Lehrstuhl für
Werkzeugmaschinen und Fertigungstechnik
der Technischen Universität München

Managing Quality and Delivery Reliability of Suppliers by Using Incentives and Simulation Models

Patrick Neise

Vollständiger Abdruck der von der Fakultät für Maschinenwesen der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs (Dr.-Ing.)

genehmigten Dissertation.

Vorsitzender: Univ.-Prof. Dr.-Ing. G. Reinhart

Prüfer der Dissertation:

1. Univ.-Prof. Dr.-Ing. M. Zäh
2. Prof. Dr. sc. P. Schönsleben, Eidgenössische Technische Hochschule Zürich / Schweiz

Die Dissertation wurde am 15.09.2008 bei der Technischen Universität München eingereicht und durch die Fakultät für Maschinenwesen am 09.01.2009 angenommen.

Patrick Neise

Managing Quality and Delivery Reliability of Suppliers by Using Incentives and Simulation Models

Herbert Utz Verlag · München

Forschungsberichte IWB

Band 231

Zugl.: Diss., München, Techn. Univ., 2009

Bibliografische Information der Deutschen Nationalbibliothek: Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.

ISBN 978-3-8316-0878-2

Printed in Germany
Herbert Utz Verlag GmbH, München
089-277791-00 · www.utzverlag.de

Meinen lieben Eltern Gaby und Winfried Neise

Geleitwort des Herausgebers

Die Produktionstechnik ist für die Weiterentwicklung unserer Industriegesellschaft von zentraler Bedeutung, denn die Leistungsfähigkeit eines Industriebetriebes hängt entscheidend von den eingesetzten Produktionsmitteln, den angewandten Produktionsverfahren und der eingeführten Produktionsorganisation ab. Erst das optimale Zusammenspiel von Mensch, Organisation und Technik erlaubt es, alle Potentiale für den Unternehmenserfolg auszuschöpfen.

Um in dem Spannungsfeld Komplexität, Kosten, Zeit und Qualität bestehen zu können, müssen Produktionsstrukturen ständig neu überdacht und weiterentwickelt werden. Dabei ist es notwendig, die Komplexität von Produkten, Produktionsabläufen und -systemen einerseits zu verringern und andererseits besser zu beherrschen.

Ziel der Forschungsarbeiten des *iwb* ist die ständige Verbesserung von Produktentwicklungs- und Planungssystemen, von Herstellverfahren sowie von Produktionsanlagen. Betriebsorganisation, Produktions- und Arbeitsstrukturen sowie Systeme zur Auftragsabwicklung werden unter besonderer Berücksichtigung mitarbeiterorientierter Anforderungen entwickelt. Die dabei notwendige Steigerung des Automatisierungsgrades darf jedoch nicht zu einer Verfestigung arbeitsteiliger Strukturen führen. Fragen der optimalen Einbindung des Menschen in den Produktentstehungsprozess spielen deshalb eine sehr wichtige Rolle.

Die im Rahmen dieser Buchreihe erscheinenden Bände stammen thematisch aus den Forschungsbereichen des *iwb*. Diese reichen von der Entwicklung von Produktionssystemen über deren Planung bis hin zu den eingesetzten Technologien in den Bereichen Fertigung und Montage. Steuerung und Betrieb von Produktionssystemen, Qualitätssicherung, Verfügbarkeit und Autonomie sind Querschnittsthemen hierfür. In den *iwb* Forschungsberichten werden neue Ergebnisse und Erkenntnisse aus der praxisnahen Forschung des *iwb* veröffentlicht. Diese Buchreihe soll dazu beitragen, den Wissenstransfer zwischen dem Hochschulbereich und dem Anwender in der Praxis zu verbessern.

Gunther Reinhart *Michael Zäh*

Vorwort

Die vorliegende Dissertation entstand während Tätigkeit als wissenschaftlicher Mitarbeiter am Institut für Werkzeugmaschinen und Betriebswissenschaften (iwb) der Technischen Universität München.

Herrn Professor Dr.-Ing. Michael Zäh und Herrn Professor Dr.-Ing. Gunther Reinhart, den Leitern des Instituts, gilt mein besonderer Dank für die wohlwollende Förderung und großzügige Unterstützung dieser Arbeit. Bei Herrn Professor Dr. sc. P. Schönsleben, dem Leiter des BWI an der ETH Zürich, möchte ich mich für die Übernahme des Koreferats, die sehr aufmerksame Durchsicht der Arbeit und interessante Diskussionen herzlich bedanken.

Mein Dank gilt darüber hinaus allen Mitarbeiterinnen und Mitarbeitern des Instituts sowie allen Studenten, die mich bei der Erstellung der Arbeit unterstützt haben. Insbesondere bedanke ich mich bei Herrn Dr.-Ing. Robert Cisek, Herrn Dr.-Ing. Thomas Fusch, Herrn Dr.-Ing. Christian Habicht, Herrn Dr.-Ing. Niklas Möller, Herrn Dr.-Ing. Nils Müller, Herrn Dr.-Ing. Andreas Peukert und Herrn Dr.-Ing. Wolfgang Sudhoff für fachlichen Rat, Freundschaft und spannende Unterhaltungen, letztere oft beim abendlichen Bier.

Diese Arbeit konnte nur durch die Unterstützung meiner Eltern entstehen. Sie haben mir meine Ausbildung ermöglicht und mir stets in allen Lebenssituationen liebevoll geholfen und Halt gegeben, Ihnen ist die Arbeit gewidmet.

Mein besonderer Dank gilt meiner Frau Susanne für Ihre Geduld und fortwährende Motivation bei der Fertigstellung dieser Arbeit sowie meiner Tochter Cecilia, deren Geburt und Anwesenheit mir vor der mündlichen Prüfung geholfen hat die "großen von den kleinen Steinen" zu unterscheiden.

Schließlich danke ich allen, die immer an die Fertigstellung dieser Arbeit geglaubt haben!

München, im Januar 2009 *Patrick Neise*

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Asymp. sig.	Asymptotic significance
BWI	Center for Enterprise Sciences of the Swiss Federal Institute of Technology Zurich
cdf	Cumulative density function
CODP	Customer order decoupling point
Cpk	Process capability index
DoF	Degrees of freedom
ERP	Enterprise resource planning
Et. seq.	et sequentes
GSM	Global System for Mobile Communication
IML	Fraunhofer Institute for Material Flow and Logistics
IPA	Fraunhofer Institute for Production Technology and Automization
IT	Information technology
iwb	Institute for Machine Tools and Industrial Management, Technische Universität München
Mn	Million
MTO	Make to order
MTS	Make to stock
NE	Nash Equilibrium
OEM	Original equipment manufacturer
pdf	Probability distribution function
PIN	Personal identification number
Ppk	Process performance index

Ppm	(Defective) parts per million
PPS	Production planning and scheduling
PTO	Purchase to order
SCOR	Supply chain operations reference
SCM	Supply chain management
SCM-CTC	SCM-Competence and Transfer Center
SD	System Dynamics
SQM	Supplier quality management
UICC	Universal integrated circuit card
UMTS	Universal molbile telecommunications system

List of Notations

A	Action profile
a_i^t	Action of player i at time t
$arg\ max$	Value of an argument for which the expression reaches its maximum
c	Per part production cost
δ	Discount factor
E_{ij}	Expected frequency in the i^{th} category of the row variable and the j^{th} category of the column variable
$E(r)$	Expected penalty cost
F_{ij}	Frequency in the i^{th} category of the row variable and the j^{th} category of the column variable
G	Stage game
h^t	History of actions, history of the game
I	Player set
i	Player
ir	Interest rate
k	Number of punishment periods
$\lambda_{1/2}$	Goodman-Kruskal lambda
n	Number of stages
$n_{..}$	Total number of observations
$n_{i.}$	Total number of observations in the i^{th} category of the row variable
$n_{.j}$	Total number of observations in the j^{th} category of the column variable

n_{ij}	Number of observations in the i^{th} category of the row variable and the j^{th} category of the column variable
N	Total number of observations
P	Probability of good quality
p_{ij}	Probability of the i^{th} category of the row variable and the j^{th} category of the column variable
$p_{i\cdot}$	Probability of the i^{th} category of the row variable
$p_{\cdot j}$	Probability of the j^{th} category of the column variable
$P_{C/nC}$	Part price in the cooperative / non cooperative game
q	Imperfect quality
q_{100}	Perfect quality
q_m	Quality cost of manufacturer (buyer)
q_s	Quality cost of supplier
r	Penalty cost
s^t_i	Strategy of player i at time t
s_i	Player i's strategy for the repeated game
τ	A counter that is set to 1 in the first period after a quality defection of the supplier
$\tau_{1/2}$	Goodman & Kruskal tau
t	First period of a game
T	Final period of a game
$u_i(s)$	Payoff of player i with strategy profile s
v	Value of the purchased product to the buyer
w	Part price
w^*	Part price plus quality premium

w^r	Part price with penalty
$X_{i\in I}$	Cartesian product
χ^2	Chi-square statistic

Note:

Due to the variety of notations used by the authors cited in the literature review (Chapter 2 and 5), these are explained in the corresponding sections of this thesis.

1 Introduction

1.1 Motivation and Objectives

The environment of today's production enterprises is characterized by shortened product life cycles, a rapidly growing number of products and variants, and fast technological advancements (REINHART 2003, p. 139; CISEK et al. 2002; p. 441). The resulting complexity in production has led manufacturing companies of various industries towards a continuous reduction in the amount of in-house value creation (HAMPRECHT 2003, p. 12; KALMBACH & KEINHANS 2004, p. 5; WILDEMANN 2004, p. 7; DELOITTE 2005, p. 2). Components, subassembly groups, or even entire products are increasingly provided by suppliers (MILBERG 2000, p. 320). As a consequence, vendors are seeking identical actions, which has led to complex networks or supply chains (ZÄH 2003, p. 1). Thus, many researchers (e. g. CHILD 1998, p. 322; CHRISTOPHER 2005, p. 5) emphasize competition between supply chains rather than rivalry among individual firms. This leads to strong interdependencies, as the capabilities of suppliers significantly determine the success of the buyer respectively the procuring production enterprise.

The results of a survey of 50 companies (from HABICHT & NEISE 2004) from the aerospace, automotive, electronics, and mechanical engineering industries, which was conducted during the course of this research, show that the ability of a potential supplier to deliver products in the specified quality as well as the delivery reliability are the priorities when a vendor is chosen. Figure 1 summarizes this finding in terms of the percentage of respondents who specified one of five levels of importance for each of six supplier selection priorities. This is further elaborated upon in Section 6.3.

In this thesis, quality is defined as the fulfillment of "the totality of characteristics of an entity (product) that bear on its ability to satisfy stated and implied needs" of the customer (GEIGER 1994; ANDERNACH 2005, p. 5 et seq.). The quality level of a supplier is characterized by the percentage of parts that meet the quality definition. In turn, delivery reliability may be expressed as the amount/percentage of orders that are delivered to the customer in the right quantity at the promised point in time (VDI 4400 ; ZSIDISIN 2003, p. 16).

To achieve the desired supplier quality, many companies have a supplier certification program in place to pre-assess a potential supplier's capabilities, especially when the duration of the contract between the parties is long (PARK et al.

1996). Empirical research has shown that this measure has considerable effect (> 30% reduction in defects, according to PARK et al. 1996, p. 111), but does not lead to perfect vendor quality (ACCENTURE 2005, p. 18). The remaining quality fluctuations are meant to be offset through various, sometimes contractually specified measures, such as inspection frequencies, which the supplier must carry out. Furthermore, suppliers often incur the cost of defective parts and additionally pay a quality penalty when faulty parts are delivered. Nevertheless, as discussed in Section 2.3, perfect quality is seldom achieved in most industries.

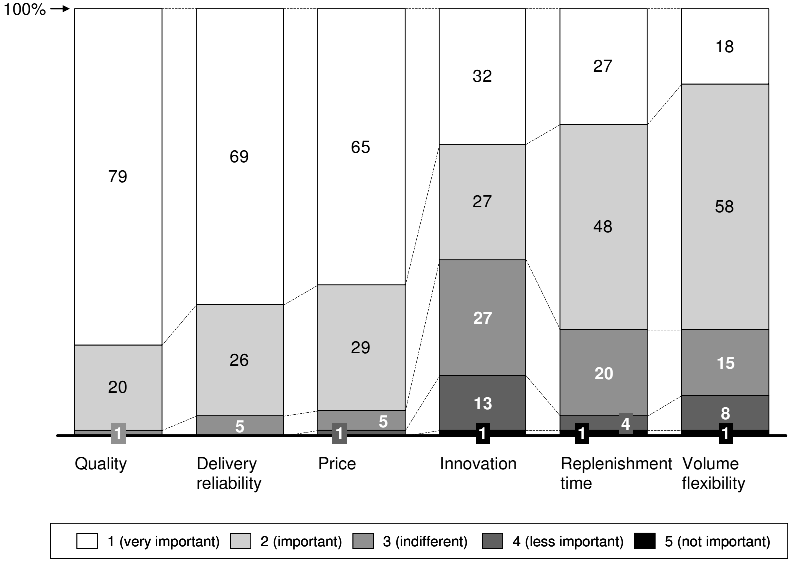


Figure 1: Supplier selection priorities based on a survey with 50 companies (ZÄH et al. 2005, p. 123)

In the view of this thesis, a significant increase in supplier quality can sometimes be achieved through offering the supplier a financial incentive when perfect quality is delivered, rather than solely employing incoming inspection and penalties as a threat. Therefore, the first objective of this thesis is

1. to assist the management of supplier quality by deriving the conditions under which a supplier is at least indifferent for delivering perfect or imperfect quality, to enhance the quality levels in the industry.

Achieving high delivery reliability is often equated to the term Supply Chain Management (SCM), which has been defined in many ways, for example: the scope of the supply chain “encompasses all activities associated with the flow and transformation of goods from the raw materials stage, through to the end-user, as well as the associated information flows” and SCM “is the integration of these activities through improved supply chain relationships, to achieve a sustainable competitive advantage” (HANDFIELD & NICHOLS 1999, p. 2). The goals of this integration are to reduce uncertainty and risks in the supply chain, thereby positively affecting lead time, inventory levels, and, ultimately, end-customer service levels (adapted from CHASE et al. 1998, p. 466; STEVENS 1989, p. 3).

To achieve this close interaction between supply chain partners and high delivery reliability, most companies have concentrated on implementing costly information technology (IT) (VON STEINÄCKER & KÜHNER 2001, p. 61). Nevertheless, the results of a global investigation with 196 participants from diverse industries, conducted by Booz Allen & Hamilton, found that the implemented IT-solutions had not complied with their expectations (HECKMANN et al. 2003, p. 2). For instance, this could be illustrated with the study by ACCENTURE (2005), that found that average delivery reliability was 84.6% in the capital goods industry.

Hence, many authors (PFOHL et al. 1998, p. 30; VON STEINÄCKER & KÜHNER 2001, p. 61; BAUMGARTEN et al. 2003 p. 10; DYER 2004, p. 76, HAMMER 2001, p. 81; BULLINGER & KÜHNER 2002, p. 257) agree with Booz Allen & Hamilton’s supplementary finding (HECKMANN et al. 2003, p. 4) that available information must be complemented by an organizational design of the involved production systems for a supply chain to unfold its full potential. Nevertheless, a series of surveys in regard to the contemporary level of integration among supply chain partners, published by the Supply Chain Management Review (POIRIER & QUINN 2003, p. 44; POIRIER & QUINN 2004, p. 27) illustrate that most companies are still optimizing their networks on a local basis and have not yet profoundly embarked on viewing the supply chain as a whole. FROHLICH & WESTBROOK (2001, p. 190) concluded that only about 14% of the 322 analyzed firms practice extensive optimization efforts in cooperation with their suppliers.

The reason for this disintegration may be that, as opposed to a proposition by FISHER (1998), most supply chains are not designed specifically for a given product, but “evolve on a somewhat ad hoc basis” (TOMLIN 2000, p. 14) and an ex post reorganization of the involved production systems is highly complex (KLEER 2005, p. 6). This industrial practice may be explained through the results of a study carried out by the Center for Enterprise Sciences (BWI) of the Swiss Federal Institute of Technology Zurich, which revealed that 50% of the 200 participating companies felt that they lack a structured approach for implementing SCM (NIENHAUS et al. 2003, p. 14) and thus, lack the ability to configure reliable supply chains.

Thus, the second objective of this thesis is

2. to provide the means for buyers to efficiently and effectively ascertain the delivery reliability of potential suppliers by accounting for the organizational integration of the production systems of the supply chain.

1.2 Focus and Delimitation

To achieve the above objectives, this thesis focuses on supply chains involved in the production of discrete products (as in the automotive, mechanical engineering, electronics, and aerospace industries) that have a convergent product structure, or consist of multiple sub-assembly groups or components, requiring multiple process steps and are subject to continuous but not necessarily constant demand (for a classification of products, see SCHÖNSLEBEN 2004, pp. 110).

Consequently, permanent (see GUDEHUS 1999, p. 37), multi-site and/or company networks are investigated, as opposed to temporary, cross plant activities, that are common to competence networks (see BROSER 2002, p. 5; NEISE 2002, p. 161). Collaboration forms (see DATHE 1998, p. 85) such as fusions, consortia, strategic alliances or joint ventures, etc. will not be considered, since these constructs are primarily concerned with legal issues (for a differentiation of network relationships see SCHLIFFENBACHER 2000, p. 22 et. seq.).

Even though various descriptions of SCM exist, this thesis employs the definition provided in Section 1.1. Alternative descriptions “may differ in terminology, but are reasonably consistent in meaning” (TOMLIN 2000, p. 13). One exception is a differentiation criterion, pointed out by SEURING (2001, p. 4), who distinguishes two groups of authors in this regard. The first group views SCM as the cross-enterprise coordination of material and information flows (e.g., KOPCZAK 1997, p. 226; FIALA 2005, p. 1), whereas, the second group emphasizes that product design processes must additionally be included into the scope of SCM, since the product structure significantly affects the supply chain design (e.g., FEITZINGER & LEE 1997, p. 117). The latter view fully corresponds to the understanding prevailing in this thesis. Nevertheless, this research is mainly concerned with deriving organizational guidelines for a given product type and for this reason, the initially proposed definition is sufficient for this investigation.

A further delimitation of the focus of this thesis can be derived from the SCM task reference model (Figure 2), developed by the SCM Competence and Transfer Center (SCM-CTC), an independent research group consisting of the Fraunhofer Institutes in Dortmund (IML) and Stuttgart (IPA) and the BWI of the Swiss Federal Institute of Technology Zurich (see SCM-COMPETENCE-AND-TRANSFER-CENTER 2005). As are many models for describing SCM tasks (see e.g., GANESHAN et al. 1999, p. 848) it is also subdivided into strategic, tactical, and operational levels.

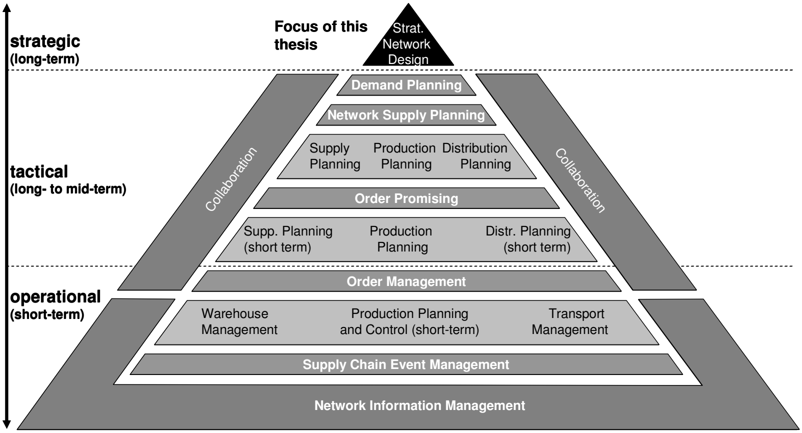


*Figure 2: SCM task reference model of the SCM-CTC (*adapted from *HIEBER 2005, p. 24)*

In representing the strategic level, *strategic network design* is primarily concerned with the cost efficient configuration and design of the network over the long-term (KUHN & HELLINGRATH 2002, p. 156). According to FLEISCHMANN et al. (2000, p. 63) long-term decisions involve strategic sales planning, definition of the product and material program, determination of plant locations, specification of the physical distribution structure, supplier selection, cooperation arrangements, and design of the production systems (see also ROHDE et al. 2000, p. 10).

The main focus of the tactical level is on the allocation of resources (such as personnel, materials, and production capacities) within the production network, to meet the expected and forecasted demand. Thus, *demand planning* represents the basis for *network supply planning*, which disaggregates end product demand, according to the responsibilities of the supply chain partners that, in turn, conduct long- to mid-term supply, production, and distribution planning. The *order promising* task is the interface between the tactical and the operational levels. It serves to respond to customer inquiries by determining the earliest possible delivery date and by confirming the demanded product configuration.

The operational level is concerned with customer *order management,* including all related (short-term) planning and control functions (GÜNTHER & LAAKMANN 2002, p. 4). These tasks encompass warehouse management, short-term production planning and control, as well as transportation planning and execution. *Supply chain event management* is concerned with monitoring these supply chain activities to identify and control potential deviations in regard to such items as inventory levels or customer due dates. The above stated assignments are supported through *network information management* that can be summarized as the integration and communication of operational data, which is administered through information systems (e.g., Enterprise Resource Planning) within and across the participating firms or sites (KUHN & HELLINGRATH 2002, p. 156).

As depicted in Figure 2, the focus of this thesis lies within the strategic network design, which is mainly intended to support the subtasks of the supplier selection as well as the cooperation arrangement.

As HIRSCHMANN (1998, p. 9 et. seq.) has shown, a single definition of the term “cooperation” is not easily derived. Thus, this thesis concentrates on an aspect of cooperation arrangement, as discussed by TSAY et al. (1999, p. 304). They highlight the impact that supply chain contracts, which define the rights, responsibilities, and financial duties of supply chain partners, have on inventory and service levels, and, especially relevant for this thesis, quality. Thus the increase of supplier quality will be mitigated through the design of a robust contractual agreement between the buyer and the supplier.

