (2006); Kulp et al. (2004); Morishima (1991); Steckel et al. (2004); Yee (2005) and Zhou and Benton Jr. (2007). Overall, it can be stated that information sharing is beneficial, but the benefits or the values differ from case to case.

3 Variability in supply chains

The main purpose of this chapter is to discuss the causes of variability within supply chains. Therefore, general definitions of relevant terms are presented as well as a framework to organize the different types and sources of variability. After presenting the framework the different types are discussed in greater detail. Particular attention is paid to the impact of those types on process performance.

3.1 Definitions

3.1.1 Supply chain uncertainty

First, uncertainty must be clarified. One possibility of defining uncertainty comes from contingency theory, an important stream of organization theory, where uncertainty plays a crucial role. According to Downey and Slocum (1975), uncertainty is "*a state that exists when an individual defines himself as engaging in directed behavior based upon less than complete knowledge* ...". In their paper, they further underline the psychological dimension of uncertainty, as they investigate differences (variance) in perceived uncertainty. A recent discussion of different definitions of uncertainty is presented by Yang et al. (2004b).

When talking about uncertainty, the term risk also comes into the discussion. In recent years supply chain risk management has become very popular. Within that context Sanchez-Rodrigues et al. (2010) state that risk can be regarded as a consequence of uncertainties. Risk can be estimated, as it is a function of outcome and probability, whereas in case of uncertainty it is not possible to estimate the outcome of an event or the probability of its occurrence. According to Collins Dictionary (N.N., 1996; Lalwani et al., 2006) risk is defined as the possibility of bringing about misfortune or loss while uncertainty is associated with those things that are not able to be accurately known or predicted. For Hirshleifer and Riley (1992) risk and uncertainty simply mean the same, as in real-world situations decision makers are almost never in a position to calculate probabilities of objective classifications.

In the context of supply chain management, van der Vorst and Beulens (2002) present a more specific definition of uncertainty: "*Supply chain uncertainty refers to decision making situations in the supply chain in which the decision maker does not know definitely what to decide as he is indistinct about the objectives; lacks information about (or understanding of) the supply chain or its environment; lacks information processing capacities; is unable to accurately predict the impact of possible control actions on supply chain behavior; or, lacks effective control actions (non-controllability).*"

Davis (1993) distinguishes between three main sources of uncertainties within supply chains: suppliers, manufacturing and customers. Geary et al. (2002) added control system as the fourth main source of uncertainty, which transforms customer demand into production plans and supplier orders. A more sophisticated view on sources of uncertainty is provided by van der Vorst and Beulens (2002), differentiating the following three main types of uncertainty:

1. ***Inherent characteristics*** *that cause more or less predictable fluctuations (which have stochastic occurrence patterns). Uncertainty may take the form of high variability in demand, process or supply, which in turn creates problems in planning, scheduling and control that jeopardize delivery performance (Fisher et al., 1997). For instance, food supply chains are especially vulnerable to this type of uncertainty, because of the specific product and process characteristics, such as perishability of end products, variable harvest and production yields and the huge impact of weather conditions on consumer demand.*

2. ***Characteristic features*** *of the chain that result in potential disturbances of system performance (non-optimality):*
    - *chain configuration (e.g., inflexible capacities);*
    - *chain control structure (e.g., wrong decision rules applied);*
    - *chain information system (e.g., information delays); and/or*
    - *chain organization and governance structure (e.g., misjudgment by a decision maker).*

	Quantity aspects	**Quality aspects**	**Time aspects**
Supply	Supply quantity	Supply quality	Supplier lead time
Demand and distribution	Customer demand for product quantities	Customer demand for product specifications	Customer order distribution lead time
Process	Production yield and scrap; write-offs	Produced product quality; product quality after storage	Production throughput times; storing time
Planning and control	Information availability	Information accuracy	Information throughput times

Table 3.1: Typology of decision-making uncertainties according to van der Vorst and Beulens (2002)

3. ***Exogenous phenomena*** *that disturb the system, such as changes in markets, products, technology, competitors and governmental regulations.*

Furthermore, van der Vorst and Beulens (2002) found a typology of decision-making uncertainties currently experienced by decision makers in food supply chains, distinguishing between quantity aspects, quality aspects and time aspects (see *Table 3.1*). Clearly, uncertainty plays an important role within supply chains, but the definition of uncertainty and its various sources or causes still differ among authors. There is a very general, common understanding of the subject matter and its importance, but precise, commonly accepted definitions are missing.

3.1.2 Variability

In any case, in this study we want to focus on variability as it is operationalized in queuing systems and the OM triangle (see *Section 2.1*). Generally, variability means that something is subject to variation or in other words is uneven (lacks uniformity). According to Germain et al. (2008) supply chain variability can be defined as the level of inconsistency in the flow of goods *into* and *out of* the firm, as well as unevenness of production flow times and production output rates. Clearly, this view can be extended easily by adding logistics aspects like transportation times. For instance, if a truck delivers an order from location A to location B, the transportation time will vary from time to time. Even if the truck always takes the same route, transportation time can fluctuate as maybe the weather conditions vary or there is congestion. Thus, transportation time from A to B, as well as the flow times of most of the different activities in a supply chain have to be treated as random variables and not as constants. A random variable is usually described by the mean and a measure of dispersion, like standard deviation, variance, or the coefficient of variation. Clearly, the more aspects of a process have to be regarded as random variables and the higher the variability of these variables, the higher the perceived uncertainty about this process (Lindley, 2006).

Usually, when talking about variability two main types are differentiated: (1) variability due to common causes and (2) variability due to special causes (Swamidass, 2000). Variability due to common causes is also known as natural variation in a process. Common causes are inherent in a process and can only be reduced but never completely removed. Examples of common causes of variation are, for instance, an unsuitable machine, untrained operators, or inherent variability in incoming material from suppliers. The second type of variability arises from special causes. These are causes to which a specific removable reason can be assigned. By getting rid of the reason, this type of variability can be removed. This differentiation is the basis for statistical process control (control charts) (Shewhart, 1931; Ledolter and Burril, 1999).

Similarly, Hopp and Spearman (2007) distinguish between *controllable* variation, arising directly from decisions (e.g., physical dimensions of a product, batch size) and *random* variation, arising from events beyond immediate control (e.g., customer demand, machine breakdowns). Another typology is suggested by Klassen and Menor (2007), shown in *Table 3.2*. They use the dimensions *form* and *source* to organize system variability. Concerning the source of variability they distinguish between internal and external sources, concerning the form of variability between random and predictable.

	Form	
Source	Random	Predictable
Internal (i.e., process)	Quality defects Equipment breakdown Worker absenteeism	Preventative maintenance Setup time Product mix (i.e., number of SKUs)
External (i.e., supply chain)	Arrival of individual customers Transit time for local delivery Quality of incoming supplies	Daily or seasonal cycles of demand Technical support following new product launch Supplier quality improvements based on learning curve

Table 3.2: Typology of sources and forms of system variability (Klassen and Menor, 2007)

Unfortunately, the distinction concerning the form of variability between *random* and *predictable* sometimes causes problems. One could argue that for instance machine breakdowns are also predictable, insofar that production management usually uses historical data to estimate the "*breakdown behavior*" of a machine. Of course, it is however impossible to forecast the exact time, when a machine will break. Concerning outages of machines Hopp and Spearman (2007) therefore suggest a differentiation between *preemptive* and *non-preemptive* outages. Non-preemptive outages are, for instance, stopping the machine for some preventive maintenance activities or for process changeovers (setup). It is up to management to schedule such activities, which are obviously executed between jobs. In contrast, preemptive outages can occur any time and whether we want them to or not. Of course, they can happen also right in the middle of a job. Causes for preemptive outages are, for instance, machine breakdowns, power outages or a lack of material.

Based on these possibilities to organize variability, a slightly different one is suggested for the purpose of this study, extending the typology of Klassen and Menor (2007) (see *Table 3.2*). To classify the different types of variability the dimensions *form* and *source* are redefined.

According to the form of variability, *management control* is suggested, distinguishing between two main groups. First, causes of variability are summarized, which are immediately subject to management control or management decisions, e.g., product mix, using a particular batch size or preventive maintenance. This group is called *variability, due to management decisions*. Second, causes of variability, which cannot be "scheduled" or influenced in the short term, are put together in the group called *variability, due to randomness* (e.g., machine breakdowns). Such causes of variability may only be influenced by management in the long term (strategic decisions), e.g., investing in a new production technology. For instance, management could replace a machine with a more reliable one to reduce machine breakdowns. Causes of variability, which are completely beyond management control are also in this group, like process flow time of activities, executed by humans, as some variation in flow times remain even if operators are perfectly trained and work under perfect conditions. There is always some variability, even in highly automated processes (Hopp and Spearman, 2007).

The different sources of variability are organized by combining the viewpoints of queu-

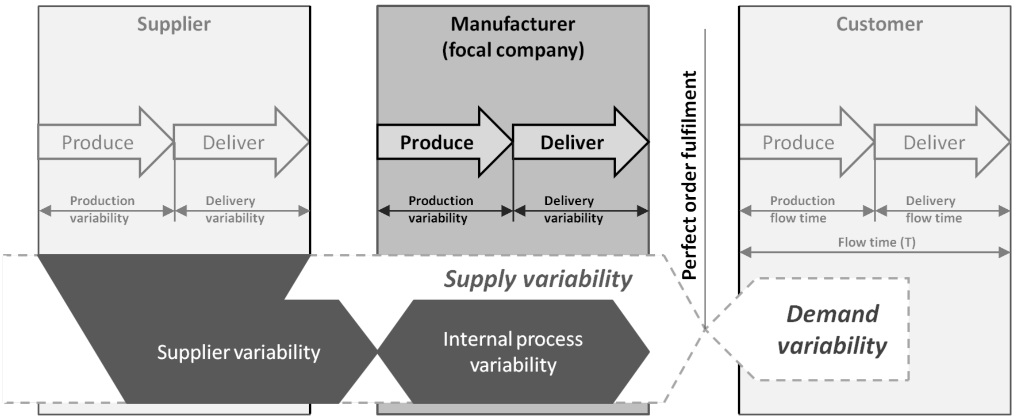

Figure 3.1: Process-oriented variability framework

ing models with the general supply chain model, introduced in *Section 1.3*. Within queuing models usually two types of variability are captured: (1) variability of interarrival times of customers or orders (=demand variability) and (2) variability of service time (=supply variability) (see *Section 2.1*). In *Figure 3.1* this differentiation is used to show that from the viewpoint of the manufacturer both supply and demand variability influence the so-called *perfect order fulfillment* (POF). Perfect order fulfillment means an order delivered (1) in the right quantity, (2) in the right quality (technical specifications) and (3) perfectly on time. Clearly, with rising variability of both demand and supply, achieving POF is becoming more difficult.

Demand variability, meaning the arrival of orders, comes from the order behavior of the customer (e.g., replenishment policy). Supply variability is composed of *internal process variability* and *supplier variability*. Internal process variability can be further divided into the groups (1) variability concerning the manufacturing process, called *production variability*, and (2) variability concerning the delivery process (transportation, etc.), called *delivery variability*. Supplier variability is nothing more than the internal process variability of the supplier, likewise composed of production variability and delivery variability. Therefore, there are no differences between these sources of variability except the fact that the manufacturer has direct control over internal process variability, whereas supplier variability can only be influenced by cooperating with or “helping” the supplier. Clearly, supplier variability may heavily influence manufacturer’s process flow time, when for instance an order cannot be finished on time, because raw material or components were not

	Form	
Source	Variability, due to randomness	Variability, due to management decisions
Demand variability	Arrival of individual customer orders	Product mix (i.e., number of SKUs) Pricing Technological change
Supply variability	Quality defects Equipement breakdown Worker absenteeism Transit time for local delivery Quality of incoming supplies	Preventative maintenance Setup time &Production batch size Transportation batch size

Table 3.3: Supply chain variability framework

delivered on time by the supplier. From the customers viewpoint in this model, supplier variability is the result of both production and delivery variability at all previous stages.

According to these suggested dimensions, *Table 3.3* gives an overview of different forms and sources of variability, which are discussed in the following sections *3.2* and *3.3*. This discussion includes qualitative descriptions as well as possibilities for quantitative evaluation of the various types of variability occurring in supply chains.

3.2 Demand variability

Demand variability is probably the most important and most obvious source of variability. Customer order behavior is mostly very uncertain, difficult to predict and of course much harder to influence than production variability. Nevertheless, there are strategies and possibilities for addressing the different types of demand variability. The most famous model with respect to "tailoring" a supply chain according to demand characteristics was provided by Fisher (1997). He suggested two main types of supply chains (efficient and responsive - see. *Section 1.1*), mainly based on the differentiation between functional and innovative products, which show different demand characteristics.

Compared with innovative products, functional products usually have a more stable, more predictable demand, longer product life cycles, lower product variety, lower contribution margins, less stock-outs, low stock-out costs, higher volume per SKU (stock keeping unit), no markdowns (discount at the end of the selling season) and low obsolescence. In contrast, innovative products usually have unstable, difficult to predict demand, short product life cycles, greater product variety, higher contribution margins, more stock-outs, higher stock-out costs, lower volume per SKU, more markdowns and higher obsolescence (Fisher, 1997; Lee, 2002).

This differentiation gives a good overview of aspects concerning demand. In the following these aspects are discussed with respect to the suggested framework of this study, classifying demand variability due to randomness as well as variability due to management decisions. The former mainly discusses the various reasons for fluctuating demand (e.g., replenishment policies), and the latter explains cases when demand variability is induced by the manufacturer, for instance, by its product portfolio consisting of many different product variants.

3.2.1 Demand variability, due to randomness

Within classical B2B relationships the manufacturer gets orders from his direct customer and delivers the products, without any further information shared. Consequently, the manufacturer has to be prepared to fulfill uncertain customer demand. In such a situation planning activities are based on forecasting. This is true for MTS-manufacturers as well as for MTO-manufacturers. The difference between these two types is just the buffer, used to hedge against demand uncertainty, as the former has mainly to determine the dimension of safety inventory of finished goods and the latter mainly of safety capacity (machinery, staff). Clearly, both have to hold raw material inventory (RMI).

Therefore, it is essential for any manufacturer to use forecasting methods which predict future demand as well as possible. Unless there is no further information or cooperation possible, forecasting tries to understand past demand by identifying the influencing factors and quantifying their impact. If past demand could have been explained by a set of influencing variables, the probability is high, that future demand can be predicted with reference to these influencing factors.

In any case, even with the best or perfect forecasting method some uncertainty remains, thus leading to the most important law of forecasting: “Forecasts are always wrong” (Hopp and Spearman, 2007). Consequently, the main goal of forecasting is to minimize the forecast error, i.e., the difference between the predicted and the real value (e.g., order quantity). Clearly, the smaller the forecast error, the better inventories as well as capacities can be adjusted to match supply with demand.

Forecast methods can be classified in (1) qualitative forecasting and (2) quantitative forecasting. Approaches belonging to the former group are used if historical data is not available (e.g., new products) and attempt to predict future demand by using the knowledge of experts. Examples for this group are the Delphi method (opinion consensus of a group of experts, see Dalkey and Helmer (1963)) or judgmental forecasting (Gaur et al., 2007).

In a B2B environment, more frequently dealing with functional goods, mathematical (quantitative) models are used, as historical data is available. There are two groups of models: (1) causal models (regression) and (2) time series models. Causal models try to predict demand for a particular product as a function of *other* parameters (e.g., average temperature, growth of GDP). Time series models try to predict future demand as a function of past demand (past values of the *same* parameter). In practice time series forecasting is probably the most relevant.

According to Silver et al. (1998) any time series is composed of five components: (1) level, (2) trend, (3) seasonal variation, (4) cyclical movements and (5) irregular random fluctuations. These components can be used to describe a demand time series. *Level* captures the amount of demand. If there is no other pattern than the level, demand is constant over time. *Trend* denotes the growth or decline of a series over time. *Seasonal variation* refers to a periodic variation of a fairly constant shape (e.g., increase of demand for mineral water during summer). The period explaining this repetitive behavior can be, for instance, a year, a month, or a week. *Cyclical variations* capture increases or decreases due to business cycles. Business cycles usually last several years, whereby the relevance for short and medium term operations and production planning is limited. *Irregular fluctuations* represent the remaining fluctuation after identifying the effects of the other four components.

Practically, the manufacturer tries to forecast demand (orders of direct customers) to be able to purchase raw material and components, especially for parts with long delivery

	Order quantity	
Review	fixed	variable
periodic	R, Q	R, S
continuous	s, Q	s, S

Table 3.4: Replenishment policies

lead times, as well as to determine the capacity of its production facilities. This means that in most of the cases the manufacturer places orders with his suppliers just based on forecasts, using some replenishment policy.

The orders received by the manufacturer are usually the result of a replenishment policy. Replenishment policies give answers to the following questions (Silver et al., 1998):

1. How often should the inventory status be determined?
2. When should a replenishment order be placed?
3. How large should the replenishment order be?

The first question is addressed by differentiating between continuous and periodic review systems. Continuous review means that the inventory level is always known, which requires monitoring and immediate updating of the inventory level after every inflow or outflow. Periodic review means that the inventory level is only determined at fixed time intervals. Questions two and three are resolved by the replenishment policy (inventory control policy). *Table 3.4* shows the four main replenishment policies using the dimensions review and order quantity.

The R,Q-policy means that after a fixed period of time (R) a fixed quantity (Q) is ordered. Using the R,S-policy, also called order-up-to-policy or base stock policy, after the fixed review period (R) the inventory level is determined and then enough is ordered to raise the inventory level up to the level S, called order-up-to-level. Using the s,Q-policy a fixed quantity (Q) is order when the continuously monitored inventory level drops to the reorder level (s), also called the reorder point. The s,S-policy means that the inventory level is continuously monitored. As soon as the inventory level drops to or below the reorder point (s) enough is ordered to raise inventory to the order-up-to-level (S).