Regarding supplier selection, the focus of this investigation is on the interplay between the structural and the process organization of the involved production systems, as many researchers emphasize the importance of this interaction for reducing inventory levels and reaching the desired delivery reliability (see e.g., WIENDAHL 2002, p. 83). In this context, the structural organization refers to the assembly and fabrication units of the supply chain partners and the process organization prescribes the rules for the (spatial and) temporal conduct of activities within the supply chain (see FRESE 1999, p. 3-1 et. seq.; REFA 1990, p. 27). Warehouse and transport management will not be considered specifically, as the first task is mainly concerned with the efficient monitoring, storage, and retrieval of materials within warehouses and has little effect on the overall supply chain organization. The second task is primarily a combinatorial problem, for which efficient algorithms have been identified and are implemented in off-the-shelf SCM software.

1.3 Thesis Structure

The preceding sections provide a general understanding of the objectives of this thesis. Further, the elements of supply chain management, the industries with respect to range of products, and the network attributes relevant to the investigation have been specified.

As depicted in Figure 3, the remainder of this thesis is arranged as follows: Chapters 2 to 4 deal with the increase of supplier quality. As a basis for this research, current industrial practices and concepts in the literature are reviewed and their implications are discussed in Chapter 2. Using these insights, an incentive structure, based on two different strategies in repeated games, namely the Grimm Trigger and the Limited Retaliation strategies, is derived Chapter 3. These ideas are applied to two industrial case studies in Chapter 4 and the chapter concludes with a presentation of managerial implications, based on the analysis of enhanced supplier quality.

Chapters 5 through 8 are dedicated to the increase in delivery reliability of suppliers. In Chapter 5, a review and discussion of the current literature gives an overview of the qualitative and quantitative models used for describing supply chains and the increase in delivery reliability. The insights of the qualitative literature review are then used as a basis for deriving a determinant model for describing the supply chains in Chapter 6. This model is employed for the design of a survey of companies in the mechanical engineering, automotive, and aircraft industries. The data collected during this investigation is used in a statistical analysis to show that supply chains are often organizationally disintegrated.

Chapter 6 is concluded with a list of requirements for deriving simulation models for selecting reliable suppliers.

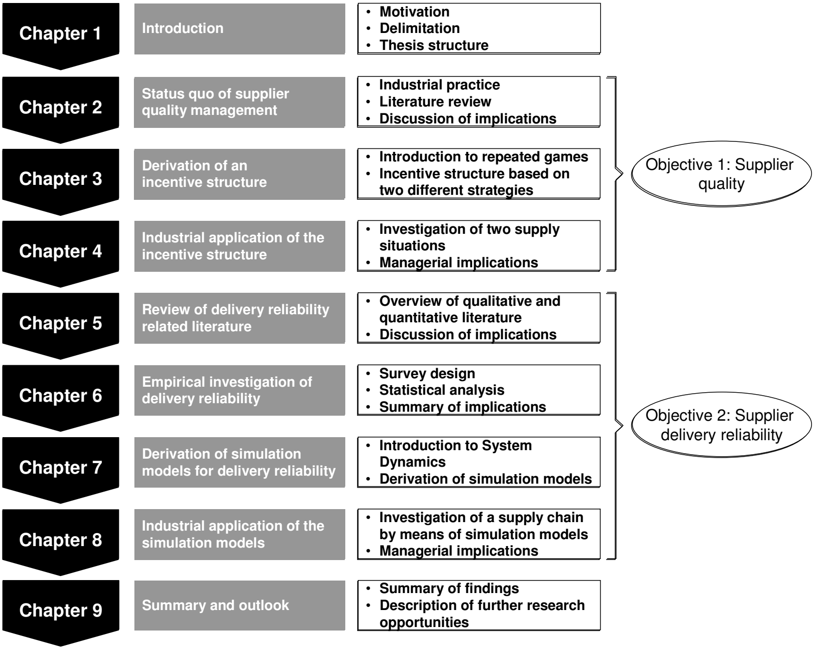


Figure 3: Thesis structure

In Chapter 7, the concept of systems dynamics modeling is introduced. Subsequently, a model for assessing the value of organizational integration in terms of delivery reliability is derived, which is based on the determinant model developed in Chapter 6. An industrial case study is described in Chapter 8, which demonstrates the applicability of the developed System Dynamics models. A summary of the presented research, as well as a recommendation for future investigations are given in Chapter 9.

2 Review of Supplier Quality Management in Practice and Literature

2.1 Introduction

As mentioned in the previous section, the following chapters focus on the first objective of this thesis, which is to assist the management of supplier quality through deriving conditions under which a supplier is at least indifferent between delivering perfect or imperfect quality, to enhance quality levels in industry.

To achieve this, the research process depicted in Figure 4 has been applied, and will be elaborated upon in the following chapters.

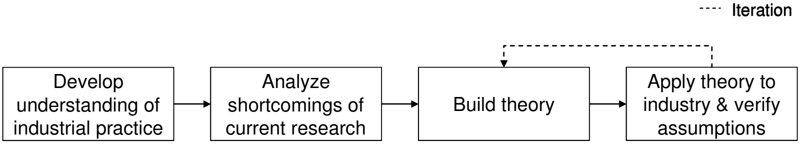


Figure 4: Research process applied for enhancing supplier quality

In the first step, informal interviews with production managers and a study of supplier quality management guidelines were used to understand industrial practice. This knowledge was then applied to analyze the shortcomings of current research and to resolve these through building an advanced theory. The application of the newly found concepts to an industrial case study was conducted to probe for a need for possible refinements of the theoretical considerations.

2.2 Supplier Quality Management in Industrial Practice

As indicated in the previous section, four companies were interviewed (one from aerospace, two from automotive, and one from mechanical engineering) and ten vendor quality guidelines published by firms of the aerospace (AEROJET 2005, AVIBANK 2005, EATON 2005), automotive (BOSCH 2005, SOUTHCO 2005, TOWER-AUTOMOTIVE 2005, WEBASTO 2005) and electronics (OPTEK-TECHNOLOGIES 2005, PACIFIC-SCIENTIFIC 2005, SATURNEE 2005) industries were reviewed to better understand supplier quality management practices. As a result of this analysis, six supplier quality management activity clusters were identified, which are summarized in Figure 5.

	Activity clusters	Measures
1	General supplier selection measures	Quality management system certification, supplier reduction, onsite process audits, guideline enforcements at suppliers' vendors
2	Process & product change measures	Support in product design, product change approval, process change approval (machines, tools, material, packaging, maintenance)
3	Quality assurance measures	Statistical process control required, rework authorizations, approval of testing methods, onsite quality inspection (buyer, 3rd party), delivery of test reports, corrective action request and approval
4	Performance feedback measures	Performance measurement and rating, penalties, cost of defectives at buyer's site / final customer are paid by supplier
5	Preventive measure	Safety stock, recording of lot numbers for traceability, incoming inspection or sampling
6	Product and process cost reduction	Continuous improvement prescribed (labor and material cost reduction)

Figure 5: Supplier quality management activity clusters based on current industrial practice

The first group of quality management activity contains general measures for the supplier selection process, such as reducing the supplier base and defining the required quality management standards for the vendor (e.g. ISO 9001: 2000 or buyer specific standards). These standards are assessed by the buyer during on-site process audits of the supplier's overall manufacturing system. Some companies have organized their procurement employees so that their staff is responsible for certain parts, rather than for a number of suppliers. With this organizational structure, these companies achieve close monitoring. One difference among the various industries is that the aircraft manufacturers emphasize that standards must not only be fulfilled by the vendor, but must also be implemented at the supplier's vendors.

The second group of quality management activity focuses on changes in the product and the supplier's production facility. All of the analyzed companies require an approval request by the supplier in case of a change in the product design, production processes, or tools. Some of these companies also require notice when the testing and calibration method (mainly in the aircraft industry), the maintenance program, or specified shipping and packaging procedures are modified. Few firms provide their suppliers with extensive support in regard to product and process design prior to the product launch.

The third group of quality management activity focuses on measures that ensure product quality during the product life cycle. For example, suppliers are expected to conduct statistical process control (measured by the Process Capability or the Process Performance Indexes, Cpk or Ppk, respectively), inspect parts and carry out 6-sigma initiatives. In this group, a distinct feature of the aircraft industry is that parts are sometimes inspected through the buyer or a third party at the supplier's premises, and test reports must be delivered with the part for them to be accepted.

The fourth group of quality activity addresses actual supplier quality through actions such as performance measurement reports (e.g., ppm) and supplier rankings. Upon detecting quality problems, buyers issue corrective action requests, to which suppliers must respond in the form of action plans within a certain time window. Some companies (except the aircraft industry) convey the quality cost to their suppliers and let them incur a penalty according to the reviewed supplier quality guidelines. A procurement manager from the automotive industry reported that some of his suppliers are charged a flat rate of 1.1 times the part price, if defects are identified. This factor may increase significantly for vendors that have severe quality issues. Penalties may not be enforced, however, especially when the buyer depends on a supplier with considerable market power, as discussions with four production managers revealed.

From the interviews, a fifth group of quality activities was identified, consisting of preventive measures that include incoming quality inspection or sampling, and quality-related safety stock. Some buyers record lot numbers to detect the root causes of deficiencies and to identify other potentially defective parts.

The last group of quality management measures comprises the prescription of continuous improvement activities to reduce the supplier's failure rate and required internal quality cost. All of the interviewed companies emphasized that they are willing to pay a higher part price, if quality levels rise to their expectations.

2.3 Implications from Industrial Practice

With reference to the preceding section, the aerospace industry is assumed to have the strictest quality management measures, which could stem from the high safety regulations required to ensure a reliable product. This assumption may also be based on an aerospace industry report by CAPS-RESEARCH (2005), which states that the 17 analyzed companies have a mean supplier quality of 100%. Aircraft manufacturers require evidence of quality tests from their suppliers and some of the industry OEMs inspect the products quality conformance at the suppliers' site. Finally, this industry seems to be strongly influenced by n-tier[1] suppliers in terms of the enforcement of quality management standards.

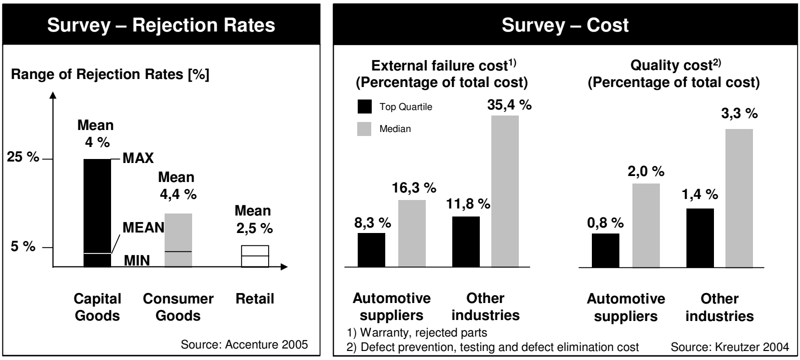


Figure 6: Survey of industrial quality levels (extracted from ACCENTURE 2005 and KREUTZER 2004)

Although empirical data is sparse, the quality levels realized by aircraft manufacturers are not matched by those of other industries. As depicted in Figure 6, the ACCENTURE (2005) study concluded that the average quality conformance rate is 95.7% over the retail, consumer, and capital goods industries.

A benchmark study (KREUTZER 2004) with data obtained from the 2004 “Factory of the Year” award (hosted by A.T. Kearney) shows that the top quartile of the participating German automotive suppliers spends an average 8.3% of their total cost for external failures (including warranty cost, cost due to insufficient parts, and administrative spending). In comparison, external failure cost amounts to 11.8% in other industries (top quartile).

Even though the proportion of warranty cost due to, for example, insufficient product design may be more significant, these numbers suggest that quality issues exist in the industry. Interestingly, the cost of quality (defect prevention, testing and cause elimination cost) is only 0.8 to 1.4% of the overall cost, according to this survey, which implies that suppliers seek to minimize quality cost. Thus, some sort of motivation needs to be provided by the buyer to ascertain high

---

[1] A first-tier supplier is one that delivers products to the OEM and is thus one stage before the customer. The products of an n-tier supplier thus go through n stages before they are transferred to the customer.

quality levels. This could be a financial incentive, a penalty or, as in the aerospace industry, a rigid form of supplier control.

2.4 Supplier Quality Management Research

An overview of the literature on the management of supplier quality has been provided by TSAY et al. (1999), which is employed as an outline for this section. The authors group the contributions to this field into three categories, namely: economics, inventory management, and game theoretic supply chain research. With regards to the first category, TIROLE (2003) offers an extensive overview of economic quality models. To differentiate products, he classifies search, experience, and credence goods (as in DARBY & KARNI 1973 and NELSON 1970). The first type encompasses products, for which the quality can be ascertained before the purchase (e.g., clothing). In the case of experience goods, the quality is learnt subsequent to procurement. If the quality of a product cannot be assessed at all, it is categorized as a credence product (e.g., toothpaste).

For the supply chain relationships addressed in this thesis, products belong to the group of experience goods, because the quality of products and thus the expected quality are learnt each time the parts are actually delivered. This is the case even though the supplier's manufacturing system may have been assessed, or the first parts have been inspected before the start of the relationship.

The economic models for experience goods, discussed by TIROLE (2003), focus on quality levels as one of the supplier's management choices. They concentrate on optimal quality levels as a reaction to a given level of customer appreciation for quality to attain the best possible profit. Since, in the production industry, a detailed definition of quality is provided to the supplier by the buyer, the level of quality is not a management choice but a requirement. This quality level may or may not be fulfilled by the vendor depending on the incentive structure of the arrangement. Nevertheless, one of TIROLE 's (2003) findings, relevant to this thesis, is that warranties (or penalties) granted by the supplier can be interpreted by the buyer as a signal for high quality prior to supplier selection. Second, repeated purchases offer the consumer valuable information regarding the expected quality. As the relationship between a buyer and a supplier is usually based on long-term agreements, this knowledge can be used to redefine the boundary conditions of procurement for the duration of the relationship.

Another economic evaluation of the cost of production quality has been developed by TAGARAS & LEE (1996). They consider a buyer who has the opportunity of increasing the quality of a procured part by paying a higher part price. The part is defective with the probability p and the buyer's production process, for which the part is an input, fails with the probability of q. From the cost that arises when the input is defective (r_1), or when the buyer's process fails (r_2), or when both apply (r_{12}), the buyer's expected unit quality cost may be calculated as $\Phi(p) = p(1\text{-}q)r_1 + q(1\text{-}p)r_2 + pqr_{12}$. From the quality cost and the unit purchase cost $C(p)$ (which is assumed to be either linear or quadric), the total acquisition cost $K(p)$ may be derived. The analysis reveals that the buyer's choice of supplier quality depends not only on the vendor's price but also on the buyer's own process capabilities. Thus, under certain circumstances, the buyer is better off when lower quality is procured.

Supplier's cost function	Buyer's inspection policy	Conditions under which zero defects are optimal
Linear	$L = n = 1$	Zero defects always optimal
	$L >> n \geq 1, c = 0$	Zero defects always optimal
	$L >> n \geq 1, c > 0$	$b\left(\sqrt{\frac{iK}{2\lambda m}}+1\right)-\frac{iLb}{2\lambda}\leq\frac{r(L-n)}{L}$
Exponential	$L = n = 1$	$b > 1$ and $m(b-1)\left(\sqrt{\frac{iK}{2\lambda m}}+1\right)-\frac{ibm}{2\lambda}-s\leq 0$
	$L >> n \geq 1, c = 0$	$b > n$ and $m(b-n)\left(\sqrt{\frac{iK}{2\lambda m}}+1\right)-\frac{iLbm}{2\lambda}-ns\leq\frac{r(L-n)}{L}$
	$L >> n \geq 1, c > 0$	$mb\left(\sqrt{\frac{iK}{2\lambda m}}+1\right)-\frac{iLb}{2\lambda}\leq\frac{r(L-n)}{L}$
Asymptotic	All	Zero defects never optimal

Table 1: Conditions under which zero defects is an optimal policy (see STARBIRD 1997, p. 527)

L	Supplier's delivery lot size
n	Buyer's sample size
c	Buyer's acceptance size
λ	Buyer's demand rate
i	Supplier's inventory holding cost
K	Supplier's set up cost
r	Cost of a lot returned by the buyer
m, a, b	Parameters of the supplier's quality cost function

The body of inventory management literature focusing on quality issues is broad. It mainly discusses optimal stock levels or order sizes when dealing with varying supplier quality. For instance, STARBIRD (1997) developed a model that identifies conditions under which delivering zero defects is an optimal strategy for an expected cost minimizing supplier facing a buyer with a fixed sampling policy. These conditions are a function of the buyer's sample (n), acceptance size (c), and demand rate (λ), as well as the supplier's delivery lot size (L), inventory holding (i), pass-through (r – the cost of a lot returned by the buyer) and set-up cost (K). As shown in Table 1, the model yields different conditions, depending on the nature of the supplier's quality cost function (with parameters m, a, and b; see STARBIRD 1997, p. 522), which is assumed to be either linear, exponential, or asymptotic.

Further examples of such research include that by ALICKE (2003) or HUANG (2004), though they are not directly related to this thesis, which has the objective to prevent deficiencies of procured parts, rather than coping with them.

The game theoretic literature relating to supplier quality management is sparse, but most relevant to the ideas elaborated in the following sections.

The most important model has been developed by REYNIERS & TAPIERO (1995). They model the effect of contract parameters, such as price rebates and after-sales warranty cost, on the choice of quality by a supplier, the inspection policy of the producer, and the resulting end-product quality. The underlying assumption of their investigation is that the supplier chooses a technology t_i (for simplicity: i = 1, 2; production cost and quality are increasing in i) and this choice is not observed by the buyer, who, in return, independently decides upon an inspection policy. Further, it is assumed that the contract between the two parties "stipulates penalties for defectives as follows: if a part is found defective by the buyer, a rebate (Δ *π*) is paid by the supplier, which in effect reduces the price (*π*) of the part to the producer. The supplier incurs a repair cost (*C*) and the buyer is supplied with a non-defective part. If a defective part is not detected by the buyer and consequently delivered to the end-customer, the manufacturing and post-sales cost is shared between the supplier and the manufacturer, according to an a priori defined quota (*αR).*

$$\begin{aligned} v(q,x)= \; & [\pi - p_1(\Delta\pi + C) - T_1]xq + [\pi - p_1\alpha R - T_1]x(1-q) \\ & + [\pi - p_2(\Delta\pi - C) - T_2](1-x)q + [\pi - p_2\alpha R - T_2](1-x)(1-q) \end{aligned} \tag{1}$$

$$\begin{aligned} u(q,x)= \; & (\theta - m - [\pi - p_1\Delta\pi])xq + (\theta - \pi + p_1(1-\alpha)R])x(1-q) \\ & + (\theta - m - [\pi - p_2\Delta\pi])(1-x)q + (\theta - [\pi + p_2(1-\alpha)R])(1-x)(1-q) \end{aligned} \tag{2}$$

$$q^{*} = [\Delta T / \Delta p - \alpha R]/(\Delta\pi + C - \alpha R)\text{[2]} \tag{3}$$

$$x^{*} = [m - p_2(\Delta\pi + (1-\alpha)R)]/[p_1(\Delta\pi + (1-\alpha)R) - p_2(\Delta\pi + (1-\alpha)R) \tag{4}$$

v(q,x)	Supplier’s expected payoff
u (q,x)	Buyer’s expected payoff
q	Buyer’s inspection probability
x	Probability of supplying bad part
Π	Price for unit from supplier
Δπ	Price reduction for defective parts
p_i	Probability of a defective part with technology i = 1, 2
C	Repair cost *C* incurred by supplier
T_i	Unit cost borne by supplier with technology i = 1, 2
R	Post sales failure cost
α	Fraction of post sales failure cost borne by buyer
M	Buyer’s inspection cost
θ	Buyer’s selling profit

---

[2] * indicates optimal parameter set (NE)

With x, as the probability of low quality being supplied by the vendor, and q, as the inspection policy of the buyer, the expected payoffs can be deducted for the supplier (formula (1)) and the buyer (formula (2)).

To find reaction functions, REYNIERS & TAPIERO (1995) optimized these equations in regard to x and q, respectively, thereby obtaining formulas (3) and (4) as the unique Nash Equilibrium (NE)[3] for this bimatrix game (plotted in Figure 7).

Consequently, for a given buyer inspection policy q, the supplier will set x (the quality policy) according to the following rule: $x = 1$ if $q < q^*$, $x = 0$ if $q > q^*$ and x is equal to any $x \in [0, 1]$ if $q = q^*$. On the other hand, the buyer will react to a given quality policy x with the following inspection policies: $q = 1$ if $x > x^*$, $q = 0$ if $x < x^*$ and $q =$ any $q \in [0, 1]$ if the reaction functions intersect.

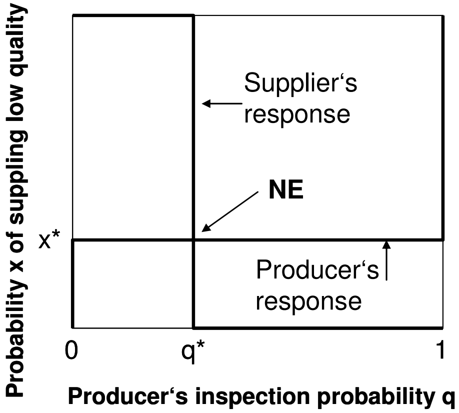


Figure 7: The unique Nash Equilibrium (NE) of the quality game (REYNIERS & TAPIERO 1995, p. 1584)

An analysis of these results for various parameter values leads to the three main results:

- The probability that the buyer inspects increases with the relative production cost differential $\Delta T / \Delta p$ (where ΔT is the incremental cost of better techn-

---

[3] A Nash Equilibrium is a set of strategies, one for each player, such that no player has incentive to unilaterally change his action. Players are in equilibrium if a change in strategies by any one of them would lead that player to earn less than if she remained with her current strategy.

ology and Δp is the incremental probability of a defective part using the inferior technology).

- The probability of using inferior technology increases with the buyer's inspection cost *m*.
- The final quality of the supplier-buyer chain is a decreasing function of the proportion of the warranty cost borne by the supplier, a decreasing function of the buyer's inspection cost and an increasing function of the ratio $\Delta T / \Delta p$.

LIM (2001) developed a model with identical parameters as those of REYNIERS & TAPIERO (1995) for considering the trade-off between inspection and warranty schemes under asymmetric information[4] and in regards to the supplier's technology type. By utilizing the revelation principle[5], LIM (2001) concludes that the supplier's expected amount of compensation cost per defective unit (either as a price rebate or as a warranty) is constant and independent of the technology type of the supplier. Furthermore, he finds pooling equilibria[6] for situations in which the buyer has to share the cost of the compensation schemes. Thus, a critical level of technology exists such that the buyer always conducts inspection, whereas a warranty scheme is preferred if the quality level is superior to the critical value.

2.5 Implications from Research

The models developed by REYNIERS & TAPIERO (1995) and LIM (2001) assume that the level of technology cannot be anticipated by the buyer, which is not the case in industrial practice, since process audits of the supplier are commonly used (see group 1, Section 2.2). Thus, the buyer can get some notion of the supplier's process capability and required quality measures (see group 2, Section 2.2).

---

[4] In economics and contract theory, an information asymmetry is present when one party to a transaction has more or better information than the other party (refer to GIBBONS 2004).

[5] To any Nash Equilibrium of a game of incomplete information, there corresponds an associated revelation mechanism that has an equilibrium where the players truthfully report their types, e.g. a bad quality or a good quality supplier (refer to SALANIÈ 1997).

[6] A pooling equilibrium is the optimal choice for various types of players.

Furthermore, REYNIERS & TAPIERO (1995), LIM (2001), and STARBIRD (1997) focus on incoming inspection for sampling policies and compensation schemes that a buyer must adopt to obtain high quality levels from a supplier.

The numbers cited in Section 2.3 suggest that, especially with today's continuously decreasing profit margins, suppliers will sometimes take the risk of paying a penalty to save quality cost. Thus, the approach of this thesis is to mitigate the risk of low quality by offering the supplier a higher part price when quality is delivered and when the required quality measures are carried out. This is in line with the statements of the interviewed production managers (see group 6) and with the assumptions of TAGARAS & LEE (1996).

The parameters for modeling supplier management, employed by REYNIERS & TAPIERO (1995) and LIM (2001), seem sufficient in terms of industrial practice. Nevertheless, these authors did not incorporate the repeated nature of the supplier-buyer relationship, as pointed out by TIROLE (2003), into their models. In the view of this thesis, conditioning the actions of the involved parties on the behavior of their counterparts is an important aspect for the design of a supplier quality management model.

In summary, it may be stated that three main shortcomings of current literature will be addressed by this thesis.

Firstly, the quality level and cost of the supplier is not viewed as private information of the vendor, as historical data can be investigated by the buyer to obtain knowledge on the supplier's quality level. In addition, the cost of quality can be made explicit by the supplier (e.g., in the proposal to the buyer) or estimated by the buyer.

Secondly, the models developed in current literature often employ incoming inspection of supplier parts as a measure to force the supplier to incur the required cost of quality. In this practice, cost is incurred on the buyer as well as on the supplier side. This thesis aims at developing a mechanism through which the value of this cost is invested into the quality system of the manufacturing system of the supplier to eventually reduce cost for both parties through the resulting quality improvements.

Thirdly, the repetitive nature of the relationship of the supplier and the buyer is viewed as a cornerstone of the models that will be developed in the following chapter.

3 Incentive Structures for the Management of Supplier Quality

3.1 Introduction to Game Theory

Game theory attempts to mathematically capture behavior in strategic situations, in which an individual's or a company's success in making choices depends on the choices of others. This is also the case in supplier quality management, as the quality choice of the supplier strongly influences e.g., the price the buyer is willing to pay for the good, the level of incoming quality inspection and, most importantly, his ability to deliver the end product to the final customer on time.

Traditional applications of game theory attempt to find Nash Equilibria in these games, which may be described as sets of strategies in which individuals are unlikely to change their behavior. Thus, a game must be designed in such a way that the desired outcome is the best choice for each player and no player will unilaterally deviate from the according strategy.

Contrary to one stage games, players have the opportunity of conditioning their behavior on past actions of the other players in a repetitive game. This means that in repeated games, players have the opportunity of building trust by acting in a cooperative way, but also punishing other players for non cooperative actions.

To capture the repetitive nature of the procurement process and to establish cooperation as a best choice for the supplier and the buyer, the theory of repeated games (refer to FUDENBERG & TIROLE 2000, GIBBONS 2004, RATLIFF 2004) is utilized to derive an incentive structure for suppliers in this thesis.

3.2 Repeated Games and Quality Management

A repeated game consists of a finite or infinite series of stage games G, which involve a player set $I = \{1, \dots, n\}$. Hence, two players are in the supplier-buyer relationship and every delivery of parts represents a stage game.

In each stage, each player's actions are a choice from their action space A_i. The space of possible action profiles is thus $A = X_{i \in I} A_i$. For each player, the set of actions available, in any period of the game, is the same regardless of which period it is and which actions have taken place in the past. Following the discussion in Section 2.5, the supplier's actions are to deliver imperfect (q) or perfect quality (q_{100}), while the buyer can pay a price that includes a quality premium (w^*, i.e.

$w^* - w$ equals the quality premium) or just the common market price (w) combined with a penalty (see group 4 in the industrial practices in Section 2.2).

Each player has a von Neumann-Morgenstern utility function[7] defined by the outcomes of G, and every player's ultimate payoff is an additively separable function of the discounted per-period payoffs, if G is played several times. The payoffs to the players from the stage game in any period depend only on the action profile played in that period and, therefore, on the quality level of the supplier and the part price paid by the buyer.

In repeated games, the typical "standard signaling" assumption is made. This means that the play which occurred in each repetition of the stage game is revealed to all players before the next stage game. Combined with perfect recall, this allows subsequent choices to be conditioned on the past actions of other players. These properties of repeated games fit particularly well with the nature of the quality management process, because the buyer learns the quality level of the supplier each time parts are delivered. The buyer records this knowledge in the form of performance reports and can decide upon quality management actions based on these metrics (see group 4 in section 2.2, Figure 5).

The first period of the game is labeled $t = 0$, whereas the final period, if it exists, is period T. Thus, the repeated game comprises a total of $T+1$ periods. Since a supplier will usually seek to deliver parts to a buyer for longer than a single product life cycle, the game is reasonably assumed to be played for an infinite number of stages (n), as the supplier does not know when the game will end.

An action, which player i executes in period t, is referred to as a_i^t. The action profile played in period t then is the n-tuple of the individuals' stage game actions $a^t = (a_1^t, ..., a_n^t)$. As the players are allowed to condition their stage game action choices in later periods upon actions taken earlier by other players, they base their decisions on the history of the game. The history, at time t, is defined as $h^t = (a^0, a^1, ..., a^{t-1})$ and the specification of h^t thus includes within it a definition of all previous histories. For instance, the history h^t is a concatenation of h^{t-1} with the action profile a^{t-1}. The set of all possible histories is thus the t-fold Cartesian product of the space of stage game action profiles A.

---

[7] A player possesses a von Neumann-Morgenstern utility function if he is indifferent between receiving a given bundle or participating in a game with the same expected value.

As mentioned above, player i 's period-t stage game strategy s_i^t is a function of this history, where $a_i^t = s_i^t(h^t)$ is the action profile that would be played in period t if the previous play had followed h^t. A player's stage game action in any period and after any history must be drawn from the player's action space for that period, but because the game is stationary, the stage game action space A_i does not change with time, which may be expressed as $(\forall i \in I)(\forall t)(\forall h^t \in A)\, s_i^t(h^t) \in A_i$. The period-$t$ stage game strategy profile is thus described as $s_i^t = (s_1^t, \ldots, s_n^t)$. Using stage game strategies as building blocks, player i's strategy for the repeated game is expressed as $s_i = (s_i^0, s_i^1, \ldots, s_i^T)$. When the repeated game strategy profile s is played, the payoff to player i is defined as:

$$u_i(s) = \sum_{t=0}^{T} \delta\, g_i(s_i^t(h^t)) \tag{5}$$

where δ is the common discount factor, which may be interpreted as an expression of time preference, and g_i is the stage game payoff resulting from the strategy profile. A repeated game strategy profile is a Nash Equilibrium for all players i when

$$\bar{s}_i \in \arg\max_{s_i \in S_i} u_i(s_i, \bar{s}_{-i}).^{8} \tag{6}$$

A subgame-perfect equilibrium strategy profile is one where the restriction of $\bar{s}$ to any subgame is a Nash Equilibrium strategy profile in that subgame[9].

3.3 Incentive Structure based on a Grimm Trigger Strategy

To derive conditions under which a supplier will deliver perfect quality, a Grimm Trigger strategy is employed (for a model of the efficiency of employment, see SHAPIRO & STIGLITZ 1984). This strategy prescribes cooperating in the initial period and then cooperating as long as both players have cooperated in previous periods. Following the action spaces A_i of the supplier and the buyer, defined in

---

[8] arg max is the value of the given argument for which the value of the given expression attains its maximum value.

[9] A subset or piece of a sequential game beginning at some node such that each player knows every action of the players that moved before him at every point

the preceding section, the Grimm Trigger strategy for the infinitely repeated game between the buyer and the supplier can be expressed as follows:

$$s_i^t\ (h^t) \begin{cases} a^0 = (w^*,\ q_{100}) \\ a^t = (w^*,\ q_{100})\ if\ a^{t-1} = (w^*,\ q_{100}) \\ a^t = (w^r,\ q)\ otherwise \end{cases} \qquad (7)$$

As shown in Figure 8, this means that the buyer will pay the supplier a part price of *w**, which includes a quality premium, in the first period of the relationship and continue to do so, provided that perfect quality is delivered.

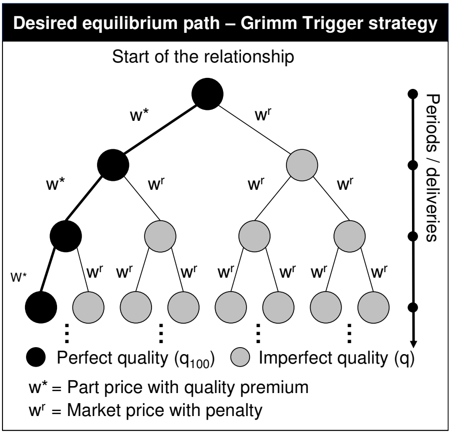


Figure 8: Equilibrium path for the Grimm Trigger strategy

If the supplier does not provide high quality, the buyer will pay the market price w and charge a penalty r (indicated by w^r) for the remainder of $G(t)$. The supplier will comply with the arrangement, provided that the buyer will pay w^* when high quality is delivered.

The sequence of events for the design of such an agreement is as follows:

1. The buyer (with perfect production processes) selects a supplier that is capable of producing the desired parts and inspects the supplier's manufacturing system (which is realistic, as mentioned in Section 2.1 – group 1).

In doing this, the buyer acquires knowledge in regards to the process capability and the quality cost of the supplier. The first can be measured by the probability (p) that a shipment of parts will include only good parts, which must be derived from historical data such as internal quality reports, process capability histograms or previous experience. Based on this knowledge and the definition of required quality measures (as described in Section 2.1 – groups 2 and 3), the cost of quality per part (q_s) may be assessed by the buyer.

2. The supplier and the buyer then agree on a per part penalty r (which includes cost for rejected materials and penalties charged by the buyer or the end-customer) that is incurred by the supplier, if bad parts are delivered.

This, according to Section 2.2 (group 4), is common practice for suppliers that have limited market power, and is also in line with the findings of TIROLE (2003).

3. With this knowledge, the buyer calculates a part price, which the supplier accepts.
4. If the supplier does not deliver perfect quality, the buyer switches back to a combination of the market price and a quality penalty until the relationship between the parties ends.

To derive the required price, the present value of the supplier's payoffs is considered. As mentioned above, if the supplier provides high quality parts in the initial period of the products' life cycle, the supplier receives a part price of w^*. The buyer continues to pay this price, if parts are free of defect. Thus, for the cooperative game between the supplier and the buyer, the present value of the supplier's payoff, according to formula (5) amounts to:

$$\begin{gathered}P_c = w^* - q_s - c + \delta(w^* - q_s - c) + \delta^2 (w^* - q_s - c) \ldots + \delta^n (w^* - q_s - c) = \\ (w^* - q_s - c) \sum_{i=0}^{n} \delta^i = (w^* - q_s - c) \sum_{i=0}^{n} \frac{1}{(1+ir)^i}\end{gathered} \tag{8}$$

where δ is the discount factor, which equals $1 / (1 + ir)$, ir is the interest rate[10], and c ($w\text{-}c\text{-}q_s > 0$) is the per part production cost (material and machine cost, etc.).

If the supplier decides not to provide high quality, but to deliver the parts without applying quality enhancing measures subsequent to production, the supplier will

---

[10] The interest rate can either reflect a finacial figure or be a measure of trust. It is recommended to utilize the interest rate common to the controlling department of the company where the analysis in conducted

receive a payoff of *w** in the first period (as the game assumes simultaneous moves in each stage) and *w** with the probability of *p* in each following period. In this case, faulty parts are supplied with the probability of *(1-p)* and thus, the buyer will pay the market price *w* and the supplier will incur an expected penalty cost *E(r)* from thereon. The present value of the supplier's payoff then results in:

$$\begin{aligned} P_{nC} &= w^* - c + p\delta(w^* - c) + (1-p)\delta(w - c - E(r)) + p^2\delta^2(w^* - c) + \\ &(1-p^2)\delta^2(w - c - E(r)) .... + p^n\delta^n(w^* - c) + (1-p^n)\delta^n(w - c - E(r)) \end{aligned} \quad (9)$$

To induce perfect supplier quality, P_c must be set greater or at least equal to P_{nC}. Through applying geometric progression and rearranging the parameters of the resulting inequality, the following result can be obtained for *w**:

$$w^* \geq w - E(r) + \left(1 + \frac{(1-\delta)}{\delta(1-p)}\right) q_s \quad (10)$$

For an interpretation of this result, five cases are differentiated, as depicted in Figure 9.

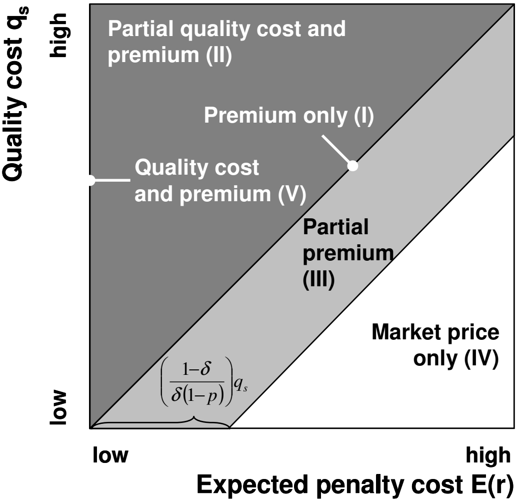


Figure 9: *Incentive structure portfolio under the Grimm Trigger strategy*

If the expected penalty cost *E(r)* equals the quality cost q_s, then the buyer must pay a quality premium of $(1-\delta) / \delta(1-p)q_s$ (I). If the cost of quality exceeds the expected penalty, the part price w^* will include the premium as well as a fraction of q_s (II). In cases where the expected penalty is greater than the quality cost, but smaller than the sum of q_s and the value of the premium, a partial premium must be included in the part price (III). Should $E(r)$ be greater than this amount, it is sufficient for the buyer to pay the market price (IV).

This occurs because, in this case, formula (10) yields values lower than w, which implies that under such an arrangement a quality premium is already included in the market price (as for instance in the case of the automobile manufacturer cited in Section 2.2 that charges a penalty of 1.1 times the part price). If a penalty cannot be enforced, for instance, when a supplier has considerable market power, then the buyer must pay the full cost of quality and the quality premium to attain perfect quality levels (V).

Nevertheless, for formula (10) to be a Nash Equilibrium (as required by formula (6)) of the repeated game, the difference between w^* and w must be smaller than the per part savings gained by the buyer from paying the quality premium and receiving perfect quality. This means that the following inequality must hold:

$$v - w^* \geq v - w - q_m + E(r) \qquad (11)$$

In this relation, v is the value of the purchased product to the buyer and q_m is the per part quality cost that arises for the buyer when defects occur. As mentioned in Section 2.2, the latter may include the cost of incoming inspection, safety stock (group 5), or quality-related production disruptions.

For the strategies specified to be a subgame-perfect equilibrium, $s_i^t\,(h^t)$ must be a Nash Equilibrium strategy profile in every subgame. To evaluate this, subgames with histories beginning after stage games are assessed, where w^* has been paid by the buyer and perfect quality has been supplied, and where at least once w has been the part price and imperfect quality has been delivered. As discussed above, subgames of the first kind represent a Nash Equilibrium of the stage game if formula (10) and formula (11) hold. Latter subgames will only occur in cases where the expected penalty cost is smaller or equal to the quality cost. Under these circumstances, the buyer's best response is to pay the part price for the duration of the relationship (as for instance when procuring from a supplier with great market power). Assuming that no other buyer will demand at least equal volumes and pay a higher part price, the described conditions are also optimal for the supplier. Thus, the Grimm Trigger strategy represents a subgame-perfect equilibrium.

To provide some intuition for the behavior of the part price w^*, the results of a numerical example (using equation *10*) with a market price (w) of 50 €, a per part quality cost (q_s) of 10, and an expected penalty cost ($E(r)$) of 11 are plotted in Figure 10. As it can be inferred from the resulting surface, the part price w^* increases nonlinearly with the quality level of the supplier (p), increases nonlinearly with decreasing discount factors (δ) and, as it can be easily seen from (*10*), linearly increases with the cost of quality (q_s) for fixed $E(r)$.

If a discount factor (δ) between 0.9 and 0.95 is assumed to be reasonable, which results from an interest rate or weighted average cost of capital between 5 and 10%, then the part price the buyer must pay to receive perfect quality only somewhat exceeds the market price for suppliers that have a quality level of close to 1, in this example. The difference between w^* and w then represents a partial quality premium, as indicated in Figure 9 (III).

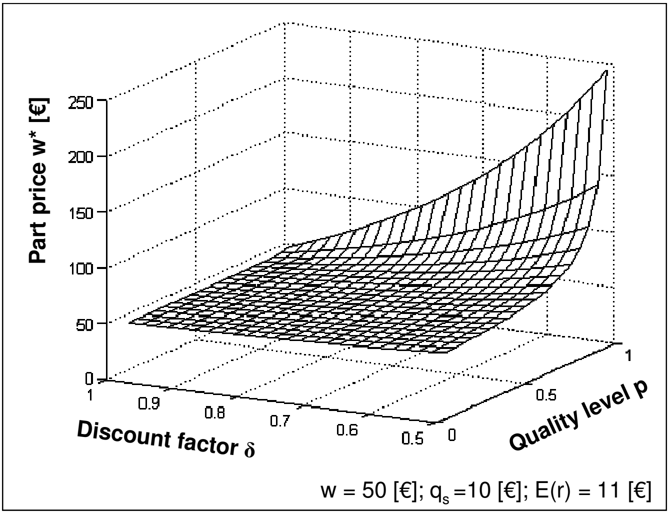


Figure 10: Numerical example of the Grimm Trigger strategy

3.4 Incentive Structure based on the Limited Retaliation Strategy

As an alternative to Grimm Trigger strategies, a more forgiving concept can be employed. As depicted in Figure 11, Limited Retaliation strategies prescribe cooperation in the first period, and *k* periods (k > 1) of punishment for every defection of any player, followed by reverting to cooperation, no matter what has occurred during the punishment phase. In terms of quality management, this implies that the buyer will pay a part price of *w** to the supplier as long as perfect quality is provided, pay only *w* for *k* periods, and charge the penalty if the supplier delivers bad quality, and then continue to incur *w** as long as the game is cooperative.