Assuming that the customer uses one of these policies to replenish his inventory, the manufacturer faces orders according to this policy. Further, it is important to know whether there is only one customer ordering a particular product or multiple customers. Generally, in a B2B environment it should easier to to get at least some additional demand information compared to retailers, serving the mass of end consumers.

3.2.2 Demand variability, due to management decisions

A very important source of variability is the product portfolio. Clearly, the more products and the more product variety, the higher the variability. If product variety is an important success factor in a particular industry, companies have to provide products in greater variety to earn money. In such a case, it is, of course, more important to design products and processes according to these customer expectations (product variety is order winner or at least order qualifier) than to minimize variability. Therefore, offering greater product variety can be regarded as “good” variability (Hopp and Spearman, 2007).

A famous example from the early days of customization is the automotive industry. At the beginning of the 20th century the pioneer of the assembly line, Henry Ford, offered cars with any desired color as long as it was *black*. This offer was an extreme reduction of variability by restricting product variety, making his manufacturing process very efficient and thereby the cars affordable to the mass. However, in the 1930s and 1940s General Motors took over much of the market share of Ford by offering greater product variety (e.g., more colors than just black). By introducing higher variability GM could not produce as efficiently as Ford, but could increase its revenues to such an extent that the additional costs were offset (Hopp and Spearman, 2007).

Therefore, it is important to know that product variety is an important cause of variability, but a possible reduction has to be in line the firm’s business and operations strategy. If product variety is crucial for the company’s success, it should not be reduced just to reduce variability, as the main purpose of a company is to earn money and not to reduce variability.

A second important aspect concerning the product portfolio is the rate at which new products are launched. In industries like for instance consumer electronics it is necessary to introduce new products rapidly to be successful in the market. This leads to very short product life cycles and the need for well-defined and short product development processes. Detailed discussions with respect to time-to-market and related trade-offs are provided by Cohen et al. (1996) and Carrillo and Franza (2006). Generally, it can be stated that the greater the product variety and the more frequent new products (or new variations of a product) are introduced, the higher the variability.

Finally, pricing has to be mentioned as a main source of variability. If the manufacturer uses discounts, demand variability is induced which does not correspond to end consumer demand. This is one major reason for the bullwhip effect, discussed in the following *Section 3.2.3*. Generally, the more volatile prices the worse for the demand variability.

3.2.3 Bullwhip effect

The *Bullwhip Effect* refers to the phenomenon that demand variability increases upstream in the supply chain, and is one of the main drivers for the development of supply chain management (see *Section 2.2*). The main reasons for the bullwhip effect are (Lee et al., 1997b,a):

- *Demand signal processing* - Even small changes in the demands of the direct customer (compared to the forecast) are interpreted as increasing (decreasing) future demand, leading to immediate adjustments of order quantities with the supplier. Possible counter measures are: Sharing point-of-sale Data (POS), single control of replenishment, lead time reduction, collaborative forecasting.

- *Order batching* - Order batching means that customer demand is not passed on to the the supplier immediately but is consolidated by using replenishment policies. One important driver for using larger order batches are the fixed order costs. Clearly, the larger the order quantity the less frequent a company has to order and the lower the overall order costs. Possible counter measures: Electronic Data Interchange (EDI), consolidation by 3rd party logistics, regular delivery appointment.

- *Prize variations* - Changing prizes within a supply chain increases the bullwhip effect, as additional demand fluctuations are induced, which are not related to end-consumer demand. Possible counter measures: Every-day-low-prize (EDLP) strategy, long-term contracts.
- *The rationing game* - When a manufacturer has limited capacity and starts rationing production output among customers, the customers start to order more, because they observe or know that they can only get a particular percentage of the ordered quantity. Possible counter measures: allocation according to past sales, shared capacity and supply information, and limited flexibility of order quantities over time.

The bullwhip effect has been studied intensively over the last decade. For instance, Chen et al. (2000) investigates the dependencies between forecasting and lead times in a simple supply chain. Boute et al. (2007) show how the bullwhip effect could be dampened for a two-echelon supply chain. Hosoda and Disney (2006) analyze the variance amplification in a three-echelon supply chain model under the assumption of a first-order autoregressive consumer demand. Motivated by this research Reiner and Fichtinger (2009) investigate the influence of demand modeling on supply chain process performance by comparing different demand forecasting models. There are also several studies providing empirical evidence for the existence of the bullwhip effect, e.g., Baganha and Cohen (1998); P. Cachon et al. (2007); Lee and Whang (2006) and Metters (1997). Recent reviews concerning the bullwhip effect were written by Geary et al. (2006); Lee et al. (2004) and Miragliotta (2006).

When talking about the bullwhip effect it is, of course, also necessary to quantify this important effect. The measurement of the bullwhip effect is discussed in several papers, e.g., Fransoo and Wouters (2000); Dejonckheere et al. (2003); Disney and Towill (2003c); Kim et al. (2006); Warburton (2004). A commonly used way to calculate a performance metric representing the bullwhip effect (B) at a particular stage in the supply chain is to divide the coefficient of variation of the outgoing orders (with the supplier) by the incoming orders from the customer (demand) (see *3.1*) (Fransoo and Wouters, 2000).

$$B = \frac{c_{out}}{c_{in}} = \frac{\frac{\sigma_{out}}{d_{out}}}{\frac{\sigma_{in}}{d_{in}}} \tag{3.1}$$

The variables d_{in} and d_{out} denote the average incoming and outgoing demand and σ_{in} and σ_{out} their respective standard deviations. If B of a particular stage in the supply chain has a value above one, this stage contributes to bullwhip effect, as it shows that the variability is increased by this stage.

Further, Fransoo and Wouters (2000) mention three main issues, which have to be considered through the course of bullwhip calculations. First, it has to be clarified to which extent data are aggregated. For instance, if POS-data are aggregated into daily or weekly demand, analysis is restricted, compared to hourly data. Second, by just calculating the above mentioned ratio it is not possible to identify to which extent different causes contribute to the bullwhip effect. Third, decisions on disaggregating data are as important as their aggregation. Disaggregating means, for instance, separating demand from different customers.

Generally, the bullwhip effect is an important aspect of demand variability within a supply chain. Concerning the general supply chain model of this study, the demand variability the manufacturer faces is to some extent due to the bullwhip effect. From the general definition it follows that the far more upstream the manufacturer in the supply chain the higher demand variability. Moreover, reducing the bullwhip effect means reducing variability and therefore comprises an important set of actions within the targets of this study. A detailed discussion of actions to reduce the bullwhip effect and thereby demand variability is provided in *Section 4*.

3.3 Supply variability

Supply variability, as already mentioned above, comprises all sources of variability coming from the internal production process as well from the upstream supply chain (supplier variability). To capture supply variability (uncertainty) within supply chains Lee (2002) extended *Fisher's* model (Fisher, 1997) by adding two types of supply. He differentiates between *stable* and *evolving* supply. Stable supply means that all processes are mature and well established, whereas evolving supply refers to processes which are under early development and are rapidly changing.

Stable supply is characterized by fewer breakdowns, stable and higher yields, fewer quality problems, more supply sources, reliable suppliers, fewer process changes, fewer capacity constraints, more flexibility (easier to change over) and a more dependable delivery flow time. Evolving supply is characterized by higher vulnerability to breakdowns, variable and lower yields, potential quality problems, limited supply sources, unreliable suppliers, more process changes, potential capacity constraints, inflexible (difficult to change over) and variable delivery flow time (Lee, 2002).

In the following two sections supply variability is discussed in further detail using again the differentiation between *randomness* and *management decisions*, where the former group stands for unplanned interruptions and the latter for intentionally scheduled interruptions. To capture supply variability quantitatively the mean effective process time (t_e) as well as the variance (σ_e^2) and the squared coefficient of variation (c_e^2) of the effective process time are used (see *Section 2.1*).

3.3.1 Supply variability, due to randomness

This group of variability captures unplanned downtimes of resources and quality problems. Downtime represents the times when the production process is not producing anything. Such disruptions like machine breakdowns can (and mostly do) happen in the middle of a job, whereas for example setups or preventative maintenance activities are done between jobs (see *Section 3.3.2*). Quality problems comprises uncertain yield rate (scrap) and rework.

Unplanned downtime of resources

Possible causes for unplanned resource downtimes are machine breakdowns, electrical power outage, worker absenteeism and running out of raw materials, components or operating material. Downtimes of the bottleneck station impact process performance in two ways: (1) process capacity is reduced and (2) variability is increased. Both effects lead to longer waiting times and process flow times (see *Section 2.1*).

Downtime behavior of a machine is usually captured by the availability (A), composed of two metrics. First, *mean time to failure* (m_f), which captures the time a machine is running between two breakdowns (=uptime) and second, *mean time to repair* (m_r), which stands for the time necessary to repair the machine (=downtime). (*3.2*) shows that the availability (A) is the proportion of the uptime in the available production time (uptime+downtime), and has values between zero and one.

$$A = \frac{m_f}{m_f + m_r} \tag{3.2}$$

Clearly, the lower the availability of a machine the lower its capacity. If this machine is the bottleneck, capacity of the whole process is reduced, as the process capacity is determined by the bottleneck capacity. (*3.3*) shows the reduction affect of the availability on the capacity (flow rate).

$$r_e = A r_0 \tag{3.3}$$

As the capacity is the reciprocal value of the process time, the effective process time t_e is, of course, also affected by the availability (*3.4*):

$$t_e = \frac{1}{r_e} = \frac{t_0}{A} \tag{3.4}$$

In addition to the obvious impact on capacity, downtimes also affect the variability. (*3.5*) and (*3.6*) (Hopp and Spearman, 2007) quantify the impact of downtime behavior on the variability of mean effective process time by means of σ_e^2 (variance of mean effective process time) and c_e^2 (squared coefficient of variation).

$$\sigma_e^2 = \left(\frac{\sigma_0}{A}\right)^2 + \frac{(m_r^2 + \sigma_r^2)(1-A)t_0}{A m_r} \tag{3.5}$$

$$c_e^2 = \frac{\sigma_e^2}{t_e^2} = c_0^2 + A(1-A)\frac{m_r}{t_0} + c_r^2 A(1-A)\frac{m_r}{t_0} \tag{3.6}$$

Both equations start with the natural variability, representing the portion of variability which cannot be explained (σ_0^2), and express the increasing effect of downtimes. In addition to the already explained variables the variance of the repair time is also used (σ_r^2), capturing the fact that different amounts of time could be required to put the machine back into operation. In the case of preventive maintenance activities executed on a regular basis and usually lasting equally long σ_r^2 is zero (see *Section 3.3.2*). Generally, the variability of the mean effective process time increases with decreased availability (A), increased repair time (m_r) and increased variability of the repair time (σ_r^2). Consequently, three main measures can be derived to reduce variability induced by downtimes:

1. The frequency of downtimes should be reduced to increase availability (m_f should be increased).
2. Independent from availability, repair times should be reduced → short, more frequent downtimes are less harmful than long, less frequent downtimes.
3. Variability of downtimes should be reduced.

Quality problems

A major issue in operations are losses due to quality problems. Usually such losses are described by the scrap rate or rework rate. Those rates capture the proportion of parts which are defective after a particular stage in the process (machine). In the case of rework perhaps only this task has to be repeated, whereas in case of scrap the part cannot be corrected or repaired and has to be processed from the beginning of the process. Thus, scrap is the worst form of rework. Generally, defective parts in case of rework or new parts in case of scrap have to be processed again, meaning that the resource is used without producing additional output. In other words, scrap or rework reduce capacity of the resource, leading to longer production flow times. This obvious effect is further increased by the variability induced by rework.

To quantitatively capture these effects Hopp and Spearman (2007) present equations for mean effective process time (t_e) and its variability (σ_e^2, c_e^2), based on the rework rate

α, to measure the probability that a particular part is defective. In some processes (e.g., pharmaceutical industry) the yield rate is measured instead of the scrap or rework rate, which is nothing more than the proportion of production which is not defective (see *3.7*).

$$\text{Yield rate} = 1 - \alpha \tag{3.7}$$

(*3.8*) and (*3.9*) show that an increasing rework rate (α) leads to a longer mean effective process time (t_e) and to a lower capacity (r_e). For instance, if the rework rate is 10% the capacity of the resouce is reduced by that 10% ($r_e = r_0 \times 0,9$).

$$t_e = \frac{t_0}{1-\alpha} \tag{3.8}$$

$$r_e = \frac{1}{t_e} = \frac{1-\alpha}{t_0} = r_0(1-\alpha) \tag{3.9}$$

In addition to the impact on capacity also variability is affected by rework. (*3.10*) and (*3.11*) show the impact of rework rate α on σ_e^2 and c_e^2.

$$\sigma_e^2 = \frac{\sigma_0^2}{1-\alpha} + \frac{\alpha t_0^2}{(1-\alpha)^2} \tag{3.10}$$

$$c_e^2 = \frac{\sigma_e^2}{t_e^2} = \frac{(1-\alpha)\sigma_0^2 + \alpha t_0^2}{t_0^2} = c_0^2(1-\alpha) + \alpha \tag{3.11}$$

From (*3.10*) it follows that the variance of the mean effective process time (σ_e^2) rises with an increased rework rate. Concerning the squared coefficient of variation (c_e^2) the impact of rework rate α is not that clear, because c_e^2 may either increase or decrease with rework rate, depending on the natural variability (Hopp and Spearman, 2007). With regard to flow time this effect is negligible, as the utilization is always increased by increasing rework, which has a more substantial impact on waiting time than a slightly reduced coefficient of variation. Generally, rework impacts both capacity and variability and thereby decreases process performance in terms of reduced process capacity and longer average flow time.

Consequently, rework and scrap should be reduced as much as possible, using quality management programs like *Total Quality Management* (TQM) (for a review see Hackman and Wageman, 1995) or *Six Sigma* (Schroeder et al., 2008), or should be even avoided by smart product and process development, like *Quality Function Deployment* (Hauser and Clausing, 1988) or *Robust Design* (Taguchi and Clausing, 1990). The remaining rework can be handled with additional rework stations or lines. In case of scrap job size inflation is used to make up for scrap. For instance, if a customer requires 180 pieces of a particular product and the scrap rate is 10% the internal order is calculated by dividing the external order by the yield rate (*3.12*).

$$\text{Internal job size} = \frac{\text{External order}}{\text{Yield rate}} = \frac{180}{0.9} = 200 \tag{3.12}$$

If 200 pieces are produced, the manufacturer can be sure that there will be enough parts to fulfill the customer order. Of course, this is only a good solution, if the scrap rate is constant. In case of varying scrap rates (yield rates) this strategy does not necessarily secure customer service. For example, if a particular stage has either 100% or 0% yield (e.g., pharmaceutical or chemical process), job size inflation, of course, does not make any sense, as either lots of inventory is produced (50% over production in case of 100% yield) or lots of scrap is produced (150% scrap in case of 0% yield). In such a case only the safety inventory of "good" products maintains customer service (Hopp and Spearman, 2007). Therefore, with variable scrap or rework rates it is even more important to reduce or eliminate scrap and rework in the long term.

OEE: Overall equipment effectiveness

A commonly used performance metric to address downtime and quality losses is the *overall equipment effectiveness* (OEE), introduced within the concept of total productive maintenance. The main purpose of OEE is to monitor manufacturing operations concerning the total equipment performance to enable the avoidance or reduction of losses (Nakajima, 1988). In their recent review Muchiri and Pintelon (2008) explain the main building blocks of OEE, discuss its advantages and shortcomings and introduce some extensions.

Generally, OEE combines availability (A), speed (S) and quality rate (Q) to one performance metric (*3.13*).

$$OEE = A \times S \times Q \tag{3.13}$$

Availability is defined as the proportion of the uptime in the available production time (see *3.2*). Speed captures to which extent the maximum production rate is used. For instance, a machine could be operated at a rate of 100 units per hour, but actually, for some reasons, the machine is run with just a rate of 80 units per hour, resulting in a performance rate of $S = 0.8$. Quality rate is the same as yield rate and is the complementary probability of the rework rate (see *3.7*). The multiplicative relationship shows that even relatively small individual loss rates result in larger overall loss. For instance, if all three variables have a value of 95%, meaning that there is a 5%-loss due to downtime, a 5%-loss due to speed reduction and a 5%-loss due to scrap or rework, the OEE has a value of 85.74%. This means the overall loss of nearly 15%!

Unfortunately, by concentrating on just the OEE, only the capacity effect of downtimes, speed loss and scrap is dealt with, but their impact on variability and thereby on average flow time is ignored. This is problematic as machines with equal availability can induce different extents of variability. For instance, a machine with downtimes every 19 hours (m_{f1}) for one hour (m_{r1}) has the same availability of 0.95 as a machine with downtimes every 95 hours (m_{f1}) for 5 hours (m_{r1}). From a capacity point of view both machines are equally good (bad?), but in terms of variability there is a considerable difference. To show this difference it is assumed that both machines have an equal mean natural process time (t_0) of six minutes (0,1 hours) with a standard deviation of 6 minutes (σ_0). Consequently, the squared coefficient of variation of the natural process time (c_0^2) is 1. The squared coefficient of variation of the repair time (c_r^2) is assumed to be one for both machines.

Based on (*3.6*), calculations *3.14* and *3.15* show that the machine with shorter, but more frequent interruptions has a much lower squared coefficient of variation of the mean effective process time than the machine with longer but less frequent outages.

$$c_{e1}^2 = 1+0,95(0,05)\frac{1}{0,1}+1\times 0,95(0,05)\frac{1}{0,1} = 1,95 \tag{3.14}$$

$$c_{e2}^2 = 1+0,95(0,05)\frac{5}{0,1}+1\times 0,95(0,05)\frac{5}{0,1} = 5,75 \tag{3.15}$$

Accordingly, the variability factor, necessary to compute the expected waiting time (*2.4*), is different for both machines (see *3.16* and *3.17*):

$$V_1 = \frac{c_a^2+c_{e1}^2}{2} = \frac{1+1,95}{2} = 1,475 \tag{3.16}$$

$$V_2 = \frac{c_a^2+c_{e2}^2}{2} = \frac{1+5,75}{2} = 3,375 \tag{3.17}$$

For this example the expected waiting time of machine two is more than double of machine one, just because of the variability induced by the different downtime behaviors of the machines.