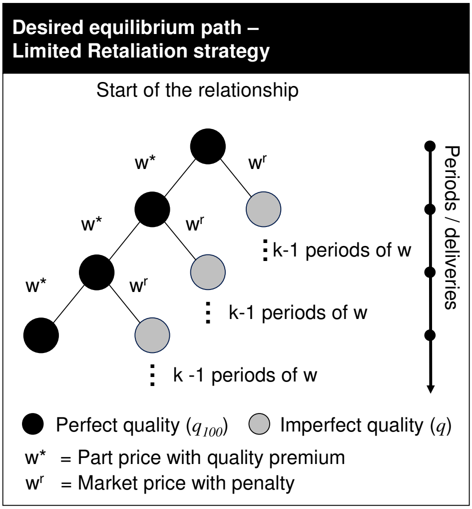


Figure 11: Equilibrium path for the Limited Retaliation strategy

In summary, this strategy can be stated as follows:

$$s_i^t\ (h^t) \begin{cases} a^0 = (w^*,\ q_{100}) \\ a^t = (w^*,\ q_{100}) \text{ if } a^{t-1} = (w^*,\ q_{100}) \\ a^t = (w^r,\ q) \text{ and } \tau = 1 \text{ if } a^{t-1} = (w^*,\ q) \\ a^t = (w^r,\ q) \text{ and } \tau = \tau + 1 \text{ if } \tau < k \\ a^t = (w^*,\ q_{100}) \text{ if } \tau = k \end{cases} \tag{12}$$

To establish this strategy as a Nash Equilibrium of the repeated game, a one-shot deviation (see FUDENBERG & TIROLE 2000) must be ascertained to be not profitable for the supplier, and formula (11) must hold. As in the preceding section, if the supplier decides to omit quality enhancing measures, then the supplier will receive a part price of w^* with probability p. If defects are detected by the buyer with probability $(1-p)$, the supplier receives the market price w and incurs a penalty of $E(r)$ for k periods followed by an infinite stream of w^* (τ is a counter that is initiated in the first period of punishment). Thus the present value of the supplier's payoff for a single deviation will amount to:

$$\begin{aligned}
&P_{nC2} = w^* - c + p\delta(w^* - c) + (1-p)\left(\left(\frac{\delta-\delta^k}{1-\delta}\right)(w-c-E(r)) + \delta^k(w^*-q_s)\right) + \\
&p^2\delta^2(w^*-c) + p(1-p)\delta\left(\left(\frac{\delta-\delta^k}{1-\delta}\right)(w-c-E(r)) + \delta^k(w^*-q_s)\right) + \ldots \\
&p^n\delta^n(w^*-c) + p^{n-1}(1-p)\delta^{n-1}\left(\left(\frac{\delta-\delta^k}{1-\delta}\right)(w-c-E(r)) + \delta^k(w^*-q_s)\right) = \\
&(w^*-c)\sum_{i=0}^{n} p^i\delta^i + (1-p)\sum_{i=0}^{n} p^i\delta^i\left(\left(\frac{\delta-\delta^k}{1-\delta}\right)(w-c-E(r)) + \delta^k(w^*-q_s)\right)
\end{aligned} \tag{13}$$

By requiring P_c to be equal to or greater than P_{nC2}, applying geometric progression, and rearranging the terms, the resulting w^* can be expressed as:

$$w^* \geq w - E(r) + \left(1 + \frac{(1-\delta)}{\delta - p\delta - \delta^k + p\delta^k}\right) q_s \quad \text{for } k > 1 \tag{14}$$

which equals formula (10) for infinite k. The Limited Retaliation strategy is a subgame-perfect equilibrium of the repeated game, if the conditions discussed in the preceding section are true.

It can easily be seen that formula (14) yields results that are greater than those obtained from formula (10), for small k. For large k, the values of w^*, calculated with formula (14), converge towards those derived from the Grimm Trigger strategy.

In cases where the Limited Retaliation strategy seems more appropriate and a part price that is by Δw^* higher than the price obtained from formula (10) can be accepted, the required number of punishment periods can be calculated by subtracting formula (14) from formula (10) and setting this term equal to Δw^*. Solving this equation for *k* then yields:

$$k = \left(1 + \frac{q_s(1-\delta)}{\delta \Delta w^* (1-p)}\right)^{-1} \tag{15}$$

Of course Δw^* can also be compensated by increasing the expected penalty. Nevertheless, since the games are designed in such a way that it will not be profitable for the supplier to consciously deliver imperfect quality, it should be sufficient to employ a Grimm Trigger strategy for the management of supplier quality. Yet, since the delivery of quality can never be completely perfect (as in the case of one of the interviewed automobile suppliers that strives towards perfect quality, but still has a two-digit ppm-rate), it may be more efficient to require a quality level that is close to 100% (i.e., zero ppm under the Grimm Trigger agreement) than to accept the more costly punishment phase for a limited duration.

4 Industrial Application of the Incentive Structure

4.1 Introduction

The Grimm Trigger strategy was applied in an industrial case study, which was conducted in cooperation with a manufacturer of credit cards and UICC's (Universal Integrated Circuit Card), chip cards used in mobile phones for GSM and for UMTS networks, respectively. For each of the products, a supplier of components was analyzed.

4.2 Foil Supplier

In the first case, the investigated vendor provides foils that are used to manufacture so-called multi-layer credit cards, which consist of between four and nine colored and transparent foils, often with a magnetic and a signature strip. At the manufacturer's site, the required amounts of foils and strips are stacked and geometrically adjusted by a fixation machine, where the top and the bottom foils are transparent. The underlying layers contain the foils with the card's design elements and a certain number of white foils for stabilization purposes. The foil stack, from which 48 cards are obtained, is then joined through laser technology. Finally, the foils are baked, cut, deflashed, and the cards are stamped with the user's personal data.

The manufacturer procures an estimated 867,020 foils per year from the supplier and incurs a part price (w) of 0.0145 €. The foils are delivered to the manufacturer between one and five times per month, depending on the level of demand. From the ERP-system (SAP$^©$ R/3) data, the probability (p) that a delivery contains zero defects is assumed to equal 0.34.

The problems that occur with defective foils mostly stem from the mixture of ingredients used in the foil production process, which result in insufficient coloring or translate to deficiencies in the lamination process.

The first quality issue requires a preventive inspection of the colored foils through which a yearly labor cost of 14,450 € arises for the manufacturer. The scrap cost for lamination failures equals 20,000 € per year. Taking this cost into account, a per part quality cost (q_m) of 0.039 € can be calculated for the manufacturer. Surprisingly, this amount represents more than double the part price, yet the manufacturer presently does not penalize the supplier for defective units.

To overcome these shortcomings, the supplier would have to invest 50,000 € for a test lamination machine and an additional 175,000 € for a chemical mixture analyzing device. Analogous to the manufacturer, the supplier would also have to incur a yearly labor cost of 14,450 €. Assuming that the testing devices can be employed for 8 years, the supplier's quality cost (q_s) of 0.049 € per part may be calculated. Using formula (10) and the manufacturer's commonly used interest rate of 4%, a discount factor of 0.9615 is calculated and a part price (w^*) of 0.066 € is obtained, which includes the full quality premium and presumes a setting where the supplier is not penalized.

As it can be already anticipated from a comparison of q_m and q_s, the cost resulting from the higher part price exceeds the manufacturer's yearly quality cost and the manufacturer would have to incur an extra 10,704.1 € to obtain perfect quality by paying a part price that includes a quality premium. Hence, formula (11) is not satisfied. For an overview of this data refer to Figure 12.

Input parameters – current setting	
• Market price (w):	0.0145000 €
• Per part quality cost of the supplier (q_s):	0.0491050 €
• Discount factor based on an interest rate of 4% (δ):	0.9615
• Probability of zero defects (p):	0.34
• Penalty per defective part (r):	0 €
• Expected penalty ($E(r)$):	0 €
• Per part quality cost of the manufacturer (q_m):	0.0397338 €

Management choices	
• Part price including quality premium (w^*):	0.0665797 €
• Savings per year (case V):	- 10,704.1 €
• Required penalty (r) for constant market price (w):	0.1533142 €
• Savings per year (case IV):	34,450 €

Figure 12: Overview of parameters and results for the foil supplier for the Grimm Trigger strategy

In this case, the only management choice that increases the supplier's quality level and reduces the manufacturer's cost is to penalize the supplier, if defective parts are delivered. To create a setting in which the supplier is indifferent between perfect and imperfect quality, the manufacturer would have to penalize the supplier with at least 0.153 € per defect. To fully eliminate the manufacturer's quality cost (q_m) of 34,450 €, the manufacturer would have to charge the supplier a penalty of 0.153 € per faulty unit. Thus, case IV (depicted in Figure 9, p. 26) is the manufacturer's best choice. Since the probability of zero defects has been drawn from historical data, Figure 13 plots a sensitivity curve for the penalty level where the supplier is indifferent between good and insufficient quality as well as for the case where the buyer's quality cost is fully eliminated.

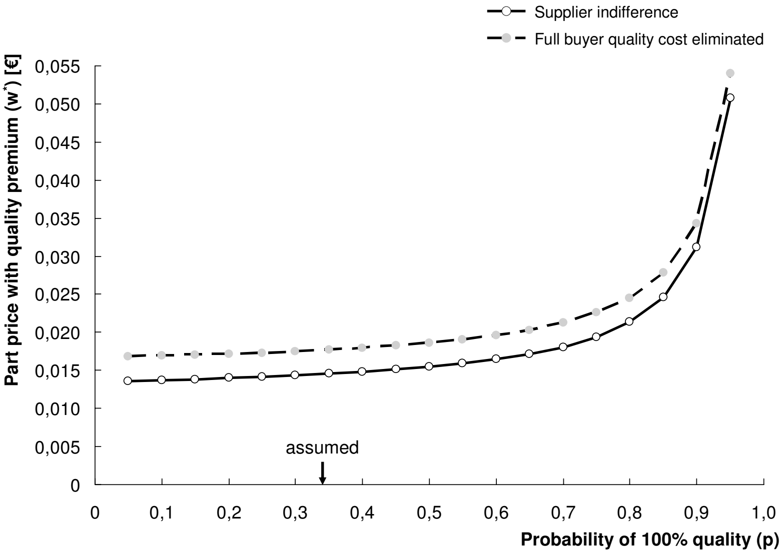


Figure 13: Sensitivity analysis of the part price vs. the probability of high quality for the foil supplier

4.3 Plastic Card Supplier

The second supplier analyzed in the course of the industrial case study provides plastic cards that have a similar size as credit cards and are used to produce UICC's. Upon arrival at the manufacturer's factory, these injection molded parts are fed into a printing machine, which applies the customer-specific design to the card. Subsequently, the UICC-bodies are stamped into the plastic while they are still connected to the card, though they can easily be detached from it by the end-user. In the next step, the chip is planted onto the UICC-body, and the so-called operating system and the customer information (e.g., the user's PIN) is installed. Finally, the cards are conveyed to the mailing center, where they are packaged and sent to the end-users together with an information kit.

The supplier produces 37,750,000 UICC's annually that are delivered to the manufacturer between 3 and 9 times per month. The manufacturer pays an average part price (w) of 0.036 €. The historical delivery data reveals that the probability (p) that the supplier will provide 100% quality is 0.59.

The most common quality issues caused by the supplier are increased surface roughness, which translates into insufficient results in the printing process, and unsatisfactory coloring of the cards, which stems from an inappropriate granule mixture in the injection molding process.

Because of these defects, the manufacturer incurs a scrap cost of 20,000 € per year. The incoming sampling, which includes a visual inspection with respect to concavity and flesh and a test print to assure color adherence results in labor cost of 40,000 €. Hence, a per part quality cost (q_m) of 0.0015 € is calculated for the manufacturer, who does not charge the supplier a quality penalty. For an overview of this data refer to Figure 14.

Input parameters – current setting	
• Market price (w):	0.0366333 €
• Per part quality cost of the supplier (q_s):	0.0013228 €
• Discount factor based on an interest rate of 4% (δ):	0.9615
• Probability of zero defects (p):	0.59
• Penalty per defective part (r):	0 €
• Expected penalty ($E(r)$):	0 €
• Per part quality cost of the manufacturer (q_m):	0.0015894 €

Management choices	
• Part price including quality premium (w^*):	0.0380863 €
• Savings per year (case V):	5,150.1 €
• Required penalty (r) for constant market price (w):	0.0024486 €
• Savings per year (case IV):	60,000 €

Figure 14: Overview of parameters and results for the UICC supplier under the Grimm Trigger strategy

To eliminate the above mentioned quality issues, the supplier would have to invest 24,000 € in a surface roughness measuring machine, 125,000 € in a test printing device, and 10,000 € in a granule control system. This investment could be used for at least one more customer of the supplier. Furthermore, the supplier would have to incur labor cost for quality assurance of 40,000 € per year to assure the quality of the products ordered by the manufacturer. Presuming a life expectancy of 8 years for all equipment, and taking into account the possibility of sharing the investment with an additional customer, a per part quality cost (q_s) of 0.0013 € is obtained for the supplier. Setting the expected penalty at zero, a part price that includes the quality premium (w^*) of 0.038 € is calculated.

With the higher part price, the manufacturer would have to pay the supplier an extra 54,849.9 € per year and thereby save 5,150.1 €, assuming that the sampling activities can be omitted and the scrap cost does not arise. In this setting, which coincides with case V (mentioned in Figure 9, p.26), formula (11) is satisfied. The manufacturer can further increase savings by applying cases I through IV (mentioned in Section 3.2) as alternative management choices. To reach the boundary of the area declared as case IV (in Figure 9, p. 26), the manufacturer would have to charge the supplier 0.00234 € per defective part and could thereby fully eliminate the full yearly quality cost of 60,000 €. Figure 15 shows a sensitivity analysis for cases where the supplier is indifferent and where the buyer's quality cost is fully eliminated. It may also be inferred from Figure 15 that the Nash Equilibrium (NE) holds up to a probability of sufficient quality of 0.86.

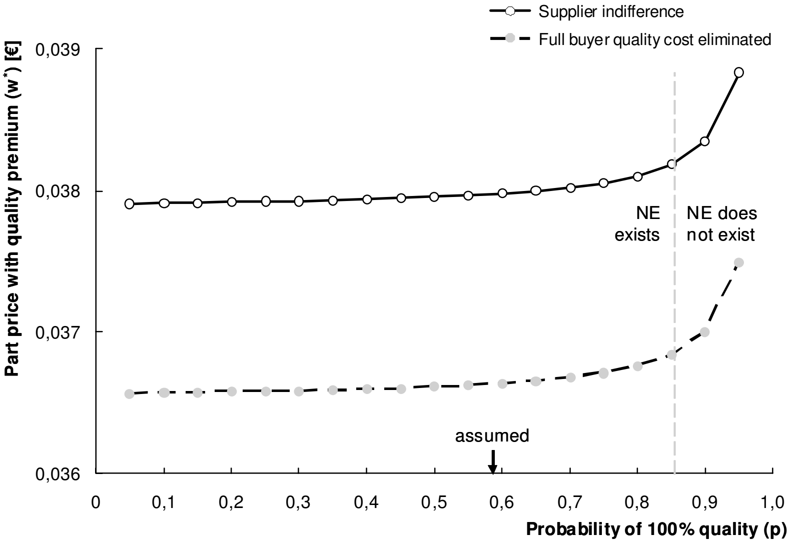


Figure 15: Sensitivity analysis of the part price vs. the probability of high quality for the UICC supplier

If the potential savings of 5,150.1 € were to be utilized to employ a Limited Retaliation strategy, an extra per part cost Δw^* of 0.000136 € would be acceptable and 19 required punishment periods are obtained from formula (14). Assuming that the supplier delivers parts to the manufacturer once per week the punishment phase would last 4 months.

4.4 Managerial Implications

These industrial examples show that managers face two basic situations in SQM.

First, if the quality cost and the quality premium exceed the manufacturer's quality cost, the manufacturer has two options. The manufacturer can penalize the supplier in the case of defects and pay the market price (case IV, Figure 2) or, if the market power of the supplier is significant, accept the quality cost that arises at the manufacturer's premises and bear the market price. In the first case, the penalty can be set in such a way that the manufacturer's quality cost is partially eliminated and the supplier is indifferent between delivering high or low quality or the manufacturer's quality cost is fully eliminated and the supplier strictly prefers to deliver high quality, as described in the case of the foil supplier. Of course, the penalty can also be set in such a way that the manufacturer can financially benefit from low supplier quality.

Should the extra cost that arises from the increased part price be less than the manufacturer's quality cost, the manufacturer can either realize this cost difference (case V, Figure 2) or increase savings through decreasing the part price by enforcing a penalty (cases I through IV, Figure 2), as seen in the example of the supplier of plastic cards. Moreover, the manufacturer also has the option of sharing the savings with the supplier, to further increase the supplier's incentive for providing high quality.

4.5 Tool for Case Study Conduct

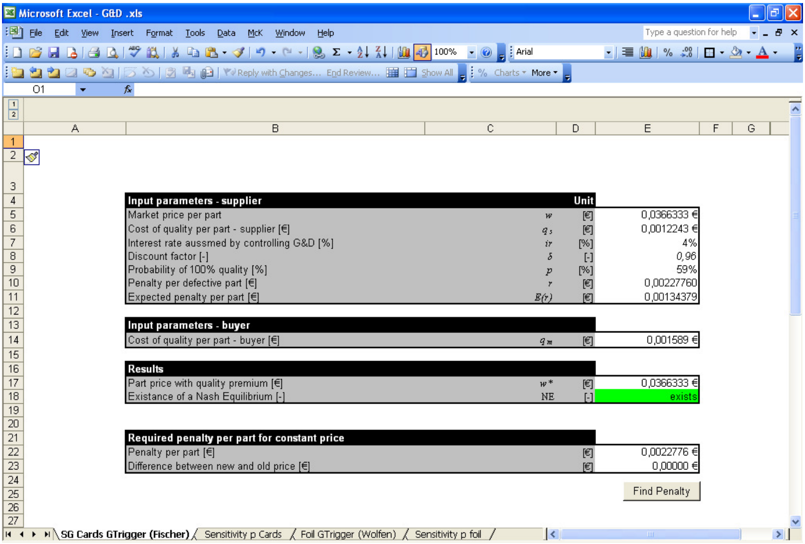
To provide a tool with which the developed concepts can easily be applied in industrial case studies, a Microsoft® Excel spreadsheet was designed, to be filled with the relevant parameters.

These can usually be collected within one working day and would be comprised of the following data:

Supplier

- current market price of the supplied part

- cost of quality per supplied part (this value can usually be estimated by a process engineer or obtained directly from the supplier)
- interest rate commonly applied by the controlling department
- probability of 100% quality (this value should be calculated from the order history of the supplier, which is usually drawn from the ERP-system and the quality management system)



Input parameters - supplier		Unit	
Market price per part	w	[€]	0,0366333 €
Cost of quality per part - supplier [€]	q_s	[€]	0,0012243 €
Interest rate aussmed by controlling G&D [%]	ir	[%]	4%
Discount factor [-]	δ	[-]	0,96
Probability of 100% quality [%]	p	[%]	59%
Penalty per defective part [€]	r	[€]	0,00227760
Expected penalty per part [€]	$E(r)$	[€]	0,00134379
Input parameters - buyer			
Cost of quality per part - buyer [€]	q_m	[€]	0,001589 €
Results			
Part price with quality premium [€]	w^*	[€]	0,0366333 €
Existance of a Nash Equilibrium [-]	NE	[-]	exists
Required penalty per part for constant price			
Penalty per part [€]		[€]	0,0022776 €
Difference between new and old price [€]		[€]	0,00000 €

Figure 16: Industrial incentive structure application tool

Buyer

- cost of quality per procured part (this information can be calculated by a production controller)

Once the spreadsheet has been completed with the required data, it automatically determines whether or not a Nash Equilibrium can be reached. Furthermore, it calculates the size of the penalty that the supplier must incur in cases of insufficient quality, to fully reduce the quality cost of the buyer. Through the considerations in chapter 3 and the development of the spreadsheet objective 1 of this thesis has been reached.

5 Review of Literature on Delivery Reliability

5.1 Introduction

Subsequent to the design of an incentive structure for the management of supplier quality, the remaining chapters focus on the second objective of this thesis, which is to provide the means through which buyers can efficiently and effectively ascertain the delivery reliability of potential suppliers.

To understand the current state of knowledge on this topic, this chapter focuses on research about managing delivery reliability and on its limitations. Both qualitative and quantitative approaches are examined: First, models that describe supply chains are elaborated to capture the full set of parameters for formalizing them.

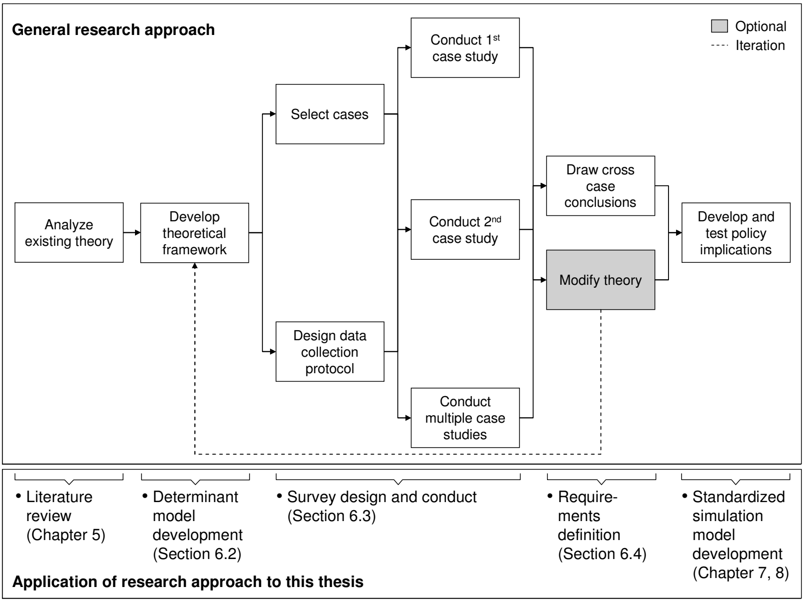


Figure 17: Research process applied for increasing delivery reliability

Subsequently, these parameters are discussed in regards to their influence on delivery reliability of the supply chains investigated by this thesis. Next, different quantitative models for supply chain management are introduced, and their strengths and weaknesses are examined.

As depicted in Figure 17, the literature review elaborated in this chapter serves as the basis for the research process described in the following chapters (see YIN 1994, p. 49; LINCK 2001, p. 87; LEEDY 1985). The delivery reliability relevant parameters identified in the literature review (Chapter 5) are utilized to develop a qualitative determinant model for describing supply chains in Section 6.2. This determinant model is then used as the structuring element for a survey in Section 6.3. The gained data is employed to draw cross-case conclusions in regards to the main requirements and levers for increasing supplier delivery reliability in Section 6.4. Depending on the outcome of the cross case conclusions, the theory developed in Section 6.2 may optionally be modfied, if any additions or changes are required. This may be neccessary, if new insights are gained during the analysis of the survey data and the research process should thus be iterated. The simulation models developed in Chapter 7 follow from the discussion of the quantitative models in the literature review and the requirements defined in Section 6.4, and are applied to an industrial case study in Chapter 8 to demonstrate how policy implications can be derived from the simulation results.

5.2 Qualitative Description of Supply Chains

Many qualitative descriptions or classifications of supply chain or network arrangements can be found in the SCM literature (SYDOW 1992, p. 85). These schemes encompass a wide range of foci. In the following sections, typologies are introduced that analyze supply chains on the basis of: structure, products, trust, influence, operations, and supply chain partner integration.

5.2.1 Structural Supply Chains

Concerning the structure, BEAMON & CHEN (2001) differentiate supply chains through four network classes (Figure 18). *Convergent* structures are assembly-type networks where each node (or facility) in the chain has at most one successor, but may have any number of predecessors. A supply chain is classified as *divergent* if each node has at most one predecessor, but any number of successors, and may thus be thought of as the structural opposite of a convergent supply chain. A *conjoined* structure is a combination of a convergent and a divergent supply chain, where each substructure (convergent and divergent) is combined in sequence to form a single, connected network. The *general* supply chain does not fall into any of the preceding three classes. Networks exhibiting a general structure are neither strictly convergent, nor divergent, nor conjoined. According to BEAMON & CHEN (2001, p. 3195 et seq.) examples of supply chains that commonly display a general structure include those for automobile and electronics manufacturing. Convergent structures are common to the aircraft industry, whereas divergent and conjoined forms may be found in mineral and food supply chains, respectively.

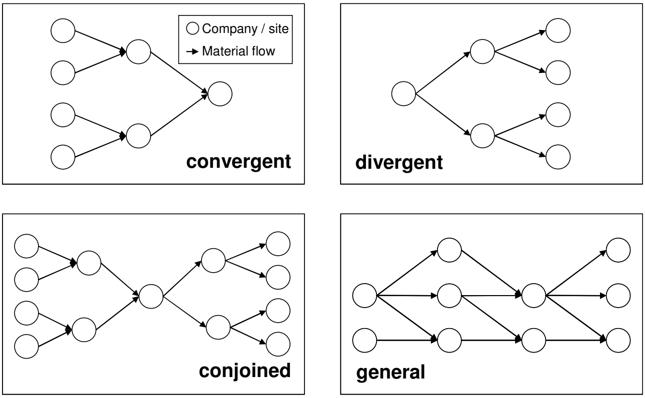


Figure 18: Structural classification of supply chains (BEAMON & CHEN 2001, p. 3196)

HUANG 2004 (2004, p. 13 et seq.) utilizes a similar classification scheme for distinguishing supply chains, which is based on the ideas of THOMPSON (1967). The concept differentiates *serial*, *pooled,* and *reciprocal* interdependencies between two plants. Serial interdependencies are related to situations where the output of one manufacturing system is the input to the next. In pooled dependence, the activities of more than one system serve as inputs for another. Thus, any of the constructs suggested by BEAMON & CHEN (2001) may be assembled through pooled and serial interdependencies. Reciprocal relationships may be summarized as “a mutual exchange of inputs and outputs between two or more parties” (HUANG 2004, p. 14), which is not addressed by the models suggested by BEAMON & CHEN (2001).

A further structural classification was derived through a Delphi study conducted by the Integrated Supply Chain Management (ISCM) program of the Massachusetts Institute of Technology (MIT). Its results (RICE & HOPPE 2001, p. 50) suggest *completely disconnected*, *completely overlapping,* and *partially overlapping* supply chains to characterize the level of competition between the networks of a given industry. The highest form of rivalry among supply chains is inherent to the first network type, since companies that constitute such chains exclusively serve firms involved in the creation of one specific end product. In completely or partially overlapping networks, however, a partner may supply products to various companies within the same industry. The latter two forms may be found, for example, in the automotive industry, where it is difficult to separate singular supply chains that compete against each other.

5.2.2 Product-Based Supply Chains

In the SCM literature, a product-based differentiation of supply chains has been described by FISHER (1997). To define the requirements of such networks, products are classified into *functional* and *innovative* products. The first group is subject to a known and nearly constant demand (e.g., dairy products), while the latter has little forecasting accuracy (e.g., computers). Moreover, FISHER (1997) states that functional products have long product life cycles and a small contribution margin, in contrast to innovative products. Additional product characteristics refer to lead times, mark downs, and stock out rates (Figure 19).

Product characteristics	Functional products	Innovative products
Demand	constant	variable
Product life cycles	more than 2 years	3 months to 1 year
Contribution margin	5 to 20%	20 to 60 %
Product variety	low (10 to 20 variants)	high (10^6 of variants)
Average margin error	10%	40 to 100 %
Average stock out rate	1 to 2%	10 to 40 %
Average end-of-season mark-down as percentage of full price	0%	10 to 25 %
Lead time required for make-to-order product	6 months to 1 year	1 day to 2 weeks

Figure 19: Characteristics of functional and innovative products (FISHER 1997, p. 107)

The two product types are complemented by *physically efficient* and *market responsive* supply chains. Efficient networks seek to minimize cost and maximize performance metrics. Thus, they focus on high average utilization rates and continuously minimize inventory levels. In contrast, market responsive supply chains concentrate on speed and flexibility and therefore deploy excess buffer capacities and significant safety stocks.

LAMMING et al. (2000) extended the product classification developed by FISHER (1997) by introducing product complexity as a second differentiator. Their research has shown that supply chains for functional and innovative products have different characteristics depending on whether the product complexity is high or low.

5.2.3 Level of Trust in Supply Chains

DAVIES (2000) classifies three kinds of enterprise relationships. This distinction is mainly based on the aspect of trust. Depending on the nature of the relationship arm’s length, less than arm’s length, and no length relationships are differentiated.

In *no-length relationships*, the parties frequently have access to sensitive information. Although this satisfies a necessary precondition for opportunistic behavior, it is offset by the fact that the parties in such relationships are insiders (e.g., mergers, inter-subsidary agreements) and for one to exploit this information, the act would be against the interests of one’s own organization.

Less-than-arm's-length relationships are characterized by the merging of interests and the sharing of privileged information, intimate cooperation and collaboration, and common goals and objectives. Partners have access to privileged information and have the opportunity and motivation to behave opportunistically.

Arm's-length relationships include all traditional sales and purchase contracts, sourcing agreements, conventional arm's-length distribution, franchising, and licensing agreements and are characterized by a simple, unambiguous buyer-seller structure. The parties provide each other with the information that is relevant to and necessary for the current transaction. A motive may exist for behaving opportunistically but, as neither party has access to privileged information, the parties do not have the means to do so.

5.2.4 Degree of Focal Firm Influence in Supply Chains

With regards to the dimension of focal firm influence, CORSTEN & GÖSSINGER (2001) distinguish *hierarchical* and *heterarchical networks*, with the first type being led by a defined focal firm and the second type characterized by uniformly distributed decision-making power among the network partners. The authors emphasize this differentiation since the customer order decomposition and allocation processes require different approaches in these settings (CORSTEN & GÖSSINGER 2001, p. 35). In hierarchical arrangements, the allocation of value creation steps to the supply chain partners is predetermined and the coordination takes place in terms of order quantity and lead time only. On the contrary, order decomposition and allocation are achieved through a coordination process that involves multiple decision-makers with potentially diverging interests in heterarchical networks.

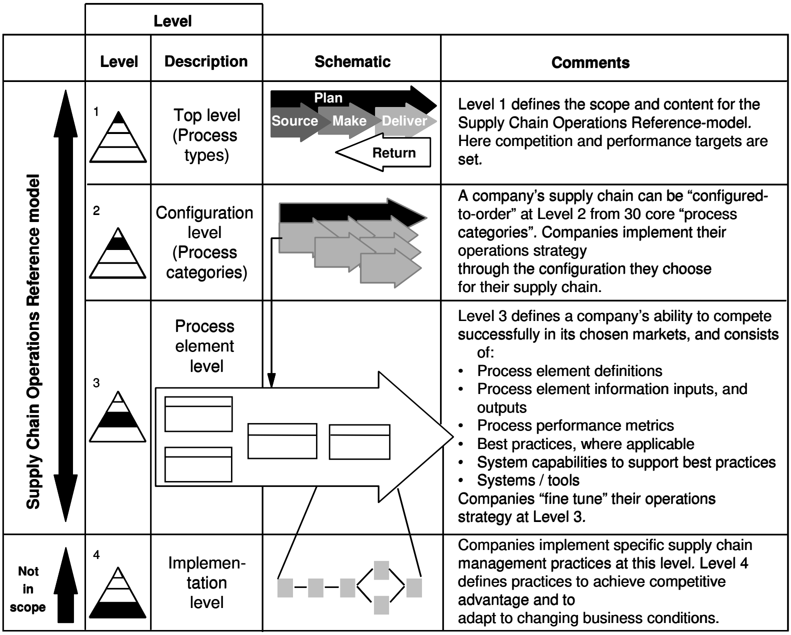
With regards to the influence distribution within a network, HARLAND et al. (2002) conducted an exploratory study of supply networks across different industries and developed a supply chain taxonomy that is divided along two dimensions: the degree of *supply network dynamics*, which refers to operational and market dynamics, and the *degree of focal firm supply network influence*. Their research suggests that networks with low focal firm influence have a distinct characteristic where partners are open to risk and benefit-sharing, whereas in networks that are led by a focal firm, the conditions are prescribed by the strongest partner.

The results of their analysis also identify that the pattern of network activities have some significant differences between *dynamic* and *routinized* supply networks. According to these findings, dynamic networks put a greater emphasis on knowledge-sharing and human resource integration. This is mainly due to the fact that these networks compete on innovation (HARLAND et al. 2002, p. 83). Routinized networks concentrate on extensive information exchange to achieve a cost advantage over their competitors.

5.2.5 Operational Description of Supply Chains

In the search for a standard language for common intra- and inter-company supply chain functions the Supply Chain Operations Reference (SCOR) model was developed by the Supply Chain Council and its partners (SUPPLY-CHAIN-COUNCIL 2005). “It consists of a system of process definitions for standardizing processes relevant to SCM" (MEYR et al. 2000, p. 38), but does not include functions such as marketing or product development, and is focused on the management of material and information. In Figure 20, the processes are seen to be divided into three hierarchical levels, namely: process types, process categories, and process elements.

The first level consists of the four elementary process types: *source, make, deliver,* and *return*, which are coordinated by the process type plan. The latter defines issues such as demand and supply planning, strategic make-or-buy decisions, and capacity planning. The necessary processes for procuring products to meet the planned and current demand are assigned to the process type source. Material transformation and customer delivery processes are subsumed under the process types *make* and *deliver*. Return processes are concerned with parts that flow back into the supply chain due to quality deficiencies or because the end of the life cycle has been reached.



	Level			
	Level	**Description**	**Schematic**	**Comments**
Supply Chain Operations Reference model	1	Top level (Process types)	Plan Source Make Deliver Return	Level 1 defines the scope and content for the Supply Chain Operations Reference-model. Here competition and performance targets are set.
	2	Configuration level (Process categories)		A company's supply chain can be "configured-to-order" at Level 2 from 30 core "process categories". Companies implement their operations strategy through the configuration they choose for their supply chain.
	3	Process element level		Level 3 defines a company's ability to compete successfully in its chosen markets, and consists of: • Process element definitions • Process element information inputs, and outputs • Process performance metrics • Best practices, where applicable • System capabilities to support best practices • Systems / tools Companies "fine tune" their operations strategy at Level 3.
Not in scope	4	Implementation level		Companies implement specific supply chain management practices at this level. Level 4 defines practices to achieve competitive advantage and to adapt to changing business conditions.

Figure 20: Detailed description of the SCOR model (SUPPLY-CHAIN-COUNCIL 2005, p. 6)

At level two, the process types are divided into 30 process categories, which support either planning, execution, or enabling tasks. Execution tasks are differentiated according to the order decoupling point (i.e., make-to-stock, make-to-order, engineer-to-order). The process categories are utilized to assemble supply chain processes in such a way that they are in synch with the defined operations strategy.

Level three decomposes the process categories into process elements (and their in- and outputs), which define the operational tasks of each process category. These may be employed to design supply chain processes on a more detailed level. This is supported by the SCOR model through documentation of best practices, performance metrics, and suitable IT tools.

The fourth level describes the transition from standardized to industry-specific supply chain processes, which are not within the scope of the SCOR model due to the prevailing diversity (GEIMER & BECKER 2001, p. 128).

To assist the application of the SCOR model, MEYR et al. (2000) developed a typology through which the characteristics of a supply chain may be described. The intent of this scheme is for the application of certain processes or IT systems to be assessed based on this typology.

The authors suggest a division of functional and structural attributes, which are then subdivided into categories. The functional attributes contain the categories *procurement*-, *production*-, *distribution*-, and *sales*-type, and their respective characteristics. The procurement-type relates to the products, ranging from standard to highly specific products, and the type of sourcing (single, double or multiple). Whether or not the amounts to be supplied are fixed, whether they have a lower or an upper boundary due to given contracts, or whether they may be freely varied, is expressed through the attribute *flexibility of suppliers*. The two most prominent attributes that form the production type are the organization of the production process (process organization, flow lines, etc.) and the repetition of operations (mass, batch, or customized production). Furthermore, the authors distinguish between the different distribution types, which describe the network of links between the entities (one-, two-, or multi-stage distribution structures). The pattern of delivery is either cyclic or dynamic and, in regards to the deployment of transportation means, one can distinguish standard or variable routes, depending on demand. The sales type of an entity in the supply chain largely depends on the relation to its customers. This attribute is closely related to the availability of future demand. Product life cycle, products sold, as well as the portion of service operations are also described.

Structural attributes contain the categories *topography of a supply chain* as well as *integration* and *coordination*. In regards to the topography of a supply chain, the attribute *network structure* describes the material flows (which are either serial, convergent, divergent, or a mixture of the three), the degree of globalization, and the location of decoupling points within the supply chain. The attributes of *integration* and *coordination* are the legal position, balance of power, direction of coordination, and the type of information exchanged.

5.2.6 Level of Integration in Supply Chains

JAGDEV & THOBEN (2001) analyzed the essential attributes and operational characteristics of network collaborations, which incorporate many of the differentiation criteria described in the preceding sections. The developed typology consists of a set of 21 attributes (JAGDEV & THOBEN 2001, p. 449) to distinguish the level of network integration. Depending on their values, the five network types (*market transaction*, *supply chain*, *extended enterprise*, *virtual enterprise* and *integrated company)* are clustered with the first being subject to the lowest, and the last being subject to the highest level of integration. Some of the attributes address legal and financial aspects, such as percentage of output and turnover associated with the partnership, balancing of added value, profit and risk sharing among the partners, and the financial commitment. Other attributes are concerned with the flow of information and the linkage of the information systems of the partners. Among these are the level of information exchange, transparency of stock levels and production schedules, and inter-company trust. A third group refers to the exchanged product, its complexity and variability, degree of standardization, and importance of the supplied products to the end-customer.

BURLAT et al. (2003) focus on small- and medium-sized industrial enterprises, that form horizontal networks of limited durations. The authors use a model for the level of integration among supply chain partners, as developed by VINCENT et al. (1999), which is then extended by one dimension. VINCENT et al. (1999) distinguish six levels of accomplishment within networks. On the first level, companies begin seeking external partners as a reaction to market dynamics. The following levels result in increased network integration, and include: (1) the development of a common culture and common objectives, (2) clear definition of roles and rules within the network, (3) the streamlining of competencies, (4) common market planning, and (5) collaborative product development. BURLAT et al. (2003) assign different network types to each integration level, but discriminate relationships on the basis of non-complementary activities and similar competencies from complementary activities and non-similar competencies. This leads to nine network types, since networks with similar competencies are not believed to pass the third level, whereas networks with complementary competencies are believed to evolve to the sixth level.

In terms of integration, CRAVENS et al. (1996) differentiate four types of networks. The first is the *hollow* network, characterized by a single company that faces highly varying end-customer demand and must draw heavily on the competencies of many suppliers to fulfill customer expectations. As the partners vary with every project, the level of integration is low and the nature of collaboration is transactional. *Flexible* networks are likely to serve markets with short product life cycles and changing customer demand. A network coordinator is responsible for product design and the network partners are strongly integrated to produce innovative products under these market conditions. In the *value added network*, an OEM would possess all the competencies required for product creation, but employs low-cost suppliers for simple value-adding tasks, which leads to a low integration level among supply chain partners. CRAVENS et al. (1996) define a *virtual* network as occurring when one company is well known to the market, responsible for product design, and integratively hedges the risks inherent to a dynamic market with suppliers that procure assembly groups and components.

5.3 Summary of Qualitative Supply Chain Research

From the research discussed above, the models that describe the networks consider various aspects of the supply chain, especially in regards to delivery reliability.

For instance, the structural classifications (e.g., BEAMON & CHEN 2001) illustrate the complexities of the interconnections between enterprises. In terms of delivery reliability, however, this thesis agrees with the work of JAGDEV & THOBEN (2001), who proposed that any given supply chain can be disaggregated into dyads, thus, making it possible to reduce the complexity by viewing each supply chain relationship separately.

Product-based classification (Fisher 1997) shows that the characteristics of the exchanged product, such as: customer lead time, number of variants, and demand fluctuations, are important when designing a reliable supply chain, as these parameters define customer expectations, in terms of delivery reliability. Other parameters, such as: contribution margin, seasonal marked-down prices, and length of the life-cycle, are not particularly relevant for the on-time delivery of products.

The aspect of trust, mentioned by Davies (2000), or the distribution of power, discussed by Corsten & Gössinger (2001) are essential facets of supply chain relationships, and are also prerequisites for highly reliable supply chains. Thus, the level of trust and the distribution of power must be such that every member of the supply chain is provided with the resources needed to deliver their outputs in a reliable fashion (e.g., engineering information).

The operational models contain various attributes that are relevant to the assurance of delivery reliability. While some parameters (e.g., demand information or number of variants) are also mentioned in the product-based classification, Meyr et al. (2000) (or the SCOR model) additionally specify: the customer order decoupling point, organization of production, replenishment principle / procurement type, and (volume) flexibility of the production system.

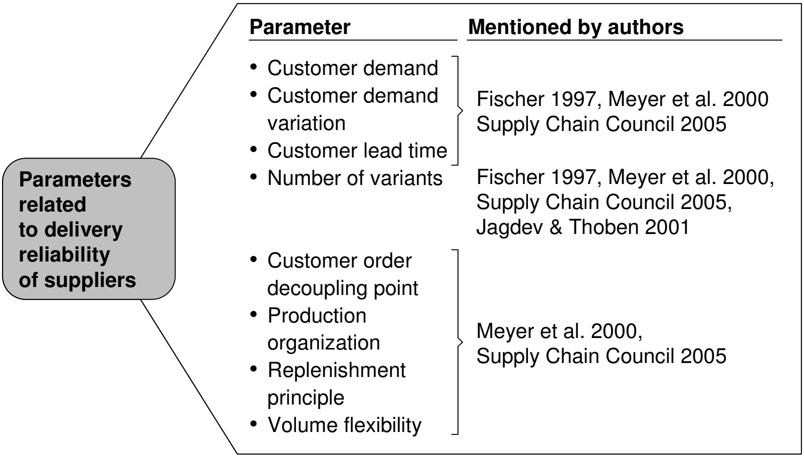


Figure 21: Summary of qualitative supply chain research

The first two parameters are crucial, as they determine where a customer order enters production and the material flow through production. In turn, the replenishment principle has a great effect on delivery reliability, as it strongly influences the availability of material at each stage of production, and the volume flexibility determines the supplier's ability to react to demand fluctuations.

The level of integration encompasses a variety of supply chain parameters that do not directly influence the delivery reliability of suppliers. The legal and financial aspects, flow of information, and trust mentioned by JAGDEV & THOBEN (2001) are again seen as prerequisites for the delivery of materials and components.

In summary, the descriptive models elaborated in Section 5.2 bring forth the parameters for the management of delivery reliability (Figure 21). These attributes are used in Chapter 6 for developing a comprehensive determinant model that describes a dyadic supply chain. The following section summarizes quantitative models for assessing delivery reliability in supply chains.

5.4 Quantitative Assessment of Supply Chains

Because of the large variety of quantitative models in supply chain research, they are not easily classified. Following the systems view of a supplier (as depicted in Figure 22), the discussion of quantitative models is grouped into two sections. The first deals with the information that the supplier obtains from the buyer as input. This discussion focuses on the demand information received by the supplier from the buyer, with all technical information being viewed as a prerequisite for the supply of parts.

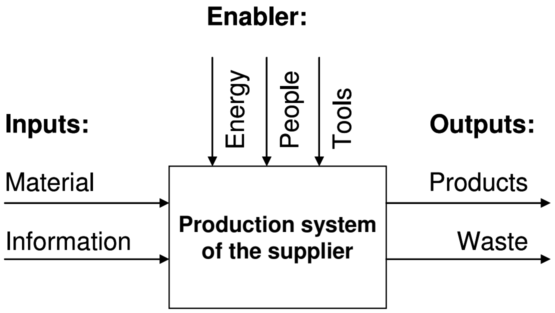


Figure 22: Systems view on a supplier (adapted from REINHART & ZAEH 2007, p. 18)

As all enablers are assumed to be as given, and the availability of raw material is also a delivery reliability problem, analytical models for manufacturing system design are discussed in section 5.4.2. This is also the most crucial factor for the delivery reliability of the finished good.

5.4.1 Supplier Demand Information

The discussion of the effect of supplier demand information encompasses two parts, where the first addresses the effect of highly variant demand and the second is concerned with information asymmetry.

Even though numerous studies deal with the effect of demand information on the supply chain (e.g., LODE 2002, RAGHUNATHAN 2001, MOINZADEH 2002, CHEN 2003), the most cited research is the investigation of the bullwhip effect first described by Forrester (see FORRESTER 1996).