Generally, supply variability due to randomness, mainly represented by machine breakdowns and quality problems, can lead to substantial worsening of process performance. Making processes more robust and reliable is a major lever for improving performance, dealt with in *Section 4.* As mentioned above, all these causes and sources of variability concern both the internal process variability as well as the supplier variability.

3.3.2 Supply variability due to management decisions

This group of variability captures interruptions which can be controlled by management, i.e, planned downtimes of resources and setups. These interruptions also reduce capacity and increase variability, but are usually not that harmful, as they are scheduled between jobs and do not happen unexpectedly in the middle of a job.

Planned downtime of resources - Preventive maintenance

In *Section 3.3.1* it was shown that from the variability point of view it is much better to have more frequent but shorter interruptions than less frequent but longer ones (for equal availability). Accordingly, it is better to stop a machine on a regular basis for short maintenance activities to avoid longer, randomly occurring outages.

To show the quantitative effect of preventive maintenance activities on process performance the example from *Section 3.3.1* is used again with slightly adjusted assumptions. First, only one machine is analyzed concerning its maintenance plan. Without any preventive maintenance activities the mean time to failure (m_f) is 95 hours and the mean time to repair (m_r) is five hours, with a coefficient of variation (c_r) of 1. Alternatively, a maintenance plan is introduced, whereby the machine is stopped after every 19 hours of operation ($m_{f,m}$) for exactly one hour ($m_{r,m}$), meaning that the coefficient of variation of the repair time ($c_{r,m}$) is zero. As the numbers concerning the availability are the same as in the example with the two machines, both strategies lead to an availability of 0.95. However, with regard to variability, the difference between the two strategies is higher than in the previous example.

(*3.18*) and (*3.19*) show that preventive maintenance strategy leads to a much lower squared coefficient of variation of the mean effective process time, mainly because of the fact that the variability of the repair time is zero.

$$c_e^2 = 1+0.95(0,05)\frac{5}{0.1}+1\times 0.95(0.05)\frac{5}{0.1}=5.75 \tag{3.18}$$

$$c_{e,m}^2 = 1+0.95(0.05)\frac{1}{0.1}+\mathbf{0}\times 0.95(0.05)\frac{1}{0.1}=1.475 \tag{3.19}$$

Accordingly, the variability factor for the case with preventive maintenance (V_m) is even lower than in the example above (see *3.20* and *3.21*):

$$V = \frac{c_a^2+c_e^2}{2}=\frac{1+5.75}{2}=3.375 \tag{3.20}$$

$$V_m = \frac{c_a^2+c_{e,m}^2}{2}=\frac{1+1.475}{2}=1.238 \tag{3.21}$$

Therefore, preventive maintenance leads to shorter flow times, as the variability factor is reduced (where availability is equal).

Variability through batching

Producing in batches is necessary if different products are produced on the same work station and a setup is necessary to switch between the products. Batching is an important cause of variability and obviously influences flow time through a process. In processes using batching in a way that only complete batches are passed on to the next station, calculating flow time per part does not make sense. To know when a part is ready for the next station the flow time T_b of a batch has to be calculated, because every part of a batch has to wait until the last part of the batch is finished. Flow time of a batch T_b (customer order) is the sum of the waiting time t_q, the setup time t_s, the wait-in-batch time t_qb and the process time per part t_0 (3.22) (Hopp and Spearman, 2007).

$$T_\mathrm{b} = t_\mathrm{q} + t_\mathrm{s} + t_\mathrm{qb} + t_0 \tag{3.22}$$

Setup time t_s and process time per part t_0 are independent from batch size, but waiting time t_q and wait-in-batch time t_qb depend on batch size.

As already shown (see *Section 2.1*), t_q is mainly determined by process time, utilization and variability. Batching influences utilization by its impact on average capacity of a station r_e. Equations 3.23 and 3.24 (Hopp and Spearman, 2007) show for a given setup time t_s that the lower the batch size N_s the higher the mean effective process time t_e per part, and consequently, the lower average capacity (flow rate) r_e.

$$t_\mathrm{e} = t_0 + \frac{t_\mathrm{s}}{N_\mathrm{s}} \tag{3.23}$$

$$r_\mathrm{e} = \frac{1}{t_\mathrm{e}} \tag{3.24}$$

For given arrival rate r_a, decreased capacity r_e leads to higher utilization ρ and thus to a longer waiting time t_{q} (see *2.4*). Utilization ρ for a batch process is defined by (3.25).

$$\rho = r_{\mathrm{a}} t_{\mathrm{e}} = r_{\mathrm{a}} \left(t_0 + \frac{t_{\mathrm{s}}}{N_{\mathrm{s}}} \right) = \frac{r_{\mathrm{a}}}{N_{\mathrm{s}}} (N_{\mathrm{s}} t_0 + t_{\mathrm{s}}) \tag{3.25}$$

Batching also influences t_{q} because it induces process variability. (*3.26*) and (*3.27*) (Hopp and Spearman, 2007) show the impact of batch size N_{s} and setup time t_{s} on the variance of mean effective process time σ_{e}^2, and on squared coefficient of variation c_{e}^2. Clearly, in the case of longer setup times a rising batch size decreases the squared coefficient of variation c_{e}^2, as less setups are executed.

$$\sigma_{\mathrm{e}}^2 = \sigma_0^2 + \frac{\sigma_{\mathrm{s}}^2}{N_{\mathrm{s}}} + \frac{N_{\mathrm{s}} - 1}{N_{\mathrm{s}}^2} t_{\mathrm{s}}^2 \tag{3.26}$$

$$c_{\mathrm{e}}^2 = \frac{\sigma_{\mathrm{e}}^2}{t_{\mathrm{e}}^2} \tag{3.27}$$

Consequently, from utilization point of view and also from variability point of view, batch sizes should be as high as possible to minimize average waiting time t_{q}.

Unfortunately, the second parameter of average flow time, affected by batch size, i.e., wait-in-batch time t_{qb}, reacts the other way around, as it rises with increasing batch size (3.28).

$$t_{\mathrm{qb}} = (N_{\mathrm{s}} - 1) t_0 \tag{3.28}$$

Therefore it is necessary to calculate a somehow “optimal” batch size, which minimizes average flow time T_{b}. *Figure 3.2* shows the factors described above. Setup time and process time are independent of the batch size and remain constant. Waiting time (for resources) first sharply decreases with batch size and then slightly increases (due to the impact of batch size on the coefficient of variation – see (3.26)), and wait-in-batch time increases linearly with batch size. These factors lead to the average flow time having this particular shape, with first a sharp decrease and afterwards a nearly linear increase.

From that it follows that first a minimum batch size is necessary to be able to produce the requested demand at all, i.e., having a utilization below 1. As soon as there is enough capacity, flow time rises nearly proportionally with batch size. Consequently, it is not

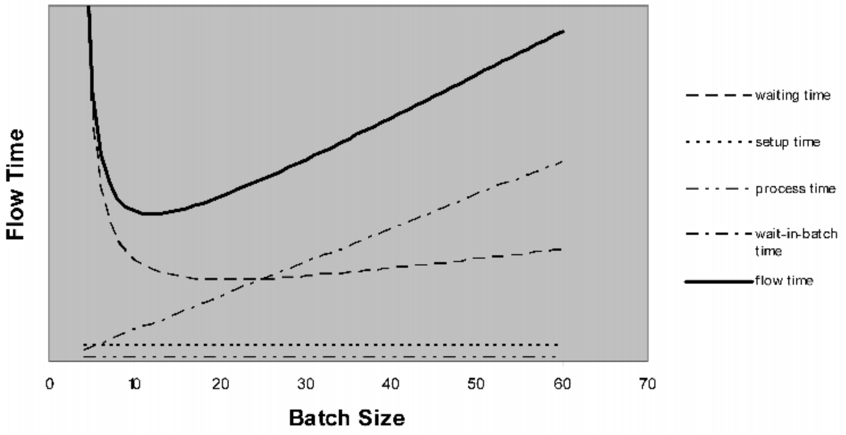

Figure 3.2: Process performance measures depending on batch size

easy to intuitively generate an appropriate batch size for a longer production process or a production network, consisting of several work stations with various routings.

3.3.3 Supplier variability

As already mentioned, all these types of supply variability can appear both at the manufacturer and at previous stages in the supply chain, leading to reduced capacity and longer flow times. In addition, supplier variability is also affected by aspects discussed in the demand variability section (see Section 3.2), namely the replenishment policies used by the manufacturer to place orders with its suppliers. *Figure 3.3* shows that a perfect order fulfillment (POF) between the supplier and the manufacturer also depends of course on the demand the supplier faces from the manufacturer. The orders the manufacturer places with its supplier are derived, of course, from the demand the manufacturer faces, but also from the delivery flow time of the supplier. The more variable the delivery flow time of the supplier, the higher the safety stock in the raw material inventory (Silver et al., 1998). Thus, the supplier indirectly influences the order behavior of the manufacturer.

Within the general supply chain model of this study for any stage in the supply chains two main activities are distinguished: produce and deliver. The different sources and causes of supply variability in this section are mainly explained by means of examples from manufacturing. Of course, all these types can be applied to delivery activities like transportation or cargo handling. For instance, a truck can be broken or is delayed by road

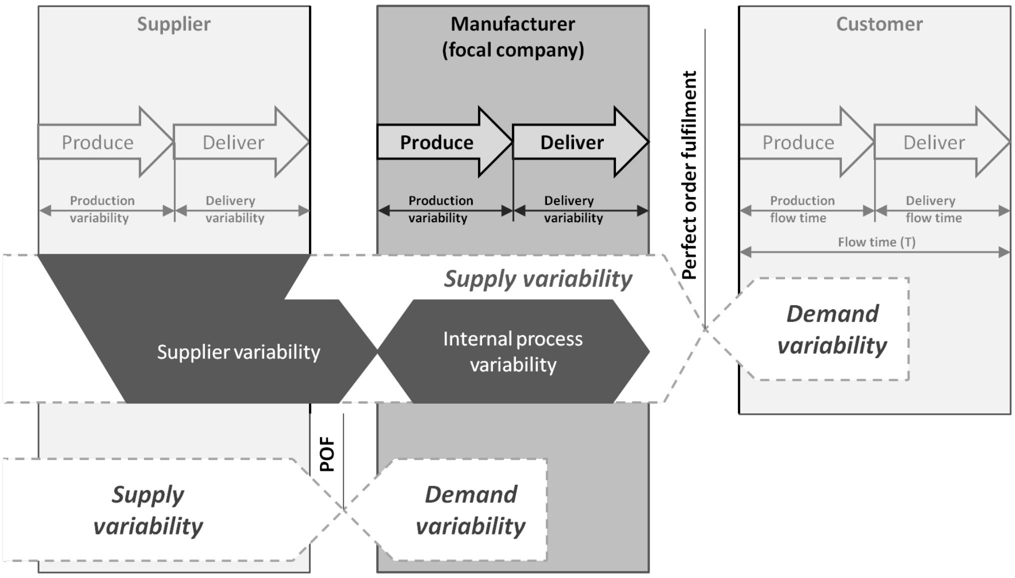

Figure 3.3: Variability framework with extended supplier variability

congestion, unloading of a train is delayed because a crane is broken (variability due to randomness), and of course batching plays an important role, as for instance trucks should be fully loaded.

Summarizing supply variability, it has to be stated that the above mentioned sources and causes of variability are possibilities for explaining variability and long flow times to some extent. Clearly, some randomness remains unexplained and thereby uncontrolled, leading to the necessity of buffers.

3.4 Propagation of variability

After discussing the various types of variability with respect to their influence on process performance, it has to be clarified how variability is passed on from one stage to the next in manufacturing processes. In addition to the bullwhip effect (see *Section 3.2.3*), denoting the increasing demand variability upstream in supply chains, variability is also propagated downstream in the supply chain. This propagated variability can be observed by looking at the departures of a particular stage, which is relevant for so-called push-processes, where in contrast to a pull-process (e.g., KANBAN), no a priori WIP limit is defined (Hopp and Spearman, 2007). In such processes an order is released by external scheduling and goes through a multi-stage process. This means the output of a particular

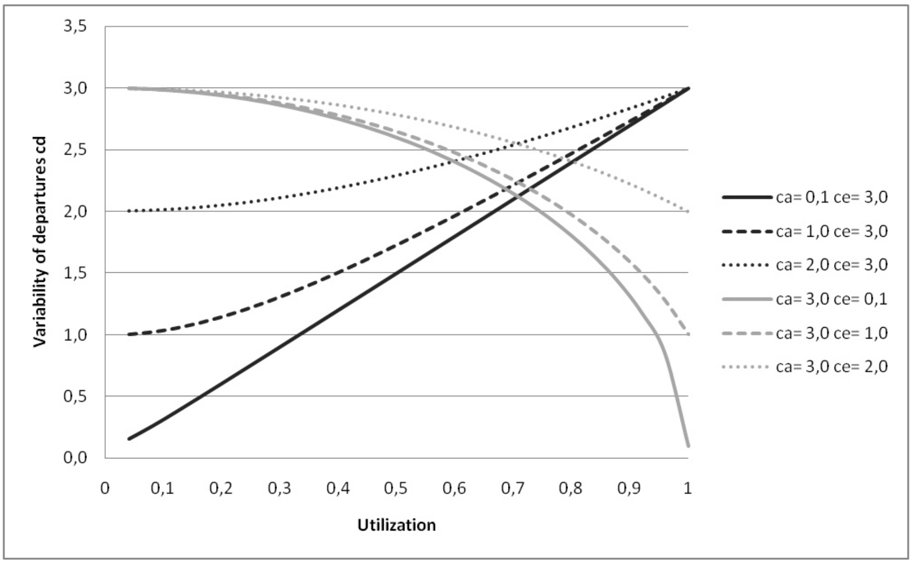

Figure 3.4: Variability of departures depending on utilization

stage is the input (arrival rate) of the consecutive stage. Consequently, the variability of customer/order arrivals (c_a) at a particular stage (i) equals the variability of departures (c_d) from the preceding stage ($i-1$) (*3.29*) (Hopp and Spearman, 2007).

$$c_a(i) = c_d(i-1) \tag{3.29}$$

The variability of departures of a particular stage depends on the variability of both the process time and the interarrival time as well as on the utilization (*3.30*).

$$c_d^2 = \rho^2 c_e^2 + (1-\rho^2)c_a^2 \tag{3.30}$$

This is an approximation model, interpolating between the variability of process time and the variability of interarrival times according to the utilization. The intuition behind this is quite obvious. If the stage has a high utilization (ρ close to one) the variability of departures nearly equals the variability of the process time ($c_d = c_e$). In this case the variability of interarrival times does not matter. Otherwise, if the utilization is very low (ρ close to zero) the variability of departures equals the variability of interarrival times ($c_d = c_a$) (Hopp and Spearman, 2007). *Figure 3.4* shows the variability of departure times (c_d^2) depending on the utilization for various combinations of c_a and c_e.

For stages consisting of more than one parallel server ($m > 1$), (*3.31*) shows an approximation to estimate c_d^2.

$$c_d^2 = 1 + (1 - \rho^2)(c_a^2 - 1) + \frac{\rho^2}{\sqrt{m}}(c_e^2 - 1) \tag{3.31}$$

Buzacott and Shanthikumar (1993) provide an comprehensive discussion of different approximations, appropriate for different levels of c_a. Generally they state that for high utilizations all models generate very good results. Concerning this study, further arguments are based on (*3.30*).

Generally, in multi-stage processes without WIP limit (push process), variability early in the process increases the flow time more than equivalent variability later in the process (Hopp and Spearman, 2007). For instance, if a process consisting of four, equally utilized (90%) stages has a high variability at the first stage and low variability at the other three stages, the high variability from stage one is passed on to the consecutive stages, leading to a substantially increased flow time. However, if the same process has low variability at the first three stages and high variability only at the last stage, the flow time is much lower than in the previous example. Therefore it is really important to reduce variability especially at the beginning of a process, to avoid propagating high variability to stages with initially low variability.

3.5 Impact of distributions - Safety time calculation

In the previous sections different causes and sources of variability have been discussed. These causes, like batching or machine breakdowns, have been explained with respect to their influence on process performance. Generally, causes of variability decrease process performance as process capacity is reduced and flow time is increased. Consequently, by reducing or avoiding these causes, process performance can be enhanced. These effects are shown by means of the general queuing model (see *Section 2.1*), which estimates the waiting time and the flow time of a particular job through a system.

Unfortunately this model only provides a mean value for the flow time but no information concerning dispersion. This means with this model the variability of the flow time cannot be estimated. Only if both the process times and the interarrival times are exponentially distributed is the flow time also supposed to be exponentially distributed (Buzacott and Shanthikumar, 1993). This situation is captured by the so-called M/M/1 Model, providing an exact solution for the waiting time, shown in (*3.32*).

$$t_q = t_e \times \frac{\rho}{(1-\rho)} \tag{3.32}$$

Compared to the general approximation model (see *2.4*) the whole variability factor is missing. The reason for this is simply the fact that an exponentially distributed variable has a coefficient of variation of one, as the standard deviation equals the mean. Consequently the variability factor ($\frac{(c_\mathrm{e}^2+c_\mathrm{a}^2)}{2}$) is one.

If process times are not exponential, as is often the case (Buzacott and Shanthikumar, 1993; Hopp and Spearman, 2007), the flow time is still exponential as long as the arrival process is exponential and the process is reasonably utilized (Kimura, 1983). If neither the process time nor the interarrival time is exponential, no statement is possible about the variability of the flow time. In such a case discrete-event simulation can be used to estimate the possible spread of expected waiting time. The second possibility is to observe and track the actual flow time to get enough data to estimate the distribution from these empirical data. To find out which distribution function fits best the empirical data, tests like for instance the *Kolmogorov-Smirnov test* or the *Pearson's chi-square test* can be used.