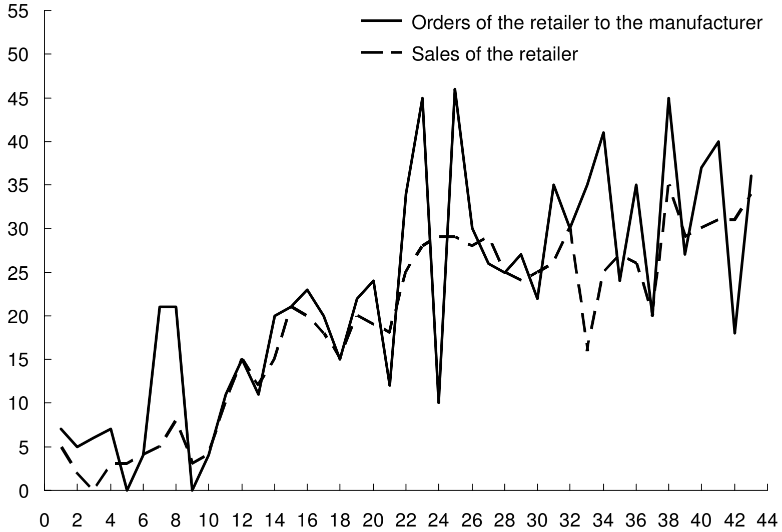


Figure 23: Orders and sales data illustrating the bullwhip effect using the example of the sales volume of a retailer and the order volume of the retailer at the manufacturer (see LEE et al. 1997a, p. 547)

This effect is based on a phenomenon where the orders of a buyer to the supplier do not coincide with actual sales to the end customer, but have a variance that is larger than the variance of the sales. Furthermore, the distortion of demand data is propagated upstream in an amplified form. This high variance of demand data can easily lead to reduced delivery reliability, when the demand from a buyer exceeds the capacity of a supplier. A first stage example of this effect is plotted in Figure 23, where the order and sales data are shown for a retailer that orders items from a manufacturer.

LEE et al. (1997a) developed mathematical models of supply chains that capture the four essential elements of this effect, which are: demand signal processing, order batching, rationing, and price changing (LEE et al. 1997b, p. 95).

The first element describes a situation where demand information is distorted because the buyer orders on the basis of the buyer's forecast, rather than on true demand information. In this scenario, the forecast is derived from historical order data instead of from a demand preview of the buyer's customer, and may thus be exaggerated or underestimated when temporary demand shocks occur.

Batching of orders is a consequence of two factors: the periodic review process and the cost of a purchase transaction. Since orders are in most cases not placed daily, but are often weekly, bi-weekly, or even monthly, depending on the internal processes of the buyer, the supplier cannot see the true demand of the buyer's customers. Furthermore, orders are often batched, for reasons such as economic lot sizes or to achieve full truck loads.

Rationing is the situation where the buyer suspects that demand will exceed possible supply and thus places higher orders, hoping to minimize the difference between the actual amount of goods received and the required supply.

Finally, price changing results in a high variance in orders, where the buyer tends to place high orders when prices are low, and minimizes demand when the cost of the product is high.

Given that rationing and price changing are mostly economical effects, the following paragraphs emphasize signal processing and order batching.

To analyze the first effect, LEE et al. (1997a) developed a model that describes a retailer-supplier relationship, that can be used to model any buyer-supplier relation, and which is based on an order-up-to policy (see SCHÖNSLEBEN 2004, p. 524).

In their model, demand D_t is serially correlated, as prescribed by (16), where d is a demand constant, ρ is a constant between -1 and 1, and μ is a zero mean continuous random variable.

$$D_t = d + \rho D_{t-1} + \mu \tag{16}$$

The cost minimization problem faced by the retailer is given by equation (17), where the expectation is taken with respect to the demand realized. Using (17), LEE et al. (1997a) proved that the variance of the retail orders (z_t) is strictly greater than that of retail sales (D_t), when ρ is between zero and one. Furthermore, they showed that the variance of orders from the retailer to the manufacturer (Var(z_t)) increases in the replenishment lead time of the manufacturer (υ).

$$\begin{gathered}\min_{S_t}\left[\sum_{t=1}^{\infty}\beta^{t-1}\,E_1\left[cz_t+\beta^{\nu}\,g\left(S_t\sum_{t=1}^{t+\nu}D_t\right)\right]\right],\\ \text{where } g\left(S_t\sum_{t=1}^{t+\nu}D_t\right)=h\left(S_t-\sum_{t=1}^{t+\nu}D_t\right)+\pi\left(S_t-\sum_{t=1}^{t+\nu}D_t\right)\end{gathered} \tag{17}$$

β	Cost discount factor per period
D_t	Demand in period t
c	Unit ordering cost
d	Demand constant
g	Discounted holding and shortage cost after υ periods[11]
h	Unit holding cost
μ	Normally distributed variable
π	Unit shortage penalty cost
ρ	Constant satisfying $-1 < \rho < 1$
S_t	Amount of goods in stock, on order at the manufacturer and in transit
t	Period in the process
υ	Replenishment lead time (time between ordering and receiving goods)
z_t	Quantity of the order to the manufacturer in period t

From these results, the general managerial conclusion may be drawn, that it is beneficial for all parties to share the true demand information to reduce variation in demand and thereby reduce excess inventory levels, as well as the probability of stock-outs, to thus increase delivery reliability.

---

[11] See HEYMANN & SOBEL 1984, pp. 75-78 for a detailed discussion

The second model elaborated on here (LEE et al. 1997a) deals with order batching and is based on a periodic-review-stationary-demand system with full backlogging with each review cycle taking place every R periods. N retailers (or buyers) are assumed to have a demand ξ with a mean of m and a variance of σ^2 in each period. Depending on how the retailers' order cycles may be independent or correlated, three different cases are differentiated: random, correlated, and balanced ordering. Random ordering describes the case where the demand from retailers is independent of each other. In this case, the expected total number of orders $E(Z_t^r)$ and the related variability $Var(Z_t^r)$ are expressed by (18):

$$E(Z_t^r) = Nm\,,\ Var(Z_t^r) = NmN\sigma^2 + m^2N(R-1) \tag{18}$$

For positively correlated ordering, the case is considered where all retailers order in the same period, which results in the expected demand and variability for the manufacturer given by (19):

$$E(Z_t^c) = Nm\,,\ Var(Z_t^c) = N\sigma^2 + m^2N^2(R-1) \tag{19}$$

The other extreme case of balanced orders occurs when demand from different retailers is evenly distributed over time. For this scenario, the cumulative demand and the variability are expressed by (20). Here, retailers are divided into R groups, where the number of retailers is calculated by $N = MR+k$ and k groups have the size $(M+1)$, and $(R–k)$ groups have the size M, such that all retailers in one group are ensured to order on the same day, and orders are placed on every day of the order cycle.

$$E(Z_t^b) = Nm\,,\ Var(Z_t^b) = N\sigma^2 + m^2k(R-k) \tag{20}$$

ξ_{ik}	Demand for retailer i in period k
k	Parameter for calculation of retailer gropus / retailers per group (balanced ordering)
m	Mean demand for ξ_{ik} for each retailer
M	Parameter for calculation of retailer gropus / retailers per group (balanced ordering)
N	Number of retailers
σ^2	Variance for ξ_{ik} for each retailer
R	Periods in review cycle, number of retailer groups (balanced ordering)
$Z_t^{r,c,b}$	Orders from n retailers under randon, correlated or balanced demand

From these expressions ((18), (19), (20)), the mean expected demand is assumed to be constant in all cases, whereas the variability differs significantly. Correlated ordering, with all orders being placed in the same period, has the highest variability, balanced ordering has the lowest variability and random ordering has a variability that is less than the first and higher than the second. In addition, the manufacturer experiences higher variability than do retailers, who face σ^2, in all cases.

The main managerial implications drawn by LEE et al. (1997a) are twofold. First, information distortion is greatly reduced by installing information technology that instantly conveys true demand to the supplier, as variability can thereby be decreased. The second opportunity is to reduce the transaction cost of an order, for example, by automating ordering or lowering the cost of a truck load. Both measures will result in a situation that comes closer to the balanced ordering case.

Hence, the bullwhip effect or demand signaling, and order batching, are phenomena that can be mitigated by a limited number of measures directed towards the ordering process and information technology.

A second effect that has a great influence on the reliability of a supplier is the symmetry or asymmetry of information between the buyer and the supplier. KALUZA et al. (2003, p. 23) categorized such information asymmetry into three categories: *hidden characteristics, hidden intention, and hidden information*. For example, a hidden characteristic is an aspect of quality that cannot be easily assessed by a buyer (as mentioned in Chapter 2, i.e., the quality of toothpaste), while a hidden intention may be a reason for one party to engage in a relationship with another party, which is not openly communicated (e.g., a buyer that seeks to learn certain engineering capabilities from a supplier). In the context of demand, hidden information could be a buyer's knowledge about the end-customer demand that is not shared with the supplier.

In regard to the latter problem, ÖZER & WEI (2006) studied how different contracts affect the optimal capacity decision, and thus, the supplier’s and the manufacturer’s (or buyer's) profit, under asymmetric forecast information in a two-level supply chain. The problem addressed here is that the supplier must secure component capacity prior to receiving firm orders from the manufacturer. In a decentralized supply chain, however, the manufacturer often has better demand information due to a proximity to the customers.

This information asymmetry creates an incentive problem: the manufacturer can influence the supplier’s capacity decision by exaggerating the end customer's forecast. Anticipating this, the supplier does not consider the information provided by the manufacturer to be credible and thus decides upon the component capacity based upon a less accurate demand forecast (ÖZER & WEI 2006, p. 1238).

In describing this problem, the expected demand is modeled according to (21), where μ is a public constant (a minimal demand forecast provided by a market research firm, for example) and ε is a zero mean continuous random variable with cdf G(•) and pdf g(•), representing market uncertainty, which is also common knowledge. The private forecast information ξ is deterministic to the manufacturer, but a random variable to the supplier (with cdf F(•) and pdf f(•)).

$$D = \mu + \xi + \varepsilon \tag{21}$$

To assess the performance of various contracts, the centralized system (CS) as the "first best" solution to this information asymmetry problem, is considered as a benchmark. The optimal capacity K^{CS} may be derived from the suppliers' expected profit (see (22), (23)) where expectation is taken with respect to the uniformly distributed ε only, as the private forecast information is known to the manufacturer and to the supplier, in the case of the centralized system.

$$\max_{K \geq 0} E[(r-c)\min(K, \mu + \xi + \varepsilon)] - c_k K^{CS}, \tag{22}$$

$$K^{CS} = G^{-1}\left(\frac{r-c-c_k}{r-c}\right) + \mu + \xi \tag{23}$$

In comparison, the very simple and most prevalent wholesale price contract, under which an a priori-negotiated wholesale price w is paid by the manufacturer for each ordered unit, suffers from two sources of inefficiency: it does not achieve credible information sharing, and is the source of double marginalization[12] (see e.g. SPENGLER 1950).

The first effect may be illustrated through the equation for the supplier's optimal capacity K^{WS} under the wholesale price contract, which is subject to the convolution of F(•) and G(•) and irresponsive to the manufacturer's private forecast information (see (24), (25)). The latter source of inefficiency stems from the fact that the supplier optimizes capacity with respect to the wholesale price w, which is strictly lower than the retail price r.

---

[12] Double marginalization is defined as the exercise of the market power at successive vertical layers in a supply chain resulting in a price increase of the good at each step (e.g. producer and OEM margins)

$$\max_{K\geq 0} E\left[(w-c)\min(K,\mu+\xi+\varepsilon)\right]-c_k K^{WS}\,, \tag{24}$$

$$K^{WS}=(F\circ G)^{-1}\left(\frac{w-c-c_k}{w-c}\right)+\mu \tag{25}$$

c	Unit production cost
c_k	Unit capacity cost
D	Market demand
ξ	Producer's private forecast information
ε	Market uncertainty
$K^{CS/WS}$	Reserved capacity
r	Market price
μ	Demand constant
w	Wholesale price

To overcome the aforementioned lack of performance, ÖZER & WEI (2006) designed the advance purchase and the capacity reservation contracts. The first achieves credible information sharing by requiring an advance purchase from the manufacturer prior to the supplier’s capacity decision. The contract is designed according to the principle of a signaling game (see FUDENBERG & TIROLE 2000) and thus gives the manufacturer the opportunity to “signal” an optimal advance purchase quantity to the supplier, based upon the negotiated advance purchase price, which will be considered credible by the supplier with the probability of one.

The capacity reservation contract utilizes the revelation principle[13], a screening game (see GIBBONS 2004, SALANIÉ 1997, MYERSON 1981), to precipitate symmetric demand information. This is realized by constructing a menu of contracts that form a nonlinear capacity reservation price curve that offers an optimal contract for each “type” (i.e. parameter set) of manufacturer with private forecast information.

Furthermore, ÖZER & WEI (2006) showed that the adverse effect of double marginalization can be mitigated through a pay-back agreement, where the manufac-

---

[13] The relevation principle states that any Bayesian Nash Equilibrium of any Bayesian game can be represented by an incentive-compatible direct mechanism (GIBBONS 2004, p. 165)

turer shares the risk of excess component capacity by offering a pay-back compensation.

From the result of a numerical study on different ratios between market uncertainty and private forecast information and capacity expansion cost, the contract portfolio was derived (Figure 24). Thus, the information asymmetry between the supplier and the buyer can be efficiently eliminated through a wide range of contracts.

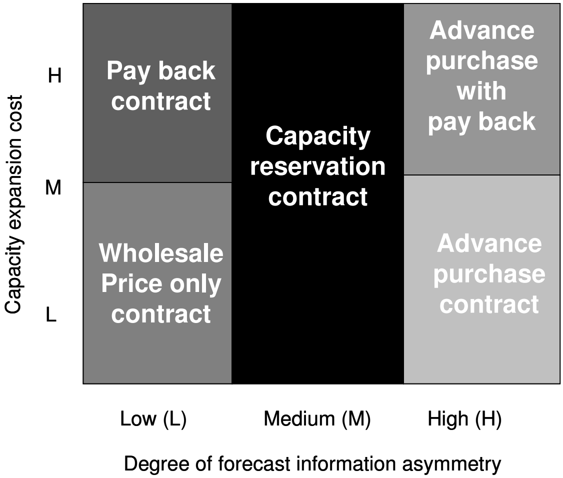


Figure 24: Map of optimal supply contracts under forecast asymmetry (ÖZER & WEI 2006, p. 1252)

Finally, a third effect concerning demand information must be briefly mentioned, for the sake of completeness. In situations where the buyer is uncertain regarding the demand of the end-customer, the buyer may understate the demand forecast to the supplier, so that the supplier builds an overly small capacity and sales may be lost in situations where the actual demand exceeds the forecast. To maximize profit, both for the buyer and for the supplier, and to safeguard delivery reliability, two similar contracts have been developed that the supplier may offer to the buyer.

First, the buy back contract is constructed so that the supplier offers to buy back unsold goods from the buyer at a prefixed price. This gives the buyer an incentive to increase the demand forecast and may increase the supplier's and the buyer's profit (see PASTERNACK 2002 or SIMCHI-LEVI et al. 2003, p. 55 for more detail).

The second contract, the revenue sharing contract, has an identical objective, but a somewhat different mechanism. In this setting, the supplier reduces the price of the goods supplied to the buyer and thus provides the buyer with an incentive to place a higher order or demand forecast. In return, the buyer shares the realized profits with the supplier (see CACHON & LARIVIERE 2005 or SIMCHI-LEVI et al. 2003, p. 54 for more detail). This again results in a more efficient profit distribution for the buyer and the supplier.

These three phenomena, the bullwhip effect, demand information asymmetry, and demand understating summarize the main research problems in terms of delivery reliability and demand information. As mentioned, the following section elaborates on the research on manufacturing system design in the context of delivery reliability.

5.4.2 Supplier Manufacturing System

The discussion on the manufacturing system design of the supplier is divided logically into two sections. The first elaborates on research that is directed towards mechanisms that give the supplier an incentive to design the manufacturing system according to the buyer's needs, which has been developed only recently. The second part describes methods and models that are employed to determine the right design of the supplier's system, depending on the external demand and the nature of the product.

Concerning the first group of research, two contract forms are introduced in this thesis that are employed to give the supplier some expectation about the buyer in regard to the supplier's system design: quantity flexibility and lead time contract.

The first contract specifies the flexibility of the buyer in the actual order quantity. For instance, TSAY & LOVEJOY designed a rolling horizon quantity flexibility contract in a multi-echelon setting that allows non-stationary demand and information updating (see also TSAY 1999). The contract is set up so that the buyer in a certain period *t* states the demand vector to the supplier

$$\{r(t)\} = [r_0(t), r_1(t), r_2(t), \ldots], \tag{26}$$

where $r_0(t)$ is the purchase quantity in period t and $r_j(t)$ is the estimate of the quantity to be purchased in period $(t + j)$, for each j greater than 1. This contract is further parameterized by $\alpha = [\alpha_1, \alpha_2, \ldots]$ and $\omega = [\omega_1, \omega_2, \ldots]$ which describes the flexibility enjoyed by the buyer in altering the demand vector and which is specified as follows:

$$\lfloor 1-\omega_j \rfloor r_j(t) \leq r_{j-1}(t+1) \leq \lfloor 1+\alpha_j \rfloor r_j(t) \ \textit{for each } t \textit{ and } j \geq 1 \ . \qquad (27)$$

Using heuristics, TSAY & LOVEJOY (1999) showed how the buyer should construct the demand vector given the variation of market demand and the supplier's flexibility limits prescribed by the contract. Furthermore, TSAY & LOVEJOY (1999) investigated how the supplier should set up the system to fulfill the contract parameters. In relation to the previous section, the intuitive result proves that the quantity flexibility contract dampens the bullwhip effect, which may be considered beneficial for the supplier. Other forms of the quantity flexibility contract have been reviewed by CACHON (2003).

In regard to the second construct mentioned above, LUTZE & ÖZER (2007) studied a promised lead time contract that reduces the supplier's risk of demand uncertainty and the buyer's risk of uncertain delivery reliability. The basic setting used for this research is depicted in Figure 27, where LUTZE & ÖZER studied a two-stage supply chain with uncertain end-customer demand D_t (with cdf F(•) and density f(•)), which is satisfied by a retailer who orders goods from a supplier.

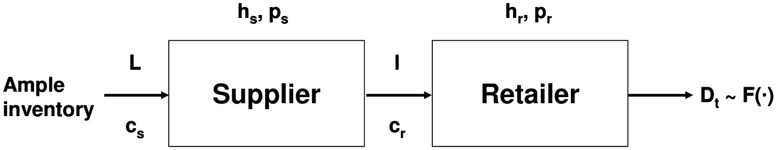


Figure 25: Two-stage supply chain under the promised lead time contract

In this model, the general sequence of events is assumed to be as follows: at the beginning of each period, the supplier and the retailer receive shipments, with the supplier obtaining these materials from a vendor with ample inventory and a lead time of L periods and the transportation time between the retailer and the supplier equal to l periods. The supplier and the retailer then incur the cost c_s and c_r for each ordered item (supplier – index s, retailer index r). The retailer satisfies end-customer demand and both the supplier and the retailer pay a shortage cost c for unfulfilled demand (if required) and a total inventory holding cost of h. The retailer places an order with the supplier, τ periods in advance, which the supplier promises to fulfill. Thus, the retailer receives the goods $\tau + l$ periods after the order has been placed.

Under these contract terms, LUTZE & ÖZER (2007) characterize the optimal promised lead time τ and the corresponding payments that the supplier should charge to minimize expected inventory cost, while ensuring the retailer's participation. In addition, they analyze the system under local and central control and under full and asymmetric information about the retailer's shortage level. The centrally controlled supply chain is used as a benchmark for the locally controlled system to show the circumstances in which the supplier and the retailer over-invest in inventory. Finally, with other analyses, the supplier is shown when to consider a promised lead time contract and when to refrain from such an agreement.

In summary, the promised lead time and the quantity flexibility arrangements are means through which the buyer can contractually specify the expected performance of the supplier's system. The actual system design is supported through various models and methods that are briefly reviewed in the following paragraphs. Again, this discussion is split logically into two parts, where the first deals with single and multi-echelon design as well as queuing theory, while the second provides a brief overview of dynamic simulation models for verifying manufacturing system design.

Since a multitude of papers deal with inventory management, this thesis focuses on a single-echelon model described by ZÄH & MÖLLER (2007), which is similar to the models described by GRABAN (1999, p. 37 et seq.).

This inventory model is used for determining the maximum amount of inventory required when facing stochastic demand from an internal or external down stream customer and lead times of the production process or factory vary.

As shown by formula (28), the resulting equation is divided into B_u and B_s, which represent the basic stock and the safety stock. The basic stock B_u is the amount of inventory required to buffer against mean demand, considering the mean lead time. The safety stock B_s has two components: I and II, marked in formula (28). The first is required because of demand variation, while the second ensures inventory availability against variable lead time. The amount of stock B is the inventory level that may be reached when no orders are on hand and when all order have been filled. Otherwise, the inventory level oscillates between this maximal value and zero.

$$B = \underbrace{\mu_d \ \mu_{KZZ}}_{B_U} + \underbrace{z\sqrt{\underbrace{\sigma_d^2 \mu_{KZZ}}_{I} + \underbrace{\mu_d^2 \sigma_{KZZ}^2}_{II}}}_{B_S} \tag{28}$$

B	Maximum stock
B_U	Basic stock
B_S	Safety stock
μ_d	Mean demand
μ_{KZZ}	Mean lean time
σ_d	Demand variation
σ_{KZZ}	Lead time variation
z	Safety stock factor, specifying the desired service level

Formula (28) can also be used for analyzing multi-echelon systems when the constituent dyads are separated, all stochastic parameters for the upstream member of the supply chain are known, and the resulting parameters can be calculated separately for each process or manufacturing system. Nevertheless, a model similar to the single-echelon model described above, which does not consider lead time variation nor instable quality was elaborated by ALICKE (2003, p. 69 et seq.). Furthermore, the research on multi-echelon models is highly mature and models for many-use cases have been developed. A comprehensive overview of these models was contributed to inventory management research by FEDERGRUEN (1993).

In addition to the inventory models discussed above, queuing models are employed to analyze the characteristics and delivery reliability (or throughput time) of single or connected manufacturing systems, while considering processes and product types.

Queuing theory models typically have the following structure: orders arrive with a certain arrival rate at the system, adding themselves to the queue, which may be empty or filled. The system has a certain number of capacities (e.g., machines, assembly stations) to process those orders. The wide field of queuing theory is structured by the mathematical characteristics of the queue or the network of queues to be treated: the type of arrival processes at the queue, types of completion processes at the capacities, and number of capacities serving the single queue. The strategy for picking the next customer is always first-come-first-serve and the queues are not limited in length. The arrival process is determined by its type of distribution, e.g., deterministic (D), Poisson-distributed (M), or generally independently distributed (GI). Similarly, the distribution of the service time process can be deterministic (D), exponentially distributed (M), or generally distributed (G). A wide number of applications of queuing theory for analyzing manufacturing system performance were mentioned by ASKIN (1993).

In contrast to the static queuing theory models, numerous researchers have considered dynamic simulation models for analyzing supply chain performance. As mentioned above, in supply chain research, a pioneering model was developed by FORRESTER (1958), using System Dynamics, which is a simulation approach that models the feedback loops and time delays within a system via stocks, flows, and decision rules regarding the flows. Further applications to manufacturing system design (see MORECROFT 1979) and supply chain management have been designed and are summarized by BHUSHI & JAVALAGI (2004). These may be divided into models that contribute to theory building, to research using System Dynamics modeling for problem-solving, and to research for improving the modeling approach. The latter group has not been extensively researched (ANGERHOFER & ANGELIDES 2000, p. 343).

Other authors have concentrated on the analysis of supply chains with standard discrete event simulation packages (such as Simulink® or emPlant®) designed specifically for analyzing production systems. Based on these (e.g. SELKE (2004)) designed algorithms for the automated generation of discrete event simulation models from operational data collected on the shop floor, which somewhat mitigates the high amount of effort and time required to create a simulation model. Logically building on this research, WIENDAHL et al. (2005) designed a set of parameterized simulation models for the simulation of supply chains which, to some extent, can be automatically generated from process plans. The model consists of a customer, a supplier, and a producer module, where the first generates demand according to a specified distribution and the second delivers raw material with a normally distributed lead time. The producer module is comprised of "throughput elements" (see WIENDAHL 1997), which resemble a capacity with certain changeover, process transportation, and queuing times. These models can be employed for the planning and operation of a supply chain (WIENDAHL et al. 2005, p. 243). During the planning phase, they can be used to select suppliers, and test the overall delivery reliability of the supply chain, whereas, in the operation phase, product availability dates can be calculated and the effect of changes in the product mix or in the processing time can be simulated. Further applications of discrete event simulation to supply chain management were reviewed by SEMINI et al. (2006).

5.5 Summary of Quantitative Supply Chain Research

The discussion of quantitative models for increasing delivery reliability of suppliers has given various insights into possible sources of insufficient supplier performance. Concerning the models dealing with demand information, the consideration of the bullwhip effect by LEE et al. (1997), specifically, the elaboration of demand signaling and order batching revealed that IT has a great impact on the performance of the supply chain. This is achieved mainly through the real-time availability of demand information to all parties within a supply chain. In accordance with this insight, companies have invested heavily in order management IT, as mentioned in the introduction to this thesis. Nevertheless, a number of surveys have shown that the installation of IT has often been insufficient to achieve close to perfect delivery reliability (e.g., HECKMANN et al. 2003, p. 2).

The information asymmetry between a buyer and a supplier, described by ÖZER & WEI (2006), is a further source of delivery risk, which, in the view of this thesis, can be avoided through certain contracts, when such situations arise in industry. As ÖZER & WEI (2006) showed, contract selection must be based on the cost of capacity expansion and the level of information asymmetry.

The buy-back and the revenue-sharing contracts, considered by PASTERNACK (2002) and CACHON & LARIVIERE (2005), respectively, are constructs that can increase the delivery reliability of the supplier and the buyer, when total end-customer demand is uncertain. The applicability of these constructs in industry, however, may require a high level of integration between the supplier and the buyer as trust is a prerequisite for the utilization of these contracts.

In summary, research on the effect of demand information on the delivery reliability of suppliers seems mostly complete, as the effects of how information is passed onto the supplier and the confidence of the supplier in the buyer, with respect to their knowledge of end-customer demand, have been addressed by current research. Additionally, initial results have been obtained in terms of real-time demand information sharing.

The contractual measures for achieving a capable manufacturing system design of the supplier, as discussed by TSAY & LOVEJOY (1999) and by LUTZE & ÖZER

(2007), show that buyers can theoretically reduce the risk of low delivery reliability by specifying their expectation in regards to the supplier's output. Furthermore, the shortage cost incurred by the supplier in the case of insufficient delivery reliability should be an additional incentive for a suitable manufacturing system design on the supplier side. Nevertheless, from the view of this thesis, these constructs are often applied by buyers, but do not significantly increase delivery reliability, as suppliers mostly fail to adapt their system to the requirements of the buyer.

Echelon and queuing systems are excellent ways for suppliers to analyze the characteristics of their manufacturing systems. Nevertheless, they are not often utilized in industry due to their complexity. Furthermore, they are not suitable to assess dynamic effects such as short-term demand shocks.

Research focus	**Research problem**	**Solution/ Application**	**Industrial relevance**	
			Rating	Rationale
Demand information	• Demand information distortion	• Real time information, reduction of transaction cost	●	-
	• Demand information asymmetry	• Capacity reservation or advance purchase contract	●	-
	• Unpredictable end customer demand	• Buy back / revenue sharing contract	◐	• Required level of trust may not exist between buyer and supplier
Manufacturing system design	• Manufacturing system specification by the buyer	• Quantity flexibility and lead time contract	◐	• Does not directly influence manufacturing system design of the supplier
	• Manufacturing system design	• Echelon systems	◐	• Level of complexity is too high for industrial application and dynamic effects can not be evaluated
		• Queuing theory	◐	
		• System Dynamics	◐	• Suitable simulation method, little methodical application to supplier assessment
		• Discrete event simulation	◐	• Suitable simulation method, but high effort required for model adaptation and seldom used for supplier assessment

○ Concept immature ◐ Concept mature – little industrial impact ● Concept mature – industrial impact

Figure 26: Summary of quantitative supply chain management research

System Dynamics and discrete event simulation models are well suited for analyzing supply chains. System Dynamics models, however, do not have the maturity needed to be applied to supply chain delivery reliability and inventory analysis, as they have been mostly used to answer specific questions or to build theory on supply chain design in general. A clear process for applying the management of supplier delivery reliability has not yet been established.

Discrete event simulation models require costly IT packages as well as substantial expert know-how, when models need to be adapted. In the view of this research, this is also the main reason for their rare use in assessing the supplier's manufacturing system. Figure 26 summarizes the discussion of quantitative models for the management of delivery reliability, as exisiting models for assessing the manufacturing system of the supplier are not suitable for application in industry. Echelon and queuing models are too complex, System Dynamics is not applied to supply chain design because of the lack of methodology, and the generation of discrete event simulation models is costly and requires high effort.

Thus, the hypothesis of this thesis is that low delivery reliability of a supplier mostly results from insufficient manufacturing system design on the supplier side. This may be due to the fact that buyers do not have an affordable tool that can be easily applied in a supplier analysis and combines the benefits of static echelon and queuing as well as dynamic simulation models to analyze the capabilities of a potential supplier.

6 Empirical Investigation of the Management of Delivery Reliability

6.1 Introduction

To prove the hypothesis that buyers often do not ensure that the manufacturing system of the supplier is suited to achieving the desired level of delivery reliability, but rather rely on contractual measures, which leads to a lack of organizational integration, the results of a survey that was conducted in the course of this research are elaborated on in this chapter. This empirical investigation is based on a determinant model for dyadic supply chains, derived from the review of qualitative supply chain research in Chapter 5.2. In addition to the survey results, requirements for a tool for selecting a supplier base are described.

The remainder of this chapter is organized as follows: the subsequent section discusses the determinant model for describing bilateral supply chains. In Section 6.3, the design of the survey and the participation are introduced. Next, the statistical foundation for the analysis is provided and the results are discussed. Finally, recommendations for the design of a tool for analyzing suppliers are given in Section 6.4.

6.2 Theoretical Derivation of a Bilateral Determinant Model

The main objective in deriving the determinant model was to establish a parameter set that sufficiently describes all factors influencing supplier delivery reliability in a dyadic supply chain. This means that all governing factors of the manufacturing system of the buyer and of the supplier must be comprehensively described by the model. An additional objective was that these parameters must be able to be operationalized for analyzing a potential supply chain.

The derived determinants (Table 2) include the parameters extracted from the qualitative supply chain models and are grouped into three categories (see ZÄH et al. 2004a): the exchanged good, the two associated enterprises, and the fit of the two partners. In describing the exchanged good, the value of the product, volatility of demand, and yearly demand are common attributes for selecting suitable replenishment principles (see FISHER 1997). As stated in the model of functional and structural attributes by MEYR et al. (2000), the latter two also determine the repetition of operations. The extent of standardization, which is also mentioned by BEAMON & CHEN (2001) and by MEYR et al. (2000), may be taken into account by the number of variants supplied. Even though the last four parameters are specified as nominal parameters in Table 2, they may also be utilized as numerical determinants.

The shelf-life of the exchanged goods is an attribute that was not mentioned by any of the authors discussed in the literature review. Nevertheless, it is relevant to deduct the best replenishment principle (since food may go stale, and sheet-metal might rust, which would limit the storage period). This needs to be integrated into the model developed here.

Category	**Determinant**	**Characteristics**					
Exchanged good	Value	high	medium	low			
	Demand variation	constant	fluctuant	heavily fluctuant			
	Yearly demand	$<10^2$	$<10^3$	$<10^4$	$<10^5$	$<10^6$	$>10^6$
	Variants	none	<5	<50	≥50	>500	
	Shelf life	days	weeks	months	years	unlimited	
Associated enterprises	CODP – suppl.	make to stock	make to order	purchase to order			
	Org. prin. – suppl.	fixed-site	job-shop	cellular	flow line		
	Volume flexibility	none	limited	unlimited			
	CODP – buyer	make to stock	make to order	purchase to order			
	Org. prin. – buyer	fixed-site	jop-shop	cellular	line		
Entitie's fit	Distance	hours	days	weeks	months		
	Repl. prin. – buyer	pull	push				
	Repl. prin. – suppl.	pull	push				

Table 2: Determinants of bilateral supply chain relationships (see ZÄH et al. 2004b)

Regarding the involved enterprises, the Customer Order Decoupling Point (CODP) is of extraordinary significance (see MEYR et al. 2000; SUPPLY-CHAIN-COUNCIL 2005). For both the supplier and the customer, it defines the first stage when an incoming order is processed. In addition, the CODP of either the customer or the supplier limits the possible production control methods. The flexibility of suppliers, with respect to the amount of goods to be supplied, is also of special importance. For instance, this ability influences the dimensioning of safety stocks and gives the buyer an understanding of the degree of demand fluctuation that the supplier can bear. The last attribute is also mentioned by MEYR et al. (2000), and the organization principle of the production processes of the supplier and the buyer complete this category.

In the context of the fit of entities, the distance between two companies (local, global) is a frequently mentioned attribute. In the view of this thesis, however, it is not important if the two partners are located in the same country or same region, though the replenishment lead time is of great significance for managing deliver reliability (see FISHER 1997). For this reason, a determinant that characterizes the entitie's fit is the distance, measured in time for replacement of products (e.g., hours, days, etc.). The second and third attributes chosen for this category are the underlying internal production control or replenishment principles of the two companies. Thus, pull[14] and push[15] systems are distinguished, as all possible production control principles can be assigned to either group. This completes the set of parameters proposed for describing bilateral supply chains.

Considering that the set of determinants sufficiently describes the inputs to the supplier's manufacturing system and the production system of the buyer and the supplier, the first objective stated above is fulfilled. As it will be shown in Chapter 7, the parameters may be described by a simulation model and the determinants can thus be classified as operationable, and the second objective is hence equally satisfied.

6.3 Empirical Investigation

6.3.1 Survey Design and Participation

To investigate the level of organizational integration for buyers and their suppliers in industry, and to prove or disprove the hypothesis stated above, the determinant model introduced above was used as a framework for the survey.

---

[14] In this thesis a pull system is defined as replenishment system wherein material is only processed on customer request and inventory levels are strictly within predefined boundaries

[15] In this thesis a push system is defined as replenishment system wherein inventory levels do not follow predefined boundaries due to the variability within the system (e.g. lead time variability).

The underlying questionnaire was designed in a three stage process that consisted of the initial design, a revision of the first version by the statistical consultation office of the Ludwigs-Maximilians-University of Munich (LMU) and pretests with a production and a procurement manager. The questionnaire was designed to gather data in regards to the respondent's suppliers for one specific product, in order to extract the determinants for one single supply chain and to avoid any confusion with the many supply chains that may exist within a production enterprise.

An English version of the final questionnaire (the questionnaire that was used for the survey was in German) is included in an appendix of this thesis (Chapter 11.1). The questionnaire consists of four parts, with the first part mainly requesting data about the respondent's position and company. From discussions with the statistical consultation office, three open questions were added to the first part of the questionnaire to capture the full attention of potential respondents. These three questions inquired about the supplier selection process and the potential for improving the cooperation with suppliers.

Since the intended survey respondents are buyers, the second part asks for specific details about all determinants related to the buyer. In addition, some questions refer to the nature of the product and the position of the respondents company within a supply chain. The third part asks specific questions about how customers are distributed in regard to the buyer's CODPs, and the fourth part begins with identical questions for the supplier. Moreover, respondents were asked about the importance of the following supplier characteristics in the supplier selection process: organization principle, CODP, volume flexibility, distance, and replenishment principle.

Next, participants were asked to provide data regarding the determinants for a maximum of three suppliers, one for each possible order decoupling point of a supplier. Furthermore, the data used for Figure 1, specifically, the supplier selection priorities, were collected from the respondents. Finally, the questionnaire inquires about the application of certain contract forms, as well as the frequency of price changes.

As mentioned above, the pretest for the questionnaire was conducted with a production and a purchasing manager. The respondents were selected from the same mechanical engineering company and the questionnaire was filled out with regards to a product and manufacturing facility that is well known to the originator of the questionnaire. During the test, it became clear that the second part of the test was difficult to comprehend and thus, the relevant questions were rephrased in the final version of the questionnaire. From the results of the pretest, the purchasing manager was assumed to have a more substantial input for the questionnaire, mostly because he was exposed to both the shop floor and the purchasing data.

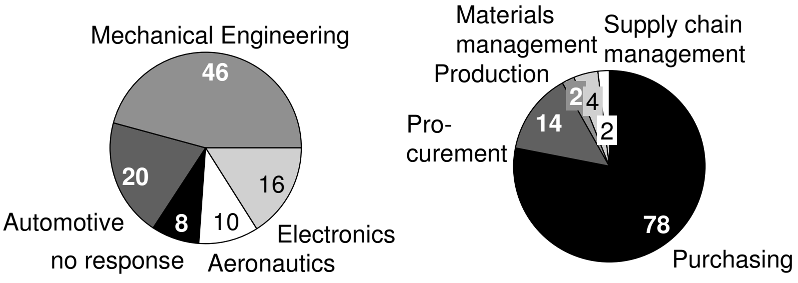
Contact data was acquired from an address agency (Schober Information Group) for 795 purchasing managers from companies with more than 500 employees in the automotive, aeronautics, electronics, and mechanical engineering industries, where the size of the companies was chosen so that the addressed firms were large enough to invest substantially in the supply chain knowledge. After reviewing the obtained data and eliminating duplicates, the questionnaire was sent to 776 purchasing managers, with a letter explaining the purpose of the survey and the role of the Institute of Machine Tools and Industrial Management (*iwb*) of Technische Universität München.

As the response rate was extremely low at the beginning of the response period, a follow-up mailing was sent to all non-respondents, six weeks after the initial mailing. The follow-up included an announcement of the possibility of completing the questionnaire by means of an online form.

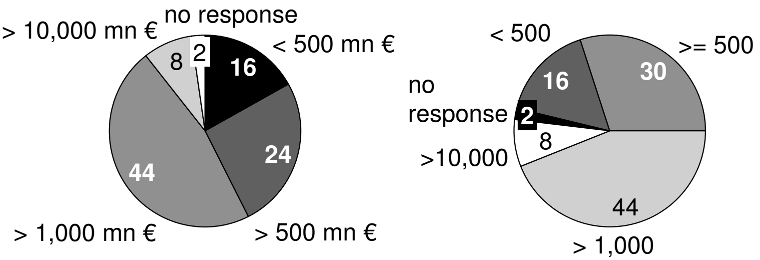
A final response rate of 6.4% was achieved. The corresponding statistical distribution of the respondents' characteristics is depicted in Figure 27. Thus, 50 companies (46% mechanical engineering, 20% automotive, 16% electronics, 10% aeronautics, and 8% no industry specified) completed the questionnaire and thereby provided data sets for 95 dyads.

The actual respondents were distributed over the following departments: purchasing (78%), procurement (14%), production (2%), materials management (4%), and supply chain management (2%). The low percentage of purchasing managers was due to the questionnaire being passed on to another respondent within the company, so that it was not completed by the actual addressee but by an employee in a different department, since some purchasing managers had felt that they could not provide substantial answers to the questionnaire.

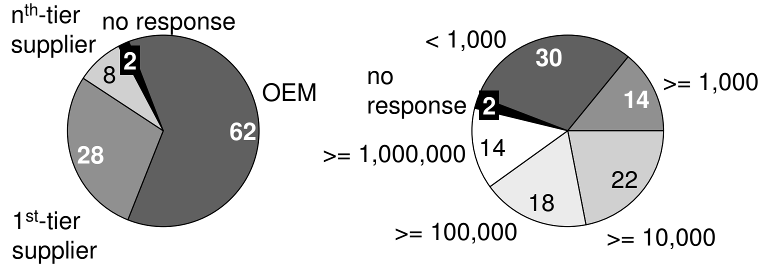
In terms of revenues, 8% of the companies are in the group with greater than 10 billion Euro, 44% are between one and ten billion Euro, while the remaining companies are below one billion. As targeted, 84% of the respondents were from companies that have more than 500 employees and the majority of these companies (64%) are OEMs. The yearly demand for the investigated products is mostly lower than 100.000 units sold per year (66%).



Industry **Department**



Revenues **Number of employees**



Company type **Yearly demand**

Figure 27: Survey participant statistics in percent

In addition to the data listed in Figure 27, it can be inferred from the data that 62% of the respondents are from companies that manufacture a final product, while 28% of the companies produce components, and the remaining firms provide norm or customized parts. Furthermore, 57% of the responding enterprises have fewer than 5 production facilities.

For the analysis of the determinant relevant data and the analysis of the hypothesis regarding the lack of organizational integration between the supplier and the buyer, different statistical methods were employed, which are reviewed in the following section.

6.3.2 Statistical Considerations

To show that the manufacturing system of the supplier often does not fit with the requirements of the buyer, possible causalities between the determinants within the survey data were analyzed in this research. To test for the existence of such causalities, two-dimensional contingency tables (see BACKHAUS et al. 2003, p. 164 et seq. or GILBERT 1993), that were constructed from the determinant data, were analyzed for nominal variables. Relations between metric (e.g., demand) and nominal variables were assessed using the Kruskal-Wallis-test (see HARTUNG et al. 1998). The application of Logit models (see ANDREß et al. 1997) was not possible due the low number of data sets.

		Columns (variable 2)							
		1	*2*	·	·	·	·	*c*	*Total*
Rows (variable 1)	*1*	n_{11}	n_{12}	·	·	·	·	n_{1c}	$n_{1\cdot}$
	2	n_{21}	n_{22}	·	·	·	·		$n_{2\cdot}$
	·								
	r	n_{r1}						n_{rc}	$n_{r\cdot}$
Total		$n_{\cdot 1}$	$N_{\cdot 2}$					$n_{\cdot c}$	$n_{..} = N$

Table 3: General form of a two-dimensional contingency table (as in EVERITT 2000, p. 4)

The general form of contingency tables is given by Table 3, where a sample of N observations is classified with respect to qualitative (nominal or ordinal) variables, with one having r categories and the other having c categories. The observed frequency in the i^{th} category of the row variable and the j^{th} category of the column variable is the frequency represented by n_{ij} within the contingency table. The total number of observations in the i^{th} category of the row variable is denoted by $n_{i\cdot}$ and the total number of observations in the j^{th} category of the column variable is expressed as $n_{\cdot j}$. The total number of observations within the sample is then denoted by $n_{\cdot\cdot}$.

To judge if the two variables are independent, the frequency (F) observed in category ij must be equal to the expected frequency (E), as specified by the following equation

$$F_{ij} = E_{ij} = Np_{ij} = Np_{i\cdot}p_{\cdot j}\,, \tag{29}$$

where the required probabilities can be easily estimated from the marginal frequencies in categories i and j, and the total number of observations. The hypothesis that this is generally true is called the null hypothesis, denoted by H_0. To see this, the Chi-square-test, as suggested by PEARSON (1904), which employs the χ^2 statistic, is given by:

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{c}\frac{(n_{ij} - E_{ij})^2}{E_{ij}}\,, \tag{30}$$

where E_{ij} is the expected frequency observed for category ij. The Chi-square distribution arises from the sums of squares of the number of independent variables, z_i, each of which has a standard normal distribution. The form of this distribution depends on the number of independent variables involved, which is represented by the number in independent terms within the contingency table, given that the row marginal totals and column marginal totals are fixed. This value is often referred to as the degrees of freedom (DoF) of a contingency table. The acceptance or rejection of the null hypothesis is then based on the probability distribution of χ^2, where low probability values lead to the rejection of the hypothesis and a dependency between two variables thus exists. Generally, a low probability value is taken to be 0.05 and is referred to as a 5% significance level of the test.