Why is this important? The distribution is necessary to quote reliable delivery dates, which is usually done by taking the mean flow time and adding some safety time (Hopp and Spearman, 2007). For normally distributed flow times, safety time depends on variability of the flow time and the desired delivery reliability. Delivery reliability concerning the flow time means the probability that an order is delivered within the defined customer lead time.

For the following explanation it is assumed that the manufacturer produces on a make-to-order basis and the customer does not define a lead time. The customer just wants a reliable quote, when the order is delivered, further denoted as quoted delivery lead time L. (*3.33*) shows how L can be calculated for normally distributed flow times, using the flow time T, the standard deviation of the flow time σ_T and a safety factor z.

$$L = T + z\sigma_T \tag{3.33}$$

The safety factor z depends on the distribution of the flow time and determines the probability that flow time of a particular order (T_i) is below the quoted delivery lead time.

Let us assume that the analysis of the last 200 deliveries of a particular process has shown that the mean flow time is 8 days with a standard deviation of 8 days. Let us further assume that the deliveries appeared to be normally distributed. In addition to this information the manufacturer should define a desired service level, meaning the probability that the flow time of a particular delivery is below the quoted delivery lead time L. Let us assume the manufacturer sets the desired service level to 95% ($P(T_i \leq L) = 0.95$). Now z can be taken from the standard normal distriution table, which is in this case 1.645. (*3.34*) shows the calculation of L based on these data.

$$L = T + z\sigma_T = 8 + 1.645 \times 8 = 21.159 \text{ days} \tag{3.34}$$

If in this case the flow time is normally distributed and the desired service level is 95% the company has to quote a delivery lead time of at least 21 days, to be "95%" sure of delivery within the quoted time.

To show the relevance of finding the right distribution, the quoted delivery lead time L is now calculated using the same numbers but assuming that the flow time is exponentially distributed (see *Figure 3.5*). (*3.35*) shows the probability density function for the exponential distribution and (*3.36*) the cumulative distribution function, of which both are

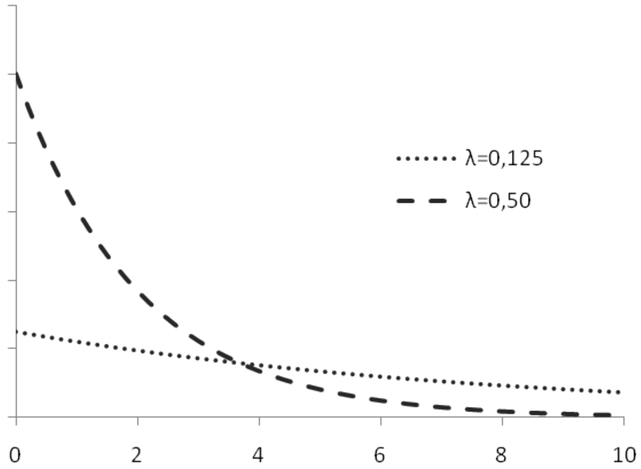

Figure 3.5: Probability density function of an exponential distribution

based just on the parameter λ.

$$f(x,\lambda) = \lambda e^{-\lambda x} \tag{3.35}$$

$$F(x,\lambda) = 1 - e^{-\lambda x} \tag{3.36}$$

The mean of an exponential distribution is $1/\lambda$. Consequently, a mean of 8 days implies a λ of 0.125. For this example the service level remains 95%. Now L has to be found that $P(T_i \leq L)$=0,95 is satisfied. This can be done by solving the cumulative distribution function for x, shown in (*3.37*) and (*3.38*).

$$0,95 = 1 - e^{-0,125x} \tag{3.37}$$

$$x = 23,97 \tag{3.38}$$

This simple example nicely illustrates that ignoring the underlying distribution or assuming the wrong distribution may lead to wrong quotes. The reason for this is that the mean and the standard deviation are sometimes not sufficient for describing a distribution. Usually distributions are described by the moments. The first moment of a distribution is the expected value (or mean), and the second central moment is a measure of dispersion, e.g., range, variance, standard deviation. These two moments were used so far throughout this thesis, as they are relatively easy to calculate and interpret.

In addition to the first and second moment, random phenomena are also influenced by the third moment, called skewness, and the fourth moment, called kurtosis (Hopp and Spearman, 2007), capturing the shape of the distribution. Skewness is a measure for the lopsidedness of the distribution (either left or right). A distribution that is skewed to the left has a negative skewness, a distribution skewed to the right has a positive skewness. The standard normal distribution is symmetric and therefore has a skewness of zero. Kurtosis measures whether the distribution is tall and skinny or short and squat, compared to the normal distribution of the same variance.

A nice example of balancing safety time and safety stock or safety capacity is provided by Vandaele and Nieuwenhuyse (2009). He also addresses the issue of distribution.

4 Tackling variability in supply chains

After clarifying and organizing the different types and sources of variability in supply chains in *Chap. 3*, now ways will be presented to tackle those. When talking about variability within operations and supply chains two concepts immediately emerge: lean management and the bullwhip effect.

The term lean management became popular with James Womack (Womack et al., 1990; Womack and Jones, 1996), as he summarized the success factors of Japanese manufacturing based on the Toyota production system. The basic principles of lean management are: (1) specify the value desired by the customer, (2) identify the value stream for each product providing that value and remove unnecessary steps (remove waste), (3) make the product flow continuously through the value-added steps, (4) introduce pull between all steps where continuous flow is possible and (5) manage toward perfection so that the number of steps and the amount of time and information needed to serve the customer continually falls. Thus lean management is characterized by process orientation, continuous improvement, the reduction of any kind of waste (inventory, capacity, time) and a focus on perfect quality.

These principles together with similar concepts, especially from quality management, like *TQM*, *Six Sigma* (see *Section 3.3.1*) and *TPM* (Total Productive Maintenance - see Nakajima, 1988), address the issues discussed within supply variability.

As the bullwhip effect is such an important concept concerning variability reduction the well-known measures to reduce the bullwhip effect should be analyzed with respect to the variability framework, presented in *Section 3.1.2*. According to Lee et al. (1997b,a) the following actions can be taken to reduce the causes for the bullwhip effect, listed in *Section 3.2.3*. *Demand signal processing* can be avoided or reduced by sharing information on end-consumer demand throughout the entire supply chain, by implementing vendor managed inventory (VMI - see *Section 4.1.2*) and by reducing production and delivery flow times. *Order batching* is reduced by decreasing fixed order costs, using assortment trucks instead of a full truck just loaded with one product, and consolidating loads from different suppliers with the help of third-party logistics companies. *Prize variations* are avoided by the every-day-low-prize (EDLP) strategy, or by contracts with longer horizons. The *rationing game* can be avoided by sharing sales, capacity, and inventory data and by using past sales to allocate production quantities in case of limited capacity. The actions concerning batching are the only ones targeting supply variability. All other measures mainly reduce demand variability

Now the supply chain best practices *Postponement* (process design), *Vendor Managed Inventory* (centralized supply chain) as well as *Quantity flexibility contract* (decentralized supply chain) are analyzed with regard to their ability to reduce or deal with variability. This is done by discussing whether and which form or source of variability is reduced, and how the remaining variability is dealt with in terms of changes in safety stock and safety capacity. Afterwards, the role of information in reducing variability is discussed in greater detail according to the different types of variability, introduced in *Chap. 3.1.2*.

4.1 Supply chain best practices and variability

4.1.1 Postponement

The literature on postponement has a long tradition as it dates back to the seminal works of Alderson (1950) and Bucklin (1965). However, its potential for industry and academia seemed to have remained undiscovered until recent years when an reasonable amount of new publications appeared. Van Hoek (2001) interprets the recent interest as a *rediscovery* of an old concept. Since the famous review of Van Hoek (2001), many more review papers and classifications appeared (Boone et al., 2007; Graman and Magazine, 2006; Swaminathan and Tayur, 2003; Yang and Burns, 2003; Yang et al., 2004b,a). However, postponement is not always defined in the same way: e.g., Graman and Magazine (2006)

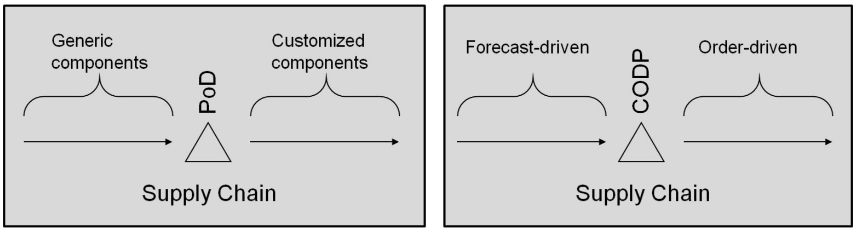

Figure 4.1: Point of differentiation - customer order decoupling point

define postponement as "delayed product differentiation". Boone et al. (2007) see postponement as a "concept whereby activities in the supply chain are delayed until a demand is realized". Bowersox and Closs (1996) distinguish between three different types of postponement: (1) time postponement, the delayed forward shipment of goods, (2) place postponement, the storage of goods in central locations, and (3) form postponement, the delayed product finalization. Van Hoek (2000) identifies six different drivers for the application of postponement: (1) improving product customization, (2) lowering logistics costs, (3) improving speed of delivery, (4) raising delivery reliability, (5) improving inventory cycle-times, and (6) lowering obsolescence risks.

One of the biggest challenges in supply chain management is the trade-off between low production costs and the increasing demand for customized products. Many concepts evolved over the last decades that deal with this trade-off, like mass customization and postponement, using terms like responsive supply chains, customer order decoupling point (COPD), and point of differentiation (PoD). As the definitions of these concepts are often not unambiguous, researchers sometimes do not clearly distinguish between them. In this respect, the COPD and the PoD are very important examples. They are often used as synonyms, but have different meanings (Meyr, 2003; van der Vorst et al., 2001). The CODP is the boundary between the forecast-driven and the order-driven part of the process (see *Section 1.1*), which means the customer order is the relevant information. The PoD is the point in the process when a generic product is customized, which means that the product features are relevant (see *Figure 4.1*).

The difference between those terms can be shown easily by means of the famous Hewlett-Packard (HP) case, published by Feitzinger and Lee (1997). As many countries have different regulations concerning power supply, HP had to produce its printers in multiple of different variations. At first, the printers were produced on the basis of forecasts. As demand was highly volatile this strategy led in some countries to stock-outs, whereas other countries faced immense oversupply. Because of the different power adapters used in the printers HP faced the problem that the printers available in one country could not be used to satisfy demand in another country. HP then decided to postpone the differentiation of printers to the very last step in the supply chain, to the warehouses. They redesigned the printers in a way so that the power adapters could be easily inserted at the central warehouses when better demand information was available.

In the initial situation HP adopted a make-to-stock strategy, which means the CODP is located at the very end of the supply chain (downstream), whereas the PoD is located somewhere in the manufacturing process. In the postponement case the PoD is moved downstream in the supply chain by "postponing" the customizing activities (inserting power adapters). In addition, the power adapters are plugged in after receiving better demand information, meaning the CODP is moved upstream the supply chain. Now the PoD and CODP are at the same point in the supply chain. Further famous examples for successfully using postponement are Benetton with the re-sequencing of dyeing end knitting (Dapiran, 1993; Heskett and Signorelli, 1985) and Dell with on-demand assembling of computers (Magretta, 1998).

The question is now whether particular types of variability are reduced by postponement. First, neither demand variability due to randomness nor variability due to management decision are touched by this concept. Also supply variability due to randomness is not touched in a substantial way. Only supply variability due to management decision is reduced, as a larger share of the process deals with generic products and the customization is later in the process (see *Figure 4.2*). Operating with generic products means that probably fewer setups are necessary.

Finally, it should be clarified how postponement deals with the remaining variability. Generally, inventories are reduced without reducing customer service. This is true because of the pooling principle (Hopp and Spearman, 2007; Cachon and Terwiesch, 2008) which states that stocking generic parts and finishing products upon demand requires

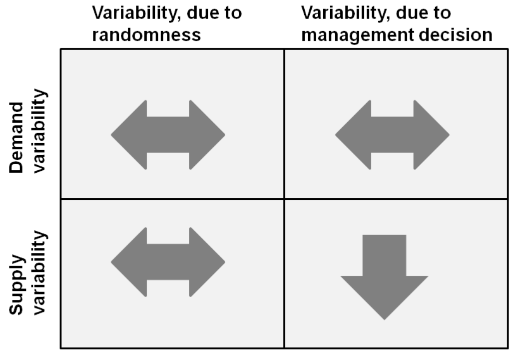

Figure 4.2: Reducing variability by postponement

much lower safety stock than holding safety stock of every product variant. The idea behind the pooling principle is that demand variability can be compensated. In the case of holding stock of finished goods, it frequently happens that some products are stock-out whereas other products are over-supplied. With holding generic semi-finished products this situation is avoided. An important aspect of the pooling principle is that it works well only in the case of negatively correlated demand.

To be able to finish the products upon demand it is probably necessary to increase capacities in the order-driven part of the process to ensure sufficiently quick delivery. To evaluate whether a postponement strategy is advantageous for a particular process it is important to perform an integrated process analysis capturing process dynamics. Jammernegg and Reiner (2007); Reiner (2005); Reiner and Jammernegg (2005) and Reiner and Poiger (2010) provide examples for such analyses using discrete-event simulation.

4.1.2 Centralized supply chain: Vendor managed inventory

Vendor managed inventory (VMI) is a supply chain coordination concept, mainly based on the idea that the vendor (supplier) makes all decisions concerning inventory at the customer (Angulo et al., 2004). This means the customer does not order anymore but provides demand and inventory information to the supplier, who is responsible for replenishing inventory to maintain a predefined service level.

The concept was introduced by Wal-Mart and Procter & Gamble in the late 1980s (Waller et al., 1999) and was successfully implemented by companies in the retailing sector (Andel, 1996; Cachon and Fisher, 1997; Hammond, 1994, 1995; Lee and Whang, 2000). Up to now, the concept has become the most famous *continuous replenishment* approach (Sari, 2007) and is used in many industries.

With a properly designed VMI agreement both the buyer and the supplier benefit: retailers (buyer) because of higher product availability and lower inventory monitoring and ordering costs, and suppliers (vendors) because of the reduced bullwhip effect and better utilization of manufacturing capacity as well as better synchronization of replenishment planning (Sari, 2007).

In a VMI agreement the retailer usually specifies a certain service level (availability) and space requirements (Sari, 2008). Fry et al. (2001) explains and analyzes a special form called (z, Z)-Type VMI, where the retailer sets a minimum inventory level z and a maximum inventory level Z. The supplier agrees to pay a penalty amount of b^+ (b^-) per unit to the retailer for every unit of the retailer's inventory that is less than z (more than Z) after customer demand. A recent discussion of German VMI-contracts is provided by Gutjahr (2008).

Actual reports on successful as well as failed implementations of VMI are provided by Kulp et al. (2004); Sari (2007); Vigtil (2007), recent discussions on the value of VMI are given by Darwish and Odah (2010); Lee and Chu (2005); Sari (2008) and Yao and Dresner (2008). The coordination of inventory and transportation decisions is studied by Cetinkaya and Lee (2000). The mitigating effect of VMI on the bullwhip effect is explicitly addressed by Disney and Towill (2003a,b).

Contrary to postponement, VMI is mainly a variability reduction strategy, as demand and supply variability are potentially reduced (see *Figure 4.3*). To show the various effects it is assumed that the manufacturer of the study's generic supply chain models has a VMI agreement with its customer. From the viewpoint of the manufacturer, demand variability due to randomness is substantially decreased, as the demand the customer faces from its customers is directly passed on to the supplier. There is no replenishment policy tampering with the demand patterns from the downstream stages of the supply chain. Furthermore stable prices are used within used within VMI contracts, reducing demand variability due to management decisions, as discounts are not applied. Concerning supply, variability due to management decisions is reduced, as capacity and inventory planning can be better synchronized with demand, for instance by combining deliveries for several customers. Demand variability due management decisions and supply variability due to randomness are not affected by VMI.

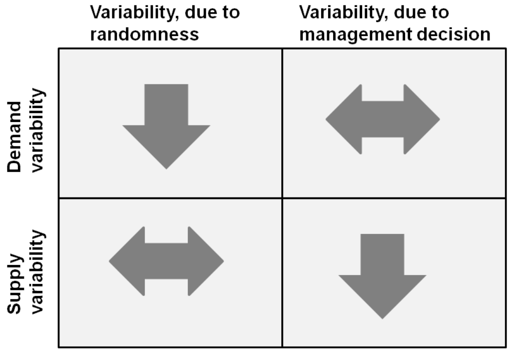

Figure 4.3: Reducing variability by VMI for the seller (vendor)

Of course, the manufacturer can also be in the role of the buyer when it has a VMI contract with its supplier. In this case demand variability between manufacturer and supplier is reduced, leading to a reduced supplier variability. Concerning the goal of the manufacturer to achieve perfect order fulfillment (POF) with its customer, demand variability remains unchanged. Only supply variability is reduced, leading to a shorter and more table flow time.

Finally, it should be clarified how the remaining variability is dealt with. Probably the main buffer in VMI supply chains is still safety stock, but similar to postponement, here too some safety capacity may play a reasonable role (e.g., transportation).

4.1.3 Decentralized supply chain: Quantity flexibility contract

Supply chains consisting of independent players and without any central planning can be coordinated by supply chain contracts. Such contracts try to ensure fair allocation of revenues and risk between two supply chain partners. Without supply chain contracts the players would optimize only their own objectives, which may lead to a suboptimal overall supply chain performance. The main supply chain contracts are (Cachon and Terwiesch, 2008): buy-back contract, quantity discounts, options contracts, revenue sharing, quantity flexibility contracts, and price protection. Reviews of the different supply chain contracts are provided by Anupindi and Bassok (1999); Corbett and Tang (1999); Corbett et al. (2004); Cachon (2003); Lariviere (1999) and Tsay et al. (1999).

As the quantity flexibility contract is often used in B2B partnerships this contract is further analyzed with respect to its ability to reduce or cope with variability. To explain the quantity flexibility contract the general supply chain model (see *Section 1.3*) is used (similar to the explanation by Cachon and Terwiesch, 2008). It is assumed that the manufacturer requires forecasts from the customer to be able to build enough capacity. The orders placed by the customer can be above or below the forecast. To ensure that the manufacturer builds enough capacity the customer will probably send overly optimistic forecasts. On the other hand the manufacturer is no fool and will anticipate such behavior and treat the forecasts carefully. The problem in this situation is that the manufacturer bears the whole risk of idle (excess) capacity.

To achieve a better supply chain performance (higher customer service, lower supply chain cost) it is necessary to share the risk of idle capacity among the customer and the manufacturer. The quantity flexibility contract is a commonly used solution for this discrepancy. By using a quantity flexibility contract the supplier guarantees to deliver the forecast plus a particular percentage α ($q_{max} = \text{forecast} + \alpha$), and the customer guarantees to order at least the forecast minus a percentage β ($q_{min} = \text{forecast} - \beta$).

By using such an agreement the manufacturer is protected in case of very low demand, as the customer has committed himself to buy at least the forecasted quantity minus the agreed percentage β. In case of very high demand the customer is protected as the manufacturer has committed himself to build enough capacity to deliver to the extent of the forecasted quantity plus the agreed percentage α. Detailed discussions on different types of quantity flexibility contracts can be found in Bassok and Anupindi (2008); Cachon (2003) and Tsay and Lovejoy (1999).

The evaluation of quantity flexibility contracts concerning their capability to reduce variability is a little bit more tricky. Demand variability due to randomness is not influenced directly, as the order behavior of the customer is not influenced, but it could be supposed that the customer places better forecasts with the manufacturer, leading to de-

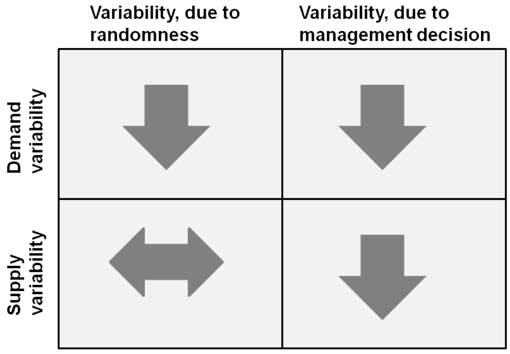

Figure 4.4: Reducing variability by quantity flexibility contracts

creased forecast errors. Furthermore, the range of demand is restricted by the boundaries derived from the agreed percentage. Therefore demand variability due to randomness is reduced by such contracts. Similar to VMI, demand variability due to management decisions may be reduced by avoiding any price fluctuations, which is obviously true for any of the supply chain contracts.

Supply variability due to management decisions may be regarded as reduced because the capacity planing is facilitated by customers' commitments. Supply variability due to randomness is not affected by this contract (or any other of the above mentioned). *Figure 4.4* summarizes the variability reducing effects of quantity flexibility contracts.

The main idea of the quantity flexibility contract is to share the risk of uncertain demand. Variability can be reduced to some extent. The remaining variability can be buffered by both safety stock or safety capacity, depending on the customer lead time and the manufacturer's delivery flow time.

4.2 Reducing variability through information

After discussing various strategies and best practices of operations and supply chain management with respect to their ability to reduce and cope with variability now the special role of information has to be clarified. In *Section 2.3* the main types of information exchanged within supply chains were mentioned. Li et al. (2006) differentiate between three types of information sharing between organizations. First, transactional information comprising order quantities, prices, sales, product specifications as well as quality and delivery specifications. Second, operational information meaning data on inventory levels, costs and schedules, production and transportation capacities, lead times and shipments. Third, strategic information meaning point-of-sale (POS) information, real-time demand, understanding of market trends, the things customers value most, and product designs. Lee and Whang (2000) distinguish between inventory level, sales, order status for tracking/tracing, sales forecasts (upstream), production or delivery schedule, performance metrics and capacity. These types of information will be explained and further analyzed by means of the general supply chain model, defined for this study (see *Section 1.3*), from the perspective of the manufacturer.

Exchanging information on *inventory level* is the basis for continuous replenishment programs like VMI (see *Section 4.1.2*). In case that the manufacturer has a VMI agreement with its customer, he has to receive inventory information to be able to replenish that inventory properly. On the other hand, the manufacturer can also have a VMI agreement with a supplier. In that case the manufacturer has to provide the inventory level. Of course, the inventory level has to be shared in real-time, meaning that any inflow or outflow has to be recorded immediately. Generally, exchanging information on inventory level may reduce overall supply chain inventory as duplicate safety inventories are avoided.

Sharing *sales* data is also necessary for continuous replenishment programs like VMI. In case of a VMI agreement the manufacturer either provides or receives sales information, depending on whether he is the buyer or the seller. Generally, providing sales data to upstream partners in the supply chain is a prominent measure in reducing the bullwhip effect, as companies further upstream in the supply chain are better informed about end consumer demand. Sales data can either represent just the sales of the next stage in the supply chain or the point-of-sale (POS) data. If POS information is shared upstream partners know actual end consumer demand.

Sharing *order status for tracking/tracing* enables quick localization of a particular order. This has nothing to do with variability reduction or safety inventory and safety capacity, but has a positive impact on customer satisfaction and the payment cycle, because delivery problems which delay payment can be resolved faster (Lee and Whang, 2000).

In addition to sales data *sales forecasts* can also be provided to upstream partners, as stages further downstream the supply chain are closer to the market and have thus better knowledge about the market. This is a common practice to reduce or avoid the bullwhip effect and is also a major part of CPFR (see *Section 2.2*). Furthermore, forecasts are shared within quantity-flexibility contracts (see *Section 4.1.3*).

To coordinate production planning and to be able to better quote due dates, *production or delivery schedules* can be shared. The manufacturer can use such data from its suppliers to improve its own production schedule, and the supplier can also use the production schedule from the manufacturer. This means production or delivery schedules can be shared upstream and downstream the supply chain (Lee and Whang, 2000).

Performance metrics can be shared among supply chain partners to jointly identify bottlenecks and to improve overall performance, and data on *capacity* are shared to prevent shortage gaming (Lee and Whang, 2000).

Generally, information sharing can reduce demand variability (Li et al., 2006). In the next two chapters the above mentioned types are analyzed with respect to their ability to reduce the different types of variability, defined in the variability framework (see *Section 3.1.2*)

4.2.1 Information and demand variability

First, the role of information for reducing demand variability must be clarified. According to the variability framework, demand variability comprises variability due to randomness and variability due to management decisions. Variability due to randomness mainly represents the arrival of customer orders. Demand variability due to management decisions comes from the product mix and from pricing.

In *Section 3.2.1* it was shown that demand can be regarded as composed of five components: (1) level, (2) trend, (3) seasonal variation, (4) cyclical movements and (5) irregular random fluctuations. The goal for every company is to understand the demand pattern as well as possible to be able to generate forecasts as accurately as possible. It was also mentioned that forecast is important for MTS and MTO companies. Even if a company does not produce on a MTS basis, it has to plan capacities and has to order raw material and components in advance. Otherwise orders could not be fulfilled within customer lead time.

As already mentioned above, information concerning inventory level, sales and sales forecasts are well suited to reduce demand variability for the manufacturer. Let's assume that the manufacturer enters a VMI agreement with his customer. Contrary to the initial situation the manufacturer gets now real-time information on the inventory level as well as the sales. Now the manufacturer can plan and organize the replenishment of this inventory based on the sales the customer faces. As according to the bullwhip effect, stating that the variability of the replenishment orders is higher than the variability of the sales, demand variability decreases for the manufacturer. Another possibility for the manufacturer to reduce demand variability is to enter a quantity-flexibility contract. Then the customer provides forecasts and commits himself to place orders within predefined boundaries (see *Section 4.1.3*).

An even further reduction can be achieved by sharing production and delivery schedules. For instance, in the automotive industry different levels of delivery schedules are provided by the customer. Within a so-called Just-In-Sequence agreement, the customer continuously provides delivery schedules with different horizons and different levels of accuracy (Reiner and Poiger, 2010). The longterm information, which is more or less a forecast for the six to eight months, is used to order raw materials. For the following two weeks the manufacturer gets delivery schedules, where the daily quantities are already fixed (frozen horizon). Depending on the production flow time the manufacturer can either plan to produce the requested parts according to this schedule, or has to fulfill those orders from stock, which was replenished on the basis of the rolling forecasts. The final information the manufacturer gets is the so-called JIS delivery schedule. This information is the exact production sequence of the customer determining how the parts have to be packed. The idea is that at the assembly line the requested parts can be taken from the transport container already in the correct sequence. Clearly, with such detailed information a closer coordination between the manufacturer and the customer is possible, as the demand variability is reduced.

Finally, information on capacity also contributes to the reduction of demand variability, as the shortage gaming can be avoided. Contrary to the production schedule, which can be shared upstream and downstream, capacity information rather makes sense when shared downstream.

Demand variability due to management decision is not affect by information in such a direct and operational way. Decisions on the product mix are usually based on the corporate strategy, including also the pace of new product or technology introduction. Concerning the price there are models dealing with jointly optimizing inventory and prizing decisions. This is a rather new stream within inventory management, as in traditional inventory models the prize is regarded as given. By combining models from operations management and marketing price is treated as a decision variable (Gimpl-Heersink, 2008). One famous example of extending traditional inventory models by adding price as a decision variable is the price-setting newsvendor (Petruzzi and Dada, 1999).

As these models mostly deal with the pricing decisions of the retailer facing anonymous end-consumer demand, these models seem to be rather unsuitable for a manufacturer in a B2B environment. For the manufacturer, supplying just a few business customers, it is more beneficial to look for long-term contracts with stable prices ("Every-day-low-price") (Lee et al., 1997b,a).

In general, additional information like inventory levels, sales and sales forecasts can substantially reduce demand variability due to randomness for the manufacturer. This is the main reason why the "low-variability" point in the OM triangle is called information point (see *Section 2.1*). Variability due to management decisions is not influenced by information sharing.

4.2.2 Information and supply variability

Supply variability comprises variability due to management decisions, like preventive maintenance and batching, and variability due to randomness, like quality defects, breakdowns and the quality of incoming supplies. Concerning the process view, internal process variability and supplier variability are distinguished (see Section 3.3).

For reducing internal process variability information does not play an important role. As mentioned at the beginning of this section, concepts like lean management, quality management and total productive maintenance provide useful approaches and tools to reduce variability.

Information comes into play when dealing with supplier variability. As shown in *Figure 3.3* perfect order fulfillment of the supplier is of course affected by the demand variability induced by the manufacturer. Therefore, sharing information on inventory levels, sales and sales forecasts with the supplier also make sense. Consequently, information also reduces supply variability, more precisely the supplier variability.

Further possibilities to address supplier variability are selecting the best supplier or developing suppliers. The selection is usually done by monitoring and evaluating supplier performance based on a set of criteria, of course containing metrics on reliability (Chen et al., 2006; Ittner and Larcker, 1999; Shin et al., 2000; Simpson et al., 2002). Supplier development programs have the main purpose of improving the capabilities of the suppliers, of course also based on supplier evaluation (Hahn et al., Spring 1990; Krause et al., 1998; Watts and Hahn, Spring 1993).

As mentioned in *Section 3.3* supply variability is not only divided into internal process variability and supplier variability but also into variability concerning manufacturing and variability concerning delivery. To ensure reliable supply it is not sufficient to only improve the reliability of the manufacturing process of the supplier but also the reliability of the logistics activities like transportation or cargo handling, independent of who is responsible for the delivery (supplier, manufacturer, logistics service provider).

Finally it can be stated that information and information sharing play an important role for reducing variability, but are not the only levers for management.

4.3 Extended OM triangle

In *Section 4.1* the supply chain best practices *Postponement* (process design), *Vendor Managed Inventory* (centralized supply chain) as well as *Quantity flexibility contract* (decentralized supply chain) are analyzed with regard to their ability to reduce or deal with variability. This is done by discussing how the remaining variability is dealt with in terms of changes in safety stock and safety capacity. Overall, it can be stated that VMI and the quantity flexibility contract reduce variability and deal with the remaining variability by mainly holding safety inventory. Postponement, an important concept in redesigning a process, reduces supply variability by using generic products and deals with the remaining variability by mainly holding safety capacity, as the products are completed on binding orders.

Based on the findings of this study a slightly extended OM triangle is suggested. The main adjustment compared to to original one is the suggestion for renaming the information point. As variability is not only reduced by additional information but also by improved (excellent) processes the point should be referred to as *Information and Excellence Point*. Figure 4.5 shows the adjusted triangle, using abbreviations for the capacity point (CP), the inventory point (IP) and the newly named information and excellence point (IEP).

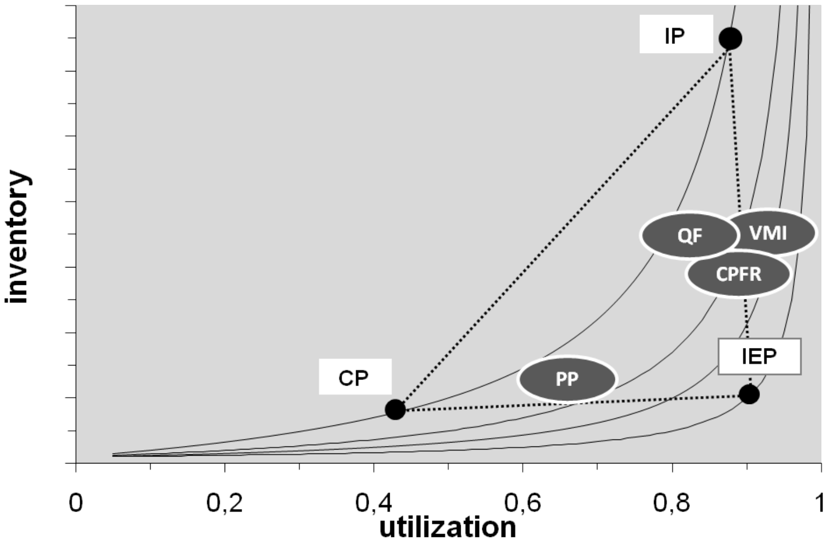

Figure 4.5: Extended OM triangle

As pointed out in *Section 2.1* there is no perfect point on the triangle. Where a company positions itself and its processes depends on customer's expectations, overall corporate strategy, industry, cost structure, and so forth. To deal with uncertainty and variability without decreasing customer service a company can use a combination of the following three levers: holding safety stock, holding safety capacity or reducing variability. From the above mentioned supply chain best practices (see *Section 4.1*) VMI (CPFR) and the quantity flexibility contract reduce variability compared to a traditional buyer-supplier relationship. For the remaining variability safety inventory is held. Therefore, processes using these concepts are somewhere between inventory point and the information and excellence point.

In case of postponement only supply variability is reduced, and for the remaining variability, safety capacity is used. Therefore, processes using postponement are somewhere between capacity point and information and excellence point. In the following section two real-world supply chains are presented and used to further illustrate the extended OM triangle.

5 Supply chain analysis and improvement by means of real-world examples

In this chapter two real-world supply chains are described to further illustrate the different aspects of variability and the extend OM triangle. As there are not too many empirical studies on process level (Silver, 2004), providing results on the impact of different types of variability on process performance by means of empirical data could be of great value. To be precise, the study wants to illustrate and quantify the impact of variability on the performance of supply chains by means of two real manufacturing supply chains. Supply chain one (SC1) manufactures and delivers frequency inverters and supply chain two (SC2) assembles and delivers sliding glass top systems. For the inverter supply chain the operational impact of reduced demand variability (reduced forecast error) is shown, achieved by implementing VMI or CPFR. In the glass top supply chain supply variability is addressed by assessing the impact of the production lot size. Both processes are mainly evaluated by using WIP and flow time as key performance measures. The analysis is conducted with rapid modeling software based on open queuing networks (see *Section 1.4*).

5.1 Supply chain 1: Frequency inverter assembling

The focal company of supply chain 1 is a manufacturer located in Vienna producing electric devices like frequency inverters, intelligent rectifiers, asynchronous motors and mains active restoring systems. The manufacturer is part of an international group with its headquarters in France. The manufacturer performs the manufacturing and assembling process of the above mentioned products and has also a development department. The manufacturer is part of a global supply network with suppliers from all over the world. The cus-

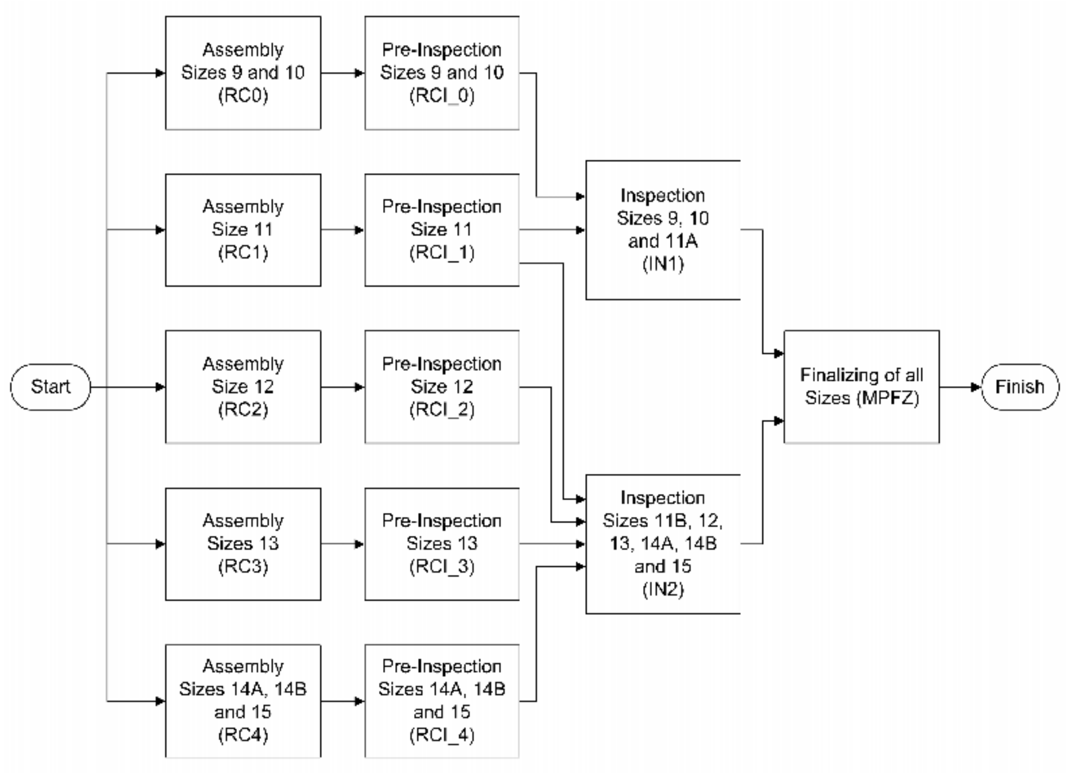

Figure 5.1: Process flow chart of inverter production

tomers of the manufacturer are organizations within the group organizing the distribution in different markets. From a group point of view the manufacturer has only “internal” customers.

The starting point of the supply chain analysis was a massive problem with the delivery flow time. The manufacturer was not able to fulfill the customer orders on time. Generally, demand was volatile (without understandable patterns) and expected to increase in the future. Therefore, the main question for the company was how to improve the assembling process and the whole supply chain to be able to deliver on time and to be in a position to deal with future increased demand.

The first idea discussed in the course of the analysis was to better collaborate with the direct customer, as interestingly enough, the manufacturer only receives orders from its customers. Especially the sharing of forecasts and additional demand information could perhaps facilitate the manufacturers operations. The implementation of VMI was likewise discussed. However, even though the manufacturer and the direct customers belong to the same group, all these ideas were rejected by the group’s headquarters. Simply with the argument that logistics was the domain of headquarters, and the manufacturer should just stick to delivering the ordered quantities.

In such a situation demand variability is given. The only remaining lever regarding demand is trying to achieve better forecasts. Consequently, the company has to analyze its processes to be able to better cope with the variability, meaning that either safety stock or safety capacity has to be built.

5.1.1 Initial situation of frequency inverter assembling

For this study the supply chain and the manufacturing process of frequency inverters are analyzed. The frequency inverters are produced in 9 different sizes: 9, 10, 11A, 11B, 12, 13, 14A, 14B, 15. These sizes are further differentiated by software and labeling, which has no impact on process times. Therefore, we analyze the production on the product size level, and not the final brand level (overall 48 different final products are produced). The production process, which is mainly an assembly process, consists of the activities (1) assembly, (2) pre-inspection, (3) inspection and (4) finalizing (see *Figure 5.1*). In the current situation the assembling is done on five parallel roller conveyors (RC0 – RC4), each for particular sizes. After the assembling a pre-inspection is conducted. This is done by one person for all conveyors with a mobile inspection device at the very end of each roller conveyor. After pre-inspection the inverter is transferred to one of two inspection stations (IN) by crane. After passing inspection the inverter is completed at station MPFZ. Seven per cent of the products do not pass inspection and have to be repaired on the roller conveyor.

The MPX analysis shows that some of the stations are highly utilized (above 90%), which lead to very long flow times, mainly driven by long waiting time for equipment. The highest utilized stations are the inspection stations and the roller conveyor RC0 and RC4. *Table 5.1* shows flow time and WIP for the various sizes of the initial situation (IS).

5.1.2 Process improvements and impact of demand variability

Various process alternatives were evaluated to identify an appropriate design for the process after the analysis of the current situation. It turned out that two main improvements should be made. First, some activities of the roller conveyor should be transferred to a new station to reduce the work load, and second, an additional inspection station should be installed (a detailed report can be found in Hummer, 2008). Flow times and WIP of the improved process are shown in *Table 5.1.* The improved process performs much better in terms of WIP and flow time.

product sizes	WIP		waiting time for equipment		waiting time for labor		process time		flow time	
	IS	IP	IS	IP	IS	IP	IS	IP	IS	IP
	[pieces]	[pieces]	[days]	[days]	[days]	[days]	[days]	[days]	[days]	[days]
9	9.669	4.045	1.081	0.146	0.01	0.01	0.583	0.544	1.83	0.7
10	3.836	1.602	1.096	0.152	0.01	0.01	0.586	0.547	1.854	0.71
11A	3.967	2.807	0.564	0.174	0.058	0.058	0.709	0.709	1.563	0.942
11B	0.311	0.252	0.394	0.174	0.058	0.058	0.709	0.709	1.393	0.942
12	1.551	2.524	0.365	0.148	0.057	0.057	0.743	0.743	1.37	0.948
13	5.415	4.543	0.531	0.305	0.009	0.009	0.859	0.859	1.713	1.172
14A	9.077	6.141	3.723	2.149	0.009	0.009	1.244	1.209	7.134	3.367
14B	5.599	3.85	3.723	2.149	0.009	0.009	1.396	1.367	7.286	3.525
15	0.843	0.581	3.905	2.252	0.009	0.009	1.489	1.464	7.664	3.725

Table 5.1: WIP and flow time for the initial situation (IS) and for the improved process (IP)

Finally, the impact of different coefficients of variation on process performance is shown. Variation is achieved by using a scaling factor in MPX to multiply the basic model coefficient of variation. By scaling the coefficients of variation of the demand, different levels of demand volatility are simulated. *Figure 5.2* shows that an increase as well as a decrease of the variability factor heavily impacts flow time of some of the products. Sizes 14A, 14B, and 15 (size 15 is shown in *Figure 5.2*) are particularly sensitive to changed variability. This sensitivity is caused by high utilization, which means there is no safety capacity to address increased demand volatility.

For the improved process the sensitivity to variability is much lower. *Figure 5.3* shows that flow times are generally on a lower level, but further they hardly react in increased (scaled) variability.

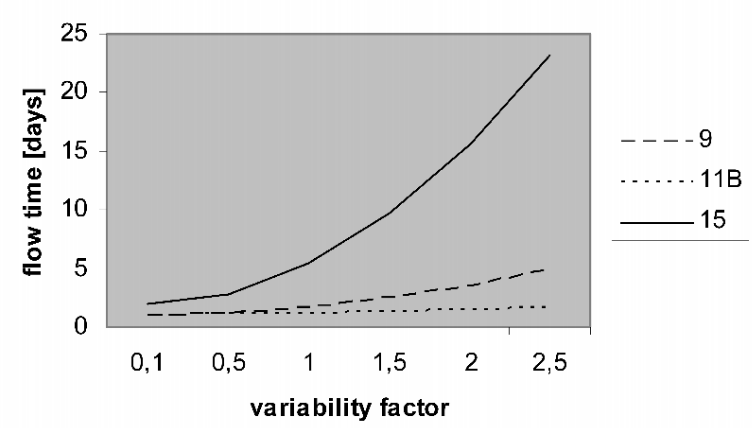

Figure 5.2: Flow time depending on variability factor

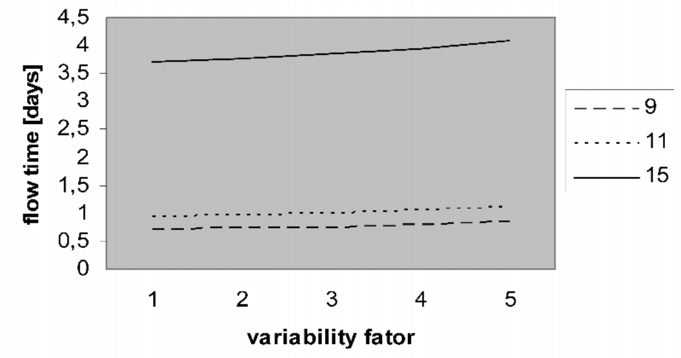

Figure 5.3: Flow time depending on different variability factors for the improved process

These results also show that a comprehensive process evaluation has to take "robustness" of the results into consideration and not only the "ideal" solution based on average values. In the presented example the variability sensitivity has been applied. Based on this variation of the variability, further evaluation model extensions in terms of different risk level analysis, e.g., process risks and disruption risks can easily be implemented.

For the company it was essential to increase capacity at the bottleneck stations to both be able to handle increased future demand and to handle the inherent demand variability.

Finally, *Figure 5.4* shows the improvements in supply chain one, which were presented above. In the initial situation some of the stations were highly utilized, leading to long flow times and high WIP. By increasing bottleneck capacity average utilization was substantially reduced, which lead to much shorter flow times. Thus, the operating point within the OM triangle was moved towards the capacity point (broad arrow). In addition, *Figure 5.4* shows that in the initial situation an increase or decrease of variability has a much higher impact on inventory than in the improved situation, as the vertical distance between two curves representing different coefficients of variation is much higher next to IS than next to IP.

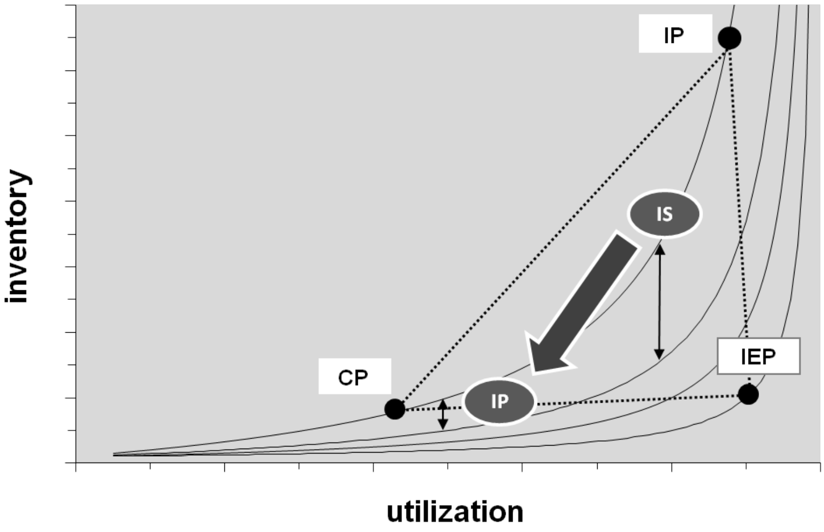

Figure 5.4: Supply chain 1 and the extended OM triangle

5.2 Supply chain 2: Glass Top Assembling

The focal company in this supply chain is a manufacturer near Vienna mainly producing polymer products. This manufacturer also belongs to an international group with its headquarters in Germany. Among its product mix, the manufacturer produces sliding glass tops for industrial refrigerators. The main supplier for the glass is located in France. The glass top is delivered to an Austrian company manufacturing industrial refrigerators for retail chains.

The starting point for the analysis of this supply chain were massive problems with fulfilling customer orders on time and huge amounts of inventory. This process was also modeled and analyzed with MPX. Besides its other effects, this process is used to show explicitly the impact of internal variability induced by batch production. Producing in batches is necessary if different products are produced on the same work station and a setup is necessary to switch between the products. Batching is an important cause of variability and obviously influences flow time through a process (see *Section 3.3.2*).

5.2.1 Initial situation of glass top assembling

The top is delivered in six different variants (A1, A2, A3, B1, B2, and B3) and in sets of one upper top and one lower top. Both the upper and the lower top consist of a glass pane and a plastic frame. *Figure 5.5* shows the simplified process flow diagram of the assembly procedure. The important point to mention is that for a particular batch of glass top sets, first all upper tops are assembled and packed into a box. Then, after setup, all lower tops are assembled and packed into the same box with the upper tops to complete the sets.

Figure 5.5: Assembly process of glass tops

The process was again modeled and analyzed by MPX. *Table 5.2* shows the quarterly production, the used batch size, and the flow time calculated by MPX. Batch sizes were calculated and fixed by the company using the standard EOQ-model, but without taking into account the model's restrictions and assumptions. Especially because of the consideration of very high and questionable fixed costs the batch size was very high and of course responsible for the long flow time (along with some other factors).

Product name	Demand per quarter	Batch size	Flow time [h]
$A1$	2921	288	153.7
$A2$	13696	720	198.5
$A3$	6051	277	160.9
$B1$	2232	156	154.8
$B2$	3303	98	112.5
$B3$	594	24	72.5

Table 5.2: Production quantities, batch sizes and flow time per batch for the six different glass top sets

During the process analysis many alternatives were evaluated and compared. It turned out that the process could be significantly enhanced by adding a second assembling table, enabling parallel assembling of upper and lower tops. By that one part of the long waiting time can be canceled as upper and lower tops have their own equipment and do not have to wait for each other. The analysis of course brought some further measures to improve the process which are not discussed (a detailed report can be found in Kovar and Wiesmühler, 2007). Within this study the focus lies on the impact of batching and the batch size on process performance.

5.2.2 Process improvements and impact of batching

To explicitly illustrate the impact of batch size, we use the model of the improved process, in which the additional assemble table and some other measures are implemented. *Figure 5.6* shows the flow time for a batch of A1 depending on the batch size.

The minimum batch size necessary to be able to produce at all is 37. Batch sizes below 37 lead to an over-utilized process. From batch sizes 37 to 40, flow time sharply decreases with batch size. With batch sizes between 43 and 48 the flow time is a minimum of 7.5 hours. From batch size 49 upward, the flow time increases nearly linearly with batch size. From that, it follows that the batch size used in the initial situation is much too high in terms of flow time.

This example clearly shows that it does indeed make sense to identify the flow time

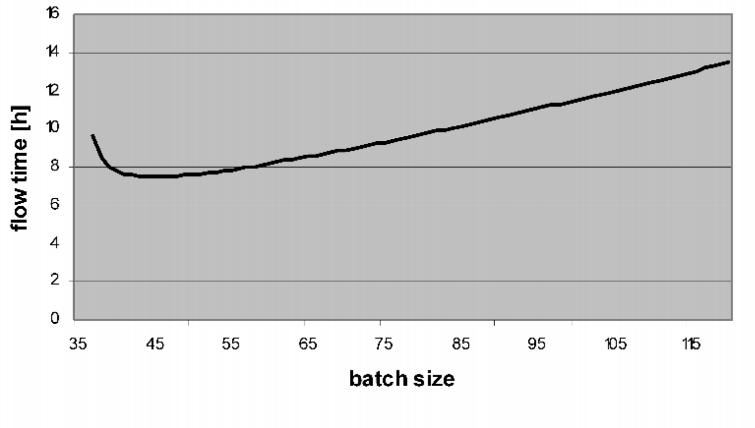

Figure 5.6: Flow time for a batch of A1 depending on batch size

minimal batch size. In this case inappropriately using the EOQ-model as well as state of the art extensions with at least questionable cost information resulted in exceedingly high flow times.

The process has also been improved in reality. The company has installed the second assemble table, reduced the setup time from 30 minutes to 18 minutes and now uses much lower batch sizes. The sum of process improvements doubled the output of the assembly station.

Finally, *Figure 5.4* shows the improvements in supply chain two. In the initial situation some of the stations were highly utilized, leading to long flow times and high WIP. In addition to the utilization, the large batch sizes contributed to long flow times and high WIP. The improvement in this case comprised again an increase of the bottleneck capacity as well as a substantial reduction of the batch size, leading to a much shorter flow time and lower WIP. Thus, the position of the operating point in the OM triangle is moved downwards, as shown in *Figure 5.4*. If regarding just the effect of batch size reduction, the position is also shifted slightly towards the information and excellence point, as with decreased batch size capacity is reduced and utilization is increased.

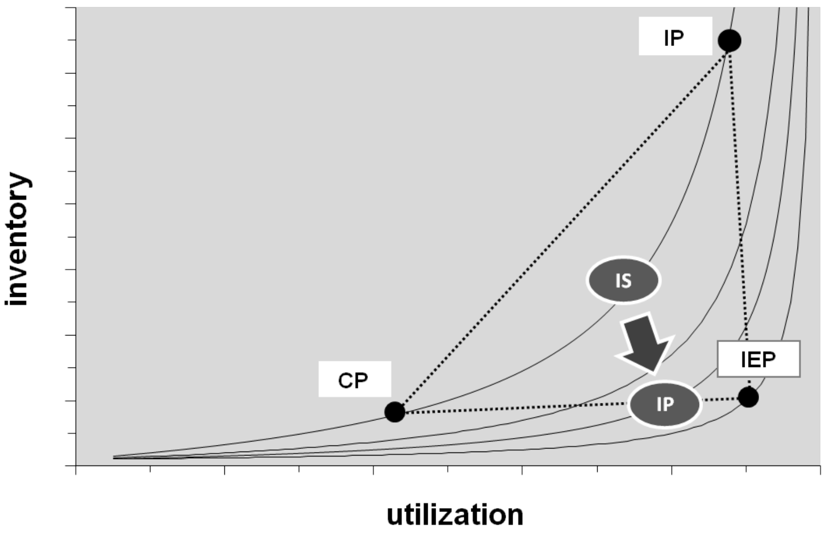

Figure 5.7: Supply chain 2 and the extended OM triangle

6 Conclusion

The main goal of this study is to analyze whether and how variability can be reduced within supply chains and thereby improve the process performance of supply chains. This means that the concept of the OM triangle is extended to the whole supply chain, with a special focus on the analysis of the role of information and its capability of reducing variability. To reach that goal the concepts of uncertainty and variability as well as information sharing and other supply chain and operations management best practices were analyzed.

To analyze the different variability reduction concepts this study takes the viewpoint of a manufacturing company (focal company), working together with suppliers and delivering to business customers. By that, the study is restricted to the business-to-business (B2B) context. Further, the analysis is done on a process level and not on a network level, meaning that supply chain processes of particular products are studied.

6.1 Results

There are two research questions which should be answered in the course of this study (see *Section 1.2*). The first question is how supply chains can get “close” to the information point. From the general queuing model underlying the OM triangle (see *Section 2.1*), it follows that getting close to the information point means reducing variability. Therefore the terms uncertainty and variability have to be clarified. In *Section 3* the different types and sources of variability are discussed and organized in a variability framework. This framework differentiates between supply and demand variability (source) and between variability due to randomness and variability due to management decisions (form) (see *Figure 3.3*). Further, the quantitative impact of the different types of variability are also

Type of variability	Examples	Counter measures
Demand variability due to randomness	Arrival of individual customer orders	Better forecasting Information sharing & coordination with downstream partner (e.g., VMI, CPFR)
Demand variability due to management decision	Product mix (i.e., number of SKUs) Pricing Technological change	“Every-day-low-price” long-term contracts
Supply variability due to randomness	Quality defects Equipment breakdown Worker absenteeism Transit time for local delivery Quality of incoming supplies	Quality management (TQM, Six Sigma) TPM Supplier selection & development Information sharing & coordination with upstream partner (supplier)
Supply variability due to management decision	Preventative maintenance Setup time &Production batch size Transportation batch size	Lean management (e.g., reduction of setup time) Reducing batch size

Table 6.1: Overview of measures to reduce different types of variability from the perspective of a manufacturer

presented. Following from the general queuing model, variability leads to longer waiting times and thereby to longer flow times. In addition, supply variability in particular leads to a decreased capacity, which again increases waiting time, as a decreased capacity implies an increased utilization.

Based on the variability framework various possibilities for reducing variability are presented and analyzed in *Section 4*. Concepts to reduce supply variability are for instance lean management, quality management (TQM, Six Sigma) and Total Productive Maintenance (TPM). The main levers to reduce demand variability are information sharing and coordination. *Table 6.1* gives an overview of the main measures to reduce variability from the perspective of the manufacturer.

The second research question is which information and information sharing concepts reduce variability? This question is mainly addressed in *Section 4.2*, showing that information sharing primarily reduces demand variability, by exchanging data on inventory level, sales and sales forecasts. For supply variability information is only relevant concerning supplier variability, as the manufacturer impacts supplier variability by its ordering behavior. Therefore, sharing information on inventory level, sales and sales forecasts between the manufacturer and the supplier reduces supply variability with respect to the perfect order fulfillment of the customer demand (see *Figure 3.3*).

In the empirical part of the study two real-world production processes are analyzed, using empirical data from the process level. By means of these processes the impact of variability on process performance is shown. In particular, process one (frequency inverter) shows the impact of demand variability, and process two (sliding glass top) shows the impact of supply variability induced by batching. For the analysis, MPX was used, a rapid modeling software based on open queuing networks.

The process improvements concerning demand variability show two things. First, a process properly designed, i.e., with sufficiently high capacity, is much more robust against demand variability. Second, decreasing demand variability, achieved by VMI or other information sharing concepts, leads to an improved process performance in terms of WIP and flow time.

The main finding from process two is the huge impact of high batch sizes on process performance in terms of WIP and flow time. The presented approach to identify the "ideal", i.e., flow time minimal batch size is an interesting alternative compared to existing approaches based on mathematical optimization in a deterministic environment. The advantages of the presented approach are on the one hand low hardware and time requirements for solution finding, compared to the classical approaches. On the other hand, it is possible to take the variability of the input-parameters into account.

6.2 Managerial implications

Finally, some managerial implications should be derived. First, variability has a substantial impact on the process performance of a supply chain, and hedging against variability is costly, as either safety stock or safety capacity has to be held. Consequently, it makes sense for a company to try to decrease variability as much as possible. The range of possible actions are provided in *Table 6.1*.

Second, a manufacturer can reduce variability without having to deal with suppliers or customers, just by eliminating any kinds of variability from the internal manufacturing process. Reducing variability is not just a matter of cooperation and information sharing. Process performance can be substantially enhanced by achieving a more stable and more reliable internal process.

Third, information sharing is a good way to eliminate demand variability. From the manufacturer's point of view it is important to see that he is both a seller (interface with the customer) and a buyer (interface with the supplier). To improve the process performance for the manufacturer concerning perfect order fulfillment (see *Figure 3.1*), it would make sense to seek collaboration with the supplier as well as the customer.

Fourth, the remaining variability can be handled by using a combination of safety stock, safety capacity or safety time. To what extent this depends on the customer's expectations, overall corporate strategy, industry, cost structure, and so forth.

Finally, it can be stated that handling variability within the supply chain is major challenge for every supply chain manager, as there is always some kind of uncertainty or variability. This study may help to organize this broad field of action within supply chains.

Bibliography

Aksin Z, Armony M and Mehrotra V (2007) The modern call center: A multi-disciplinary perspective on operations management research. *Production and Operations Management* 16(6):665–688.

Alderson W (1950) Marketing efficiency and the principle of postponement. *Cost and Profit Outlook* .

Andel T (1996) Manage inventory, own information. *Transportation & Distribution* 37(5):54–58.

Angulo A, Nachtmann H and Waller MA (2004) Supply chain information sharing in a vendor managed inventory partnership. *Journal of Business Logistics* 25(1):101–120.

Anupindi R and Bassok Y (1999) Supply contracts with quantity commitments and stochastic demand. In: Tayur S, Ganeshan R and Magazine M (Eds.) *Quantitative Models for Supply Chain Management*, vol. 17 of *International Series in Operations Research & Management Science*, chap. 7. Kluwer Academic Publishers, 197–232.

Anupindi R, Chopra S, Deshmukh SD, Mieghem JAV and Zemel E (2006) *Managing business process flows: principles of operations management.* 2nd ed. Pearson Prentice Hall.

Aviv Y and Federgruen A (1998) The operational benefits of information sharing and vendor managed inventory (VMI) programs. Working paper, The John M. Olin School of Business, Washington University, St. Louis, `http://www.olin.wustl.edu/faculty/aviv/papers/vmr.pdf`.

Baganha MP and Cohen MA (1998) The stabilizing effect of inventory in supply-chains. *Operations Research* 46(3):S72–S83.

Bailey K and Francis M (2008) Managing information flows for improved value chain performance. *International Journal of Production Economics* 111(1):2–12.

Bassok Y and Anupindi R (2008) Analysis of supply contracts with commitments and flexibility. *Naval Research Logistics* 55(5):459–477.

Bertrand JWM and Fransoo JC (2002) Operations management research methodologies using quantitative modeling. *International Journal of Operations & Production Management* 22(2):241–264.

Bitran GR and Morabito R (1999) An overview of tradeoff curves in manufacturing system design. *Production and Operations Management* 8(1):56–75.

Boone CA, Craighead CW and Hanna JB (2007) Postponement: an evolving supply chain concept. *International Journal of Physical Distribution & Logistics Management* 37(8):594–611.

Boute RN, Disney SM, Lambrecht MR and Van Houdt B (2007) An integrated production and inventory model to dampen upstream demand variability in the supply chain. *European Journal of Operational Research* 178(1):121–142.

Bowersox D and Closs D (1996) *Logistical management. The Integrated Supply Chain Process*. McGraw-Hill.

Bucklin LP (1965) Postponement, speculation and the structure of distribution channels. *Journal of Marketing Research* 2(1):26–31.

Burgess K, Singh PJ and Koroglu R (2006) Supply chain management: a structured literature review and implications for future research. *International Journal of Operations & Production Management* 26(7):703–729.

Buzacott JA and Shanthikumar JG (1993) *Stochastic models of manufacturing systems*. Prentice Hall, Englewood Cliffs.

Cachon G and Terwiesch C (2008) *Matching supply with demand: An introduction to operations management*. 2nd. ed. McGraw-Hill/Irwin.

Cachon GP (2003) Supply chain coordination with contracts. In: de Kok A and Graves S (Eds.) *Supply Chain Management: Design, Coordination and Operation*, vol. 11 of *Handbooks in Operations Research and Management Science*, chap. 6. Elsevier, 227–339.

Cachon GP and Fisher M (1997) Campbell soup's continuous replenishment program: Evaluation and enhanced inventory decision rules. *Production and Operations Management* 6(3):266–276.

Carrillo JE and Franza RM (2006) Investing in product development and production capabilities: The crucial linkage between time-to-market and ramp-up time. *European Journal of Operational Research* 171(2):536–556.

Carter CR and Ellram LM (2003) Thirty-five years of the journal of supply chain management: Where have we been and where are we going? *The Journal of Supply Chain Management* 39(2):27–39.

Cetinkaya S and Lee CY (2000) Stock replenishment and shipment scheduling for vendor-managed inventory systems. *Management Science* 46(2):217–232.

Chase RB and Aquilano NJ (2004) *Operations Management for Competitive Advantage*. 10th ed. McGraw-Hill Irwin.

Chen CT, Lin CT and Huang SF (2006) A fuzzy approach for supplier evaluation and selection in supply chain management. *International Journal of Production Economics* 102(2):289–301.

Chen F (2003) Information sharing and supply chain coordination. In: de Kok A and Graves S (Eds.) *Supply Chain Management: Design, Coordination and Operation*, vol. 11 of *Handbooks in Operations Research and Management Science*, chap. 7. Elsevier, 341–421.

Chen F, Drezner Z, Ryan JK and Simchi-Levi D (2000) Quantifying the bullwhip effect in a simple supply chain: The impact of forecasting, lead times, and information. *Management Science* 46(3):436–443.

Chen IJ and Paulraj A (2004a) Towards a theory of supply chain management: the constructs and measurements. *Journal of Operations Management* 22(2):119–150.

Chen IJ and Paulraj A (2004b) Understanding supply chain management: critical research and a theoretical framework. *International Journal of Production Research* 42(1):131–163.

Childerhouse P, Hermiz R, Mason-Jones R, Popp A and Towill DR (2003) Information flow in automotive supply chains–present industrial practice. *Industrial Management & Data Systems* 103(3):137–149.

Chopra S and Meindl P (2007) *Supply Chain Management: Strategy, Planning & Operation*. 3rd ed. Pearson Prentice Hall, Upper Saddle River, New Jersey.

Cohen MA, Eliashberg J and Ho TH (1996) New product development: The performance and time-to-market tradeoff. *Management Science* 42(2):173–186.

Cooper MC, Lambert DM and Pagh JD (1997) Supply chain management: More than a new name for logistics. *The International Journal of Logistics Management* 8(1):1–14.

Corbett C and Tang C (1999) Designing supply contracts: Contract type and information asymmetry. In: Tayur S, Ganeshan R and Magazine M (Eds.) *Quantitative Models for Supply Chain Management*, vol. 17 of *International Series in Operations Research & Management Science*, chap. 9. Kluwer Academic Publishers, 269–298.

Corbett CJ, Zhou D and Tang CS (2004) Designing supply contracts: Contract type and information asymmetry. *Management Science* 50(4):550–559.

Croom S, Romano P and Giannakis M (2000) Supply chain management: an analytical framework for critical literature review. *European Journal of Purchasing & Supply Management* 6(1):67–83.

Dalkey N and Helmer O (1963) An experimental application of the delphi method to the use of experts. *Management Science* 9(3):458–467.

Dapiran P (1993) Benetton - global logistics in action. *International Journal of Physical Distribution & Logistics Management* 22(6):7–11.

Darwish M and Odah O (2010) Vendor managed inventory model for single-vendor multi-retailer supply chains. *European Journal of Operational Research* 204(3):473–484.

Davis T (1993) Effective supply chain management. *Sloan Management Review* 34(4):35–46.

de Treville S and Van Ackere A (2006) Equipping students to reduce lead times: The role of queuing-theory-based modeling. *Interfaces* 36(2):165–173.

Dejonckheere J, Disney SM, Lambrecht MR and Towill DR (2003) Measuring and avoiding the bullwhip effect: A control theoretic approach. *European Journal of Operational Research* 147(3):567–590.

Disney S and Towill D (2003a) Vendor-managed inventory and bullwhip reduction in a two-level supply chain. *International Journal of Operations & Production Management* 23(6):625–651.

Disney SM and Towill DR (2003b) The effect of vendor managed inventory (vmi) dynamics on the bullwhip effect in supply chains. *International Journal of Production Economics* 85(2):199–215.

Disney SM and Towill DR (2003c) On the bullwhip and inventory variance produced by an ordering policy. *Omega* 31(3):157–167.

Downey HK and Slocum JW (1975) Uncertainty: Measures, research, and sources of variation. *The Academy of Management Journal* 18(3):562–578.

Enns ST (1996) Analysis of a process improvement path using rapid modeling. *Total Quality Management* 7(3):283–292.

Fawcett SE, Ellram LM and Ogden JA (2007) *Supply chain management: From vision to implementation*. Pearson International Edition.

Feitzinger E and Lee HL (1997) Mass customization at hewlett-packard: The power of postponement. *Harvard Business Review* 75(1):116–121.

Fiala P (2005) Information sharing in supply chains. *Omega* 33(5):419–423.

Field JM, Ritzman LP, Safizadeh MH and Downing CE (2006) Uncertainty reduction approaches, uncertainty coping approaches, and process performance in financial services. *Decision Sciences* 37(2):149–175.

Fisher M, Hammond J, Obermeyer W and Raman A (1997) Configuring a supply chain to reduce the cost of demand uncertainty. *Production and Operations Management* 6(3):211–225.

Fisher ML (1997) What is the right supply chain for your product? *Harvard Business Review* 75(2):105–116.

Forrester JW (1958) Industrial dynamics: A major breakthrough for decision makers. *Harvard Business Review* 36(4):37–66.

Forrester JW (1961) *Industrial dynamics*. MIT Press, New York.

Forslund H (2007) Measuring information quality in the order fulfilment process. *International Journal of Quality & Reliability Management* 24(0265-671X):515–524.

Fransoo JC and Wouters MJ (2000) Measuring the bullwhip effect in the supply chain. *Supply Chain Management: An International Journal* 5(2):78–89.

Fry MJ, Kapuscinski R and Olsen TL (2001) Coordinating production and delivery under a (z, z)-type vendor-managed inventory contract. *Manufacturing & Service Operations Management* 3(2):151–173.

Ganeshan R, Jack E, Magazine MJ and Stephens P (1999) A taxonomic review of supply chain management research. In: Tayur S, Ganeshan R and Magazine MJ (Eds.) *Quantitative Models for Supply Chain Management*, vol. 17 of *International Series in Operations Research & Management Science*, chap. 27. Kluwer Academic Publishers, 839–879.

Gaur V, Kesavan S, Raman A and Fisher ML (2007) Estimating demand uncertainty using judgmental forecasts. *Manufacturing & Service Operations Management* 9(4):480–491.

Geary S, Childerhouse P and Towill D (2002) Uncertainty and the seamless supply chain. *Supply Chain Management Review* 6(4):52–61.

Geary S, Disney S and Towill D (2006) On bullwhip in supply chains - historical review, present practice and expected future impact. *International Journal of Production Economics* 101(1):2–18.

Germain R, Claycomb C and Dröge C (2008) Supply chain variability, organizational structure, and performance: The moderating effect of demand unpredictability. *Journal of Operations Management* 26(5):557–570.

Giannakis M, Croom S and Slack N (2004) Supply chain paradigms. In: New S and Westbrook R (Eds.) *Understanding Supply Chains: Concepts, Critiques & Futures*, chap. 1. Oxford University Press, 1–21.

Gibson BJ, Mentzer JT and Cook RL (2005) Supply chain management: The pursuit of a consensus definition. *Journal of Business Logistics* 26(2):17–25.

Gimpl-Heersink L (2008) *Joint Pricing and Inventory Control under Reference Price Effects*. Ph.D. thesis, Vienna University of Economics and Business Administration.

Giunipero LC, Hooker RE, Joseph-Matthews S, Yoon TE and Brudvig S (2008) A decade of SCM literature: Past, present and future implications. *Journal of Supply Chain Management: A Global Review of Purchasing & Supply* 44(4):66–86.

Graman GA and Magazine MJ (2006) Implementation issues influencing the decision to adopt postponement. *International Journal of Operations & Production Management* 26(10):1068–1083.

Gunasekaran A and Ngai EWT (2004) Information systems in supply chain integration and management. *European Journal of Operational Research* 159(2):269–295.

Gutjahr I (2008) *Analyse und Bewertung von Vendor Managed Inventory mithilfe eines Simulationsmodells anhand eines Beispiels aus der Elektronikindustrie*. Master's thesis, WU - Vienna University of Economics and Business.

Hackman JR and Wageman R (1995) Total quality management: Empirical, conceptual, and practical issues. *Administrative Science Quarterly* 40(2):309–342.

Hahn CK, Watts CA and Kim KY (Spring 1990) The supplier development program: A conceptual model. *Journal of Purchasing and Materials Management* 26(2):2–7.

Hall RW (1991) *Queueing Methods - For Services and Manufacturing*. Prentice-Hall Int., Englewood Cliffs.

Hammond JH (1994) Barilla SpA (A). *Harvard Business Case* 694046.

Hammond JH (1995) Barilla SpA (B). *Harvard Business Case* 695064.

Hauser JR and Clausing D (1988) The house of quality. *Harvard Business Review* 66(3):63–73.

Heskett JL and Signorelli S (1985) Benetton (B). *Harvard Business Case* 9-685-020.

Hill T (2000) *Manufacturing Strategy*. 3rd ed. McGraw-Hill, Boston, Mass.

Hirshleifer J and Riley JG (1992) *The analytics of uncertainty and information*. Cambridge surveys of economic literature, Cambridge University Press.

Holmstrom J, Framling K, Kaipia R and Saranen J (2002) Collaborative planning forecasting and replenishment: New solutions needed for mass collaboration. *Supply Chain Management: An International Journal* 7(3/4):136–145.

Hopp WJ (2008) Single server queueing models. In: Chhajed D and Lowe TJ (Eds.) *Building Intuition*, vol. 115 of *International Series in Operations Research & Management Science*, chap. 4. Springer US, 51–79.

Hopp WJ and Spearman ML (2007) *Factory Physics: Foundations of Manufacturing Management*. 3rd ed. McGraw Hill, Chicago.

Hosoda T and Disney SM (2006) On variance amplification in a three-echelon supply chain with minimum mean square error forecasting. *Omega* 34:344–358.

Huang GQ, Lau JS and Mak K (2003) The impacts of sharing production information on supply chain dynamics: a review of the literature. *International Journal of Production Research* 41(7):1483–1517.

Hummer R (2008) *Auswirkung von Variabilit´at auf die Leistungsf´ahigkeit von Produktionsprozessen anhand einer Fallstudie aus der Elektronikindustrie*. Master's thesis, WU - Vienna University of Economics and Business.

Ittner CD and Larcker DF (1999) Supplier selection, monitoring practices, and firm performance. *Journal of Accounting & Public Policy* 18(3):253–281.

Jackson JR (1963) Jobshop-like queueing systems. *Management Science* 10(1):131–142.

Jammernegg W and Reiner G (2007) Performance improvement of supply chain processes by coordinated inventory and capacity management. *International Journal of Production Economics* 108:183–190.

Kaipia R and Hartiala H (2006) Information - sharing in supply chains: five proposals on how to proceed. *International Journal of Logistics Management* 17(3):377–393.

Ketzenberg ME, Rosenzweig ED, Marucheck AE and Metters RD (2007) A framework for the value of information in inventory replenishment. *European Journal of Operational Research* 182(3):1230–1250.

Kim JG, Chatfield D, Harrison TP and Hayya JC (2006) Quantifying the bullwhip effect in a supply chain with stochastic lead time. *European Journal of Operational Research* 173(2):617–636.

Kimura T (1983) Diffusion approximation for an m/g/m queue. *Operations Research* 31(2):304–321.

Kingman JFC (1961) The single server queue in heavy traffic. *Proceedings of the Cambridge Philosophical Society* 57(4):902–904.

Klassen RD and Menor LJ (2007) The process management triangle: An empirical investigation of process trade-offs. *Journal of Operations Management* 25(5):1015–1034.

Kleinrock L (1975) *Queueing systems 1*. Wiley-Interscience, New York.

Kleinrock L (1976) *Queueing Systems 2*. Wiley-Interscience, New York.

Kok AGd and Graves SC (2003) Introduction. In: de Kok A and Graves S (Eds.) *Supply Chain Management: Design, Coordination and Operation*, vol. 11 of *Handbooks in Operations Research and Management Science*, chap. 1. Elsevier, 1–14.

Koller S (2008) *Value of information in supply chains*. Master's thesis, WU - Vienna University of Economics and Business.

Kouvelis P, Chambers C and Wang H (2006) Supply chain management research and production and operations management: Review, trends, and opportunities. *Production & Operations Management* 15(3):449–469.

Kovar R and Wiesmühler G (2007) *Prozessanalyse als Schlüssel der Prozessoptimierung - Analyse und Verbesserung des Prozesses in der Glasdeckelproduktion im Werk Neulengbach (Österreich)*. Master's thesis, WU - Vienna University of Economics and Business.

Krause DR, Handfield RB and Scannell TV (1998) An empirical investigation of supplier development: reactive and strategic processes. *Journal of Operations Management* 17(1):39–58.

Kulp SC, Lee HL and Ofek E (2004) Manufacturer benefits from information integration with retail customers. *Management Science* 50(4):431–444.

Kulp SC, Ofek E and Whitaker J (2003) Supply chain coordination: How companies leverage information flows to generate value. In: Harrison TP, Lee HL and Neale JJ (Eds.) *The Practice of Supply Chain Management: Where Theory and Application Converge*, chap. 6. Kluwer Academic Publishers Group, 91–108.

Lalwani CS, Disney SM and Naim MM (2006) On assessing the sensitivity to uncertainty in distribution network design. *International Journal of Physical Distribution & Logistics Management* 36(1):5–21.

Lariviere M (1999) Supply chain contracting and coordination with stochastic demand. In: Tayur S, Ganeshan R and Magazine M (Eds.) *Quantitative Models for Supply Chain Management*, vol. 17 of *International Series in Operations Research & Management Science*, chap. 8. Kluwer Academic Publishers, 233–268.

Ledolter J and Burril CW (1999) *Statistical quality control - Strategies and tools for continual improvement.* John Wiley & Sons, Inc., New York.

Lee CC and Chu WHJ (2005) Who should control inventory in a supply chain? *European Journal of Operational Research* 164(1):158–172.

Lee HL (2002) Aligning supply chain strategies with product uncertainties. *California Management Review* 44(3):105–119.

Lee HL, Padmanabhan V and Wang S (1997a) The bullwhip effect in supply chains. *Sloan Management Review* 38(3):93–102.

Lee HL, Padmanabhan V and Whang S (1997b) Information distortion in a supply chain: The bullwhip effect. *Management Science* 43(4):546–558.

Lee HL, Padmanabhan V and Whang S (2004) Comments on information distortion in a supply chain: The bullwhip effect. *Management Science* 50(12):1887–1893.

Lee HL and Whang S (2000) Information sharing in a supply chain. *International Journal of Manufacturing Technology and Management* 20(3/4):373–387.

Lee HL and Whang S (2006) The bullwhip effect: A review of field studies. In: Carranza Torres OA and Villegas Moran FA (Eds.) *The Bullwhip Effect in Supply Chains: A Review of Methods, Components and Cases*. Palgrave McMillan, New York, 57–70.

Li G, Yan H, Wang S and Xia Y (2005) Comparative analysis on value of information sharing in supply chains. *Supply Chain Management: An International Journal* 10(1):34–46.

Li J, Sikora R, Shaw MJ and Woo Tan G (2006) A strategic analysis of inter organizational information sharing. *Decision Support Systems* 42(1):251–266.

Lindley DV (2006) *Understanding uncertainty.* Wiley, New Jersey.

Little JDC (1961) A proof for the queuing formular: $L = \lambda W$. *Operations Research* 9(3):383–387.

Lovejoy WS (1998) Integrated operations: A proposal for operations management teaching and research. *Production and Operations Management* 7(2):106–124.

Magretta J (1998) The power of virtual integration: An interview with dell computer's michael dell. *Harvard Business Review* 76(2):72–84.

Malhotra A, Gosain S and Sawy OAE (2005) Absorptive capacity configurations in supply chains: Gearing for partner-enabled market knowledge creation. *MIS Quarterly* 29(1):145–187.

Mapes J, Szwejczewski M and New C (2000) Process variability and its effect on plant performance. *International Journal of Operations & Production Management* 20(0144-3577):792–808.

Melnyk SA and Handfield RB (1998) May you live in interesting times...the emergence of theory-driven empirical research. *Journal of Operations Management* 16(4):311–319.

Melnyk SA, Lummus RR, Vokurka RJ, Burns LJ and Sandor J (2009) Mapping the future of supply chain management: a delphi study. *International Journal of Production Research* 47(16):4629–4653.

Mentzer JT, DeWitt W, Keebler JS, Min S, Nix NW, Smith CD and Zacharia ZG (2001) Defining supply chain management. *Journal of Business Logistics* 22(2):1–25.

Metters R (1997) Quantifying the bullwhip effect in supply chains. *Journal of Operations Management* 15(2):89–100.

Meyr H (2003) Die Bedeutung von Entkopplungspunkten für die operative Planung von Supply Chains. *Zeitschrift für Betriebswirtschaft* 9:1–22.

Miller H (1996) The multiple dimensions of information quality. *Information Systems Management* 13(2):79–82.

Miragliotta G (2006) Layers and mechanisms: A new taxonomy for the bullwhip effect. *International Journal of Production Economics* 104(2):365–381.

Morishima M (1991) Information sharing and firm performance in japan. *Industrial Relations* 30(1):37–61.

Muchiri P and Pintelon L (2008) Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion. *International Journal of Production Research* 46(13):3517–3535.

Nahmias S (2008) *Production and Operations Analysis*. 6th ed. McGraw Hill, Boston.

Nakajima S (1988) *Introduction to TPM: Total Productive Maintenance*. Productivity Press, Cambridge, MA.

NN (1996) *Collins Dictionary*. Harper Collins Publishers.

Nyhuis P and Wiendahl HP (2009) *Fundamentals of Production Logistics - Theory, Tools and Applications*. Springer, Berlin Heidelberg.

Oliver RK and Webber MD (1992) Supply chain management: Logistics catches up with strategy. *Outlook (1982) reprinted*. In: *Logistics: the Strategic Issues*, chap. 6. Chapman & Hall, London, 63–75.

P Cachon G, Randall T and Schmidt GM (2007) In search of the bullwhip effect. *Manufacturing & Service Operations Management* 9(4):457–479.

Pannirselvam GP, Ferguson LA, Ash RC and Siferd SP (1999) Operations management research: An update for the 1990s. *Journal of Operations Management* 18(1):95–112.

Petruzzi NC and Dada M (1999) Pricing and the newsvendor problem: A review with extensions. *Operations Research* 47(2):183–194.

Prahalad CK and Hamel G (1990) The core competence of the corporation. *Harvard Business Review* 68(3):79–91.

Rabta B (2009) A review of decomposition methods for open queueing networks. In: Reiner G (Ed.) *Rapid Modelling for Increasing Competitiveness*. Springer London, London, 25–42.

Rabta B, Alp A and Reiner G (2009) Queueing networks modeling software for manufacturing. In: Reiner G (Ed.) *Rapid Modelling for Increasing Competitiveness*. Springer London, London, 15–23.

Reiner G (2005) Customer-oriented improvement and evaluation of supply chain processes supported by simulation models. *International Journal of Production Economics* 96(3):381–395.

Reiner G and Fichtinger J (2009) Demand forecasting for supply processes in consideration of pricing and market information. *International Journal of Production Economics* 118(1):55–62.

Reiner G and Jammernegg W (2005) Bewertung unterschiedlicher Beschaffungsstrategien für Risk-Hedging Supply Chains unter Berücksichtigung intermodaler Transportprozesse. In: Günther HO, Mattfeld DC and Suhl L (Eds.) *Supply Chain Management und Logistik*. Physica-Verlag HD, 115–134.

Reiner G and Poiger M (2010) Evaluation of supply chain improvements illustrated by means of a JIS supply process from the automotive industry. In: Reiner G (Ed.) *Rapid Modelling and Quick Respone - Intersection of Theory and Practice*. Springer, London, 289–301.

Reisman A and Kirschnick F (1995) Research strategies used by OR/MS workers as shown by an analysis of papers in flagship journals. *Operations Research* 43(5):731–740.

Sahin F and Robinson EP (2002) Flow coordination and information sharing in supply chains: Review, implications, and directions for future research. *Decision Sciences* 33(4):505–536.

Sanchez-Rodrigues V, Potter A and Naim MM (2010) Evaluating the causes of uncertainty in logistics operations. *International Journal of Logistics Management* 21(1):45–64.

Sari K (2007) Exploring the benefits of vendor managed inventory. *International Journal of Physical Distribution & Logistics Management* 37(7):529–545.

Sari K (2008) On the benefits of cpfr and vmi: A comparative simulation study. *International Journal of Production Economics* 113(2):575–586.

SCC (2008) *Supply Chain Operations Reference Model - Version 9.0*. http://supply-chain.org/.

Schmenner RW and Swink ML (1998) On theory in operations management. *Journal of Operations Management* 17(1):97–113.

Schmidt GM (2005) The OM triangle. *Operations Management Education Review* 1(1):87–104.

Schroeder RG, Linderman K, Liedtke C and Choo AS (2008) Six sigma: Definition and underlying theory. *Journal of Operations Management* 26(4):536–554.

Schwarz LB (1998) A new teaching paradigm: The information/control/buffer portfolio. *Production and Operations Management* 7(2):125–131.

Schwarz LB (2005) The state of practice in supply-chain management: A research perspective. In: Geunes J, Akçali E, Pardalos PM, Romeijn HE and Shen ZJM (Eds.) *Applications of Supply Chain Management and E-Commerce Research*, vol. 92 of *Applied Optimization*, chap. 11. Springer US, 325–361.

Shewhart WA (1931) *Economic Control of Quality of Manufactured Product.* Republished 1980 by the American Society for Quality Control Quality Press, Michigan, USA.

Shin H, Collier DA and Wilson DD (2000) Supply management orientation and supplier/buyer performance. *Journal of Operations Management* 18(3):317–333.

Silver EA (2004) Process management instead of operations management. *Manufacturing & Service Operations Management* 6(4):273–279.

Silver EA, Pyke DF and Peterson R (1998) *Inventory Management and Production Planning and Scheduling*. 3rd ed. Wiley.

Simchi-Levi D, Kaminsky P and Simchi-Levi E (2008) *Designing and managing the supply chain: Concepts, Strategies and Case Studies.* 3rd ed. McGraw-Hill, Boston.

Simpson PM, Siguaw JA and White SC (2002) Measuring the performance of suppliers: An analysis of evaluation processes. *Journal of Supply Chain Management* 38(1):29–41.

Stalk Jr G (1988) Time–the next source of competitive advantage. *Harvard Business Review* 66(4):41–51.

Steckel JH, Gupta S and Banerji A (2004) Supply chain decision making: Will shorter cycle times and shared point-of-sale information necessarily help? *Management Science* 50(4):458–464.

Sterman JD (1989) Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science* 35(3):321–339.

Stidham, Jr S (2002) Analysis, design, and control of queueing systems. *Operations Research* 50(1):197–216.

Storey J, Emberson C, Godsell J and Harrison A (2006) Supply chain management: theory, practice and future challenges. *International Journal of Operations & Production Management* 26(7):754–774.

Suri R, Diehl GWW, De Treville S and Tomsicek MJ (1995) From can-q to mpx: Evolution of queuing software for manufacturing. *Interfaces* 25(5):128–150.

Swamidass PM (Ed.) (2000) *Encyclopedia of production and manufacturing management.* Kluwer Academic Publishers, Boston.

Swaminathan JM and Tayur SR (2003) Tactical planning models for supply chain management. In: de Kok A and Graves S (Eds.) *Supply Chain Management: Design, Coordination and Operation*, vol. 11 of *Handbooks in Operations Research and Management Science*, chap. 8. Elsevier, 423–454.

Taguchi G and Clausing D (1990) Robust quality. *Harvard Business Review* 68(1):65–75.

Tan KC (2001) A framework of supply chain management literature. *European Journal of Purchasing & Supply Management* 7(1):39–48.

Tsay AA and Lovejoy WS (1999) Quantity flexibility contracts and supply chain performance. *Manufacturing & Service Operations Management* 1(2):89–111.

Tsay AA, Nahmias S and Agrawal N (1999) Modeling supply chain contracts: A review. In: Tayur S, Ganeshan R and Magazine M (Eds.) *Quantitative Models for Supply Chain Management*, vol. 17 of *International Series in Operations Research & Management Science*, chap. 10. Kluwer Academic Publishers, 299–336.

University of Neuchâtel (2010) Keeping Jobs in Europe. http://www2.unine.ch/iene-kje.

van der Vorst JGAJ and Beulens AJM (2002) Identifying sources of uncertainty to generate supply chain redesign strategies. *International Journal of Physical Distribution & Logistics Management* 32(6):409–430.

van der Vorst JGAJ, van Dijk SJ and Beulens AJM (2001) Supply chain design in the food industry. *International Journal of Logistics Management* 12(2):73–85.

Van Hoek RI (2000) The thesis of leagility revisited. *International Journal of Agile Management Systems* 2(3):196–201.

Van Hoek RI (2001) The rediscovery of postponement a literature review and directions for research. *Journal of Operations Management* 19(2):161–184.

Vandaele NJ and Nieuwenhuyse I (2009) Rapid modeling in a lean context. In: Reiner G (Ed.) *Rapid Modelling for Increasing Competitiveness*. Springer London, London, 163–173.

VICS (2004) CPFR: An overview. White paper, Voluntary Interindustry Commerce Standards (VICS), `http://www.vics.org`.

Vigtil A (2007) Information exchange in vendor managed inventory. *International Journal of Physical Distribution & Logistics Management* 37(2):131–147.

Waller M, Johnson ME and Davis T (1999) Vendor-managed inventory in the retail supply chain. *Journal of Business Logistics* 20(1):183–203.

Warburton RDH (2004) An analytical investigation of the bullwhip effect. *Production & Operations Management* 13(2):150–160.

Watts CA and Hahn CK (Spring 1993) Supplier development programs: An empirical analysis. *International Journal of Purchasing and Materials Management* 29(2):10–17.

Wiengarten F, Humphreys P, Cao G, Fynes B and McKittrick A (2010) Collaborative supply chain practices and performance: exploring the key role of information quality. *Supply Chain Management: An International Journal* 15(6):463–473.

Womack J and Jones D (1996) *Lean thinking*. Simon & Schuster, New York.

Womack J, Jones D and Ross D (1990) *The Machine that Changed the World.* Rawson, New York.

Yang B and Burns N (2003) Implications of postponement for the supply chain. *International Journal of Production Research* 41(9):2075–2090.

Yang B, Burns ND and Backhouse CJ (2004a) Management of uncertainty through postponement. *International Journal of Production Research* 42(6):1049–1064.

Yang B, Burns ND and Backhouse CJ (2004b) Postponement: a review and an integrated framework. *International Journal of Operations & Production Management* 24(5):468–487.

Yao Y and Dresner M (2008) The inventory value of information sharing, continuous replenishment, and vendor-managed inventory. *Transportation Research Part E: Logistics and Transportation Review* 44(3):361–378.

Yee ST (2005) Impact analysis of customized demand information sharing on supply chain performance. *International Journal of Production Research* 43(16):3353–3373.

Zhou H and Benton Jr W (2007) Supply chain practice and information sharing. *Journal of Operations Management* 25(6):1348–1365.