Once a dependency has been found, the direction of this relation can be interpreted by various measurables, as defined by Goodman & Kruskal. In this thesis, the first of two measures that are employed, due to their good applicability, is the Goodman & Kruskal λ value (see EVERITT 2000, p. 60 et seq.):

$$\lambda_1 = \frac{\sum_{j=1}^{c}\max_i(n_{ij}) - \max_i(n_{i\cdot})}{N - \max_i(n_{i\cdot})}\,, \tag{31}$$

$$\lambda_2 = \frac{\sum_{i=1}^{r} \max_j(n_{ij}) - \max_j(n_{.j})}{N - \max_j(n_{.j})} \tag{32}$$

This measure specifies how much the knowledge on the classification of one variable improves the ability to predict the other. More specifically, the measure λ_1 given by formula (31) is the relative decrease in the probability of an error in guessing *variable 1* (in Table 3) with and without knowledge regarding *variable 2*. Formula (32) specifies this measure for the reciprocal case. If the values obtained from these formulae are zero, no directional association is present. Thus, higher values (between zero and one) indicate a stronger association.

The second directional measure utilized in this thesis to obtain results in situations where λ-values are not unequivocal is the Goodman & Kruskal τ value (see HARTUNG et al. 1998, p. 459 et seq.). This measure is based on identical reasoning as is the previous measure, but calculated somewhat differently, as given by formulae (33) and (34).

$$\tau_1 = \frac{\sum_{i=1}^{r}\sum_{j=1}^{c} \frac{\left(n_{ij} - \frac{n_{i.}n_{.j}}{N}\right)}{n_{.j}}}{n - \frac{1}{n}\sum_{i=1}^{r} n_{i.}^2}, \tag{33}$$

$$\tau_2 = \frac{\sum_{i=1}^{r}\sum_{j=1}^{c} \frac{\left(n_{ij} - \frac{n_{i.}n_{.j}}{N}\right)}{n_{i.}}}{n - \frac{1}{n}\sum_{i=1}^{r} n_{.j}^2} \tag{34}$$

Similar to the previous case, values of τ lie between zero and one. As mentioned at the beginning of this chapter, the analysis of dependencies between numerical and nominal or ordinal variables was performed by means of the Kruskal-Wallis test (see HARTUNG et al. 1998, p. 548 et seq.). Like most non-parametric tests, it is based on ranked data. Thus, the numeric observations (e.g., yearly demand) are converted to their ranks in the overall data set. This means that the smallest value gets a rank of one, the highest is assigned a rank that is equal to the population size *N,* and all remaining data receive a rank greater than one and smaller than *N.* The underlying hypothesis of the Kruskal-Wallis test is that the mean ranks of the populations, which are represented by the categories of a nominal variable, are expected to be equal. Alternatively, this may be stated as follows: when the relation of a nominal variable with *k* categories and a numerical variable is investigated, the *y* mean values of the ranks of the numerical data sets are assumed to be similar when the null hypothesis is true.

$$H = \frac{\frac{12}{N(N+1)} \sum_{k=1} \frac{R_k}{N_k} - 3(N+1)}{1 - \frac{\sum_{k=1} (T_k^3 - T_k)}{(N^3 - N)}} \tag{35}$$

N	Total number of samples
N_k	Number of cases in the k^{th} category
R_k	Sum of ranks in the k^{th} category
T_i	Ties in the k^{th} category

The test statistic *H* for the Kruskal-Wallis test is given by (35), where R_i and T_i specify the sum of the ranks within a category, and the number of ties within each category, respectively. *H* is assumed to follow a Chi-square distribution with *k*-1 degrees of freedom. The rejection or confirmation of the null hypothesis, as described above, depends on the probability obtained for a given value of *H*.

6.3.3 Statistical Analyses

In this research, the Kruskal-Wallis test was employed to analyze the relation between numerical variables such as value, demand variation, and yearly demand, and the nominal variables. All statistical calculations used the software package SPSS® and the underlying data is shown in section 11.2. The significance of the resulting correlations is denoted by the cursive numbering in Table 5. Relationships among numerical variables were not considered, since these parameters represent external boundary conditions.

As introduced above, interdependencies between nominal variables were found with two-dimensional cross tables and Chi-square tests. For both the Kruskal-Wallis and the Chi-square tests, significant interdependencies (at the 5% level and below) are displayed in bold numbers in Table 5. In the following paragraphs, the obtained correlations are discussed, with reference to the interrelationships that could not be empirically verified, but should theoretically exist.

As indicated in Table 5, determinant 1 (value) has an interrelationship with the determinants CODP-buyer, dyad and replenishment principle-buyer, where the variable dyad was constructed from the combination of the CODPs of the buyer and the supplier. This result from the Kruskal-Wallis test, which is shown in Table 4, suggests that the value of the exchanged good differs significantly for the characteristics of the mentioned determinants.

Metric variables	CODP-buyer	N	Mean rank
Value	MTS	11	19.68
	MTO	29	30.14
	PTO	23	40.24
	Total	**63**	
Demand variation	MTS	24	35.94
	MTO	35	45.01
	PTO	25	45.28
	Total	**84**	
Yearly demand	MTS	22	56.02
	MTO	34	40.96
	PTO	28	33.75
	Total	**84**	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	9.923	2.483	10.506
DoF	2	2	2
Asymptotic significance.	0.007	0.289	0.005

Table 4: Kruskal-Wallis statistics for the determinant "CODP – buyer"

Referring to the determinant CODP-buyer, the value of the exchanged good increases from MTS- to MTO-, to PTO-buyers (significance 0.01). This indicates that MTS-buyers will usually manufacture products with a low value, as it is not economically sound to keep finished goods with high value on stock. Thus, the components of the final product will be accordingly inexpensive. On the other hand, MTO-companies will keep their medium-prized raw materials on stock, whereas PTO-buyers incorporate such expensive components into their final products that they will source them from suppliers only when required by actual customer orders.

On the supplier side, the aforementioned correlation is not significant at the 5% level, though the data shows an identical tendency. Furthermore, the interrelation between the combinations of costumer order decoupling points of the buyer and the supplier, and the value of the exchanged product (significance 0.04) supports previous arguments.

The observed correlation between the internal replenishment principle of the buyer and the value of the exchanged product (significance 0.01) cannot be explained by theory. In contrast, this determinant should have an effect on the supplier's choice of internal replenishment principle, which could not be observed with relevant significance as no remarkable difference is seen between the value of products controlled by the push or by the pull principle. Nevertheless, products supplied by the MTS-supplier, which are commonly of decreased value, should be internally controlled by a pull principle, whereas the more costly goods of the MTO- and the PTO-suppliers are traditionally pushed through production.

With regards to the demand variation (determinant 2), significant differences exist between the possible organization principles that may be chosen by the supplier (significance 0.02) or by the buyer (significance 0.00). The results show that the demand variation decreases in the following order: project shop, job shop, group technology, flow line. While this result is intuitive with respect to the supplier, the correlation with the organization principle of the buyer can be explained by the fact that the variation of demand for components is strongly related to the demand fluctuations of the final product.

Similarly, a correlation (significance 0.00) was found between the variation of demand and the replenishment principle of the buyer. Thus, according to the results of the Kruskal-Wallis test, the pull principle is used when demand variation is low, while production systems are controlled via the push principle when facing increased demand variation. Surprisingly, this relation could not be identified for suppliers.

Determinant 3 (yearly demand) is correlated with the determinants organization principle of the supplier (significance 0.05) and of the buyer (significance 0.0). The data sets reveal that the demand increases in an identical order as stated in the preceding paragraph (i.e., from the project shop to the flow line). Correspondingly, the demand level increases from MTS- to MTO- and to PTO-buyers with a significance of 0.01.

This finding is also reflected by the interrelationship of the yearly demand with the determinant dyad (significance 0.02) and the determinant CODP-supplier, even though the significance level is slightly above the 5% level in the latter case.

Another association exists between the replenishment principle of the buyer and the yearly demand (significance 0.03), which suggests that the pull principle is used when demand is high. A relation between determinant 3 and the supplier's internal production control procedure could not be derived.

	Determinants	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Value														
2	Demand variation	-													
3	Yearly demand	-	-												
4	Variants	*0.26*	*0.09*	*0.36*											
5	Shelf life	*0.12*	*0.22*	*0.16*	0.23										
6	CODP – suppl.	*0.24*	*0.35*	*0.06*	0.58	0.90									
7	Org. prin. – suppl.	*0.31*	***0.02***	***0.05***	0.08	0.14	0.21								
8	Volume flexibility	*0.25*	*0.85*	*0.36*	0.57	**0.00**	0.76	0.87							
9	CODP – buyer	***0.01***	*0.29*	***0.01***	0.65	0.43	0.21	0.38	0.54						
10	Org. prin. – buyer	*0.06*	***0.00***	***0.00***	0.42	0.66	0.88	**0.00**	0.96	0.17					
11	Distance	*0.18*	*0.76*	*0.47*	0.23	0.96	**0.00**	0.77	0.46	0.25	0.07				
12	Repl. prin. – buyer	***0.01***	***0.00***	***0.03***	0.79	**0.03**	0.60	**0.00**	0.64	**0.00**	0.41	0.24			
13	Repl. prin. – suppl.	*0.31*	*0.53*	*0.23*	0.82	0.33	0.10	**0.01**	0.80	0.80	0.34	0.29	0.73		
14	Dyad	***0.04***	*0.18*	***0.02***	0.89	0.91	-	0.60	0.82	-	0.93	**0.00**	**0.01**	0.16	

Table 5: Significance of the determinant dependencies obtained from Kruskal-Wallis and Chi-square-tests (MILBERG & NEISE 2006, p. 184)

Judging from the Chi-square-tests (Table 6), no interrelationships exist at the 5% level between the number of variants (determinant 4), to which a product is supplied, and the other determinants. Nevertheless, from a theoretical point of view, a correlation between the number of variants and the organization principle of the supplier should be verifiable. This may be underlined by the fact that as the number of variants decreases, flow lines, for example, are more likely to be selected than project shops. In addition, the pull principle should be chosen in situations where few variants exist, whereas, the push principle is more effective in other situations. The significance levels (Table 5) suggest that the first proposed interrelation can be derived from the empirical data at the 8% level, whereas, the second interrelation does not seem to exist at all.

In the case of the determinant shelf life, two correlations were identified. First, the shelf life of a product is interrelated with the volume flexibility of a supplier (significance 0.0) and the Goodman & Kruskal τ values ($\tau_1 = 0.04$, $\tau_2 = 0.09$; and index 1 indicates values for dependency of the column variable), suggesting that the latter is dependent while the λ values yield no unequivocal result. This can be explained by the producers of perishable goods who are more sensitive to demand fluctuations as they cannot keep stock to buffer against demand uncertainty.

The second interrelation exists with the replenishment principle of the buyer (significance 0.03). In this case, the obtained τ values ($\tau_1 = 0.03$, $\tau_2 = 0.09$) prescribe that the replenishment principle depends on the shelf life (and the λ values do not provide a significant result), which seems reasonable, since the assembly system of the buyer cannot be controlled by a pull system, if perishable goods are integrated into the final product. Nevertheless, a statistically relevant relationship between the shelf life of the product and the replenishment principle of the supplier could not be obtained, even though it would seem to be reasonable when considering the above arguments.

Cross-Table Variants vs. Shelf Life

		Shelf life				Total
		Weeks	months	years	unlimited	
	none	1	13	3	5	22
	<50	1	11	14	10	36
	<50	1	7	14	5	27
	unlimited	0	3	2	0	5
Total		3	34	33	20	90

Chi-square Test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	11.832	9	0.223
N of valid cases	90		

Table 6: Cross-table and Chi-square statistics for the determinants: "number of variants" and "shelf life"

With regards to determinant 6 (CODP-supplier), an interrelation was identified for the distance between the supplier and the buyer (significance 0.0). The τ and λ values ($\tau_1 = 0.17$, $\tau_2 = 0.11$; $\lambda_1 = 0.24$, $\lambda_2 = 0.20$) specify that the distance depends on the characteristic of the CODP. This can be justified by considering that the system inherent order lead times increase from MTS- to MTO- to PTO-suppliers, and longer transit times are acceptable for suppliers with shorter internal order fulfillment times. As in the previous analyses, a correlation between the supplier's CODP and the internal replenishment system could not be proven. The relationship between the CODP of the supplier and the dyad was not analyzed, since these variables are coupled.

The Chi-square-tests involving the organization principle of the supplier revealed a correlation (significance 0.0) with the organization principle of the buyer, which seems realistic, as the production systems face similar boundary conditions. Nevertheless, the τ and λ values ($\tau_1 = 0.12$, $\tau_2 = 0.18$; $\lambda_1 = 0.24$, $\lambda_2 = 0.16$) yield different results in terms of the direction of the dependency. Two additional correlations show a relation between the organization principle of the supplier and the internal replenishment principle of the buyer and the supplier (significance 0.0 and 0.01). Whereas the first correlation can not be explained, the second seems natural, as different organization types result in a certain choice of replenishment principle. For instance job shop are mostly controlled by a push principle.

Whereas no correlations could be identified in regard to determinant 8 (volume flexibility), the replenishment principle of the buyer is dependent on the CODP of the buyer (significance 0.0; $\tau_1 = 0.11$, $\tau_2 = 0.24$; λ yields no result). Considering, for example, that PTO-buyers will not employ the pull principle due to the nature of the order decoupling point, this relation appears to be theoretically sound.

As seen in Table 2, no further correlations could be derived with regards to the organization principle of the buyer. Nevertheless, two interrelationships were singled out between the dyad and the determinants' distance (significance 0.0; $\tau_1 = 0.23$, $\tau_2 = 0.05$; $\lambda_1 = 0.24$, $\lambda_2 = 0.05$) as well as the replenishment principle of the buyer (significance 0.01; $\tau_1 = 0.24$, $\tau_2 = 0.03$; λ values yield no result). Concerning the first relationship, this correlation is coupled with the relationship between the CODP of the supplier and the distance, as elaborated upon earlier. Similarly, the latter relationship is connected to the interdependency of the CODP and the replenishment principle of the buyer. Unexpectedly, a correlation between the replenishment principle of the supplier and the dyad could not be shown.

In summary, the results of the correlation analyses show that buyers seem to be well organized to face their external boundary conditions, whereas, the organizational properties of their suppliers are not in synch with the characteristics of the supplied product. This is highlighted by the fact that the CODP of the supplier is not correlated with the value of the exchanged product nor with the yearly demand. In addition, a relationship could not be derived between the CODP, or the determinants pertaining to the exchanged good, and the internal replenishment principle. Furthermore, the empirical data shows no evidence of a correlation between the number of variants supplied by a vendor and the organization's principle. These results may be explained by the buyers selecting suppliers mainly because they can produce a certain product, without considering their internal organization.

The contract forms used by the companies of the industrial respondents suggest that currently, the greatest lever to ensure delivery reliability are the contracts between the buyer and the supplier.

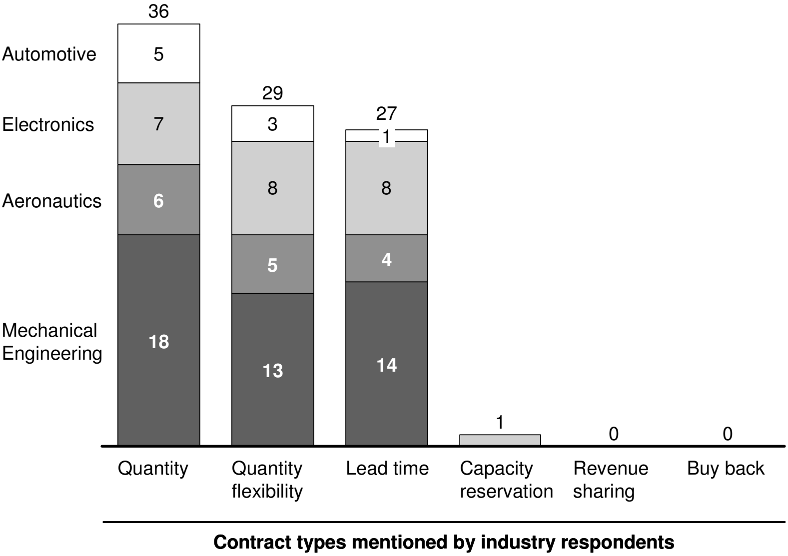


Figure 28: *Distribution of contract types used in industry based on a survey of 50 companies*

As shown in Figure 28, buyers frequently employ quantity, quantity flexibility, and lead time contracts, where the first two quantify the total demand (or a demand range) that the supplier must be able to deliver within a defined time (e.g., one year). An even stronger contractual agreement for achieving delivery reliability is the aforementioned lead time contract, which specifies a standard supplier lead time for the delivery of an order by the buyer.

These contract forms can only take effect, however, if consequences are enforced once the specified terms have not been fulfilled, which is sometimes not a realistic option in industry, since such measures are not beneficial for the overall relationship of the partners.

Thus, the delivery reliability of suppliers must be investigated prior to the set-up of a co-operation. Thereby potential changes to the organization of the supplier that enable higher delivery reliability can be identified and mutually implemented.

6.4 Requirements for an Assessment Tool for Potential Suppliers

To identify potential improvement areas at the supplier, a tool is required that offers the characteristics depicted in Figure 29, to mitigate or eliminate the limitations of the assessment tools discussed in Chapter 5.5. Of the five requirements listed, the first requires that the tool is able to fully assess the current state of the supplier's manufacturing organization by assessing the supplier’s expected delivery reliability when exposed to the buyer's order profile.

Requirements for a supplier assessment tool

1. Quick assessment of the current delivery reliability of the manufacturing system of the supplier considering all relevant characteristics of the determinant model
2. Rapid simulation of changes to the organization and measurement of the resulting effect through the quantification of on-time-delivery differences
3. Low aboriginal cost to enable the application of the supplier assessment tool in a wide range of company sizes
4. High simplicity (low complexity) of the tool in order to enable use by personnel within the purchasing and manufacturing departments without special training
5. Easy extendibility and adaptability of the tool to accommodate the integration of further analyses and the change of existing functions

Figure 29: Requirements for a tool for the assessment of supplier delivery reliability

The second requirement states that the tool must be able to rapidly assess changes to the supplier's manufacturing system to identify measures that will increase the delivery reliability of the supplier.

Third, the software required for the tool must not be costly such that it can be employed by small enterprises that may not have access to large software packages.

The fourth requirement is that the tool must be easy to use for personnel within purchasing and manufacturing departments, as they are responsible for supplier selection.

Finally, the tool should accommodate adaptations and possible extensions, in case further knowledge leads to an upgrade of supplier analysis in the future.

In the following chapter, a System Dynamics model will be developed that satisfies all requirements and can be easily operated by users.

7 Simulation Models for Assessing Delivery Risk

7.1 Introduction

To fulfill the requirements listed in the previous section, this chapter focuses on deriving a supplier assessment tool. A brief discussion of the methodology used for creating the tool is given at the beginning of this chapter. Next, the general structure of the developed tool is elaborated and the tests to ensure the model's functionality are detailed. The chapter concludes with a discussion of the guideline for the practical application of the supplier assessment tool.

7.2 Basics of System Dynamics

As a basis for creating a tool for assessing supplier delivery reliability, the System Dynamics methodology (see Forrester 1958, Forrester 1996) was selected. Considering the generic structure of System Dynamics models, it became evident that the requirement for easy adaptability and extendibility is well satisfied.

The requirement for a low aboriginal cost of the SD software is met, since the purchase price of the required software is around 10% of the cost of standard discrete event simulation packages.

To ensure easy applicability of the model for end-users, System Dynamics software in addition to a modeling layer encompasses an operating layer that can be designed to accommodate any potential user.

As shown in Figure 30, a System Dynamics (SD) model (modeling layer) consists of stocks and flows, and information feedback. In the model structure, a clear distinction is made between the physical flows through the stock-and-flow network and the information feedback that couples the stocks to the flows and closes the loops in the system by passing information from one element to other relevant elements.

Stocks are generic and can represent tangible quantities such as people, money or material, but also resemble intangible variables such as employee morale or perceived inventory, which are important characteristics when considering the extendibility of the supplier assessment tool. Inflows and outflows can be controlled by other stocks, flows, auxiliary variables, external inputs, or constants, where auxiliary variables are calculated from a constant and a flow or stock value, and external inputs are variables that are intentionally excluded from the model. The mathematical representation of a stock level, at time *t,* is thus:

$$Stock(t) = \int_{t_0}^{t} (Inflow(s) - Outflow(s))ds + Stock(t_0)\,.$$

The derivatives of the stocks are nonlinear functions of the stocks with which they are interconnected, as well as exogenous variables and any relevant constants.

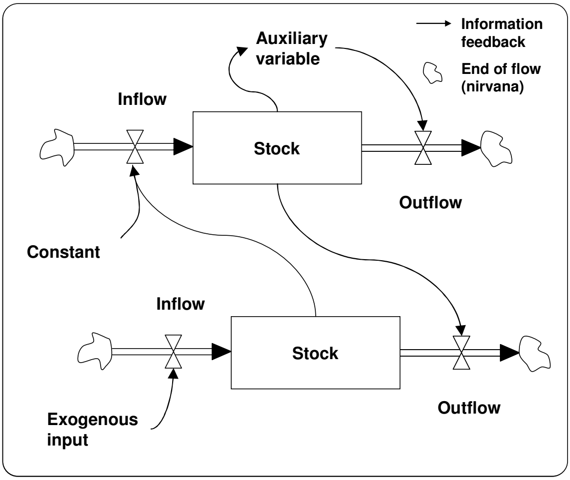


Figure 30: Elements of a System Dynamics model (adapted from STERMAN *2000, p. 204)*

To visualize the relationships between the variables (stocks, flows, or auxiliary variables) casual loop diagrams are employed, as purely visual representations of the model itself (i.e. stocks and flows) would not be sufficient for the understanding of the reader. As shown in Table 7, the main symbols used in casual loop diagrams are the arrows, indicating link polarity between the variables. The first describes a relation where variable *Y* increases with variable *X*, which is a positive link polarity. The second symbol describes the opposite situation. In casual loop diagrams, loops can be reinforcing (indicated by an R) or balancing (indicated by a B), depending on how a small change within one variable propagates within the loop. If the feedback loop enforces the polarity of the change, then it is a reinforcing loop, if the polarity changes, it can be considered a balancing loop.

When causual loop diagrams are translated into a stock and flow model (and thus the actual SD model) the modeler must decide, how the elements of the diagram are best modeled. In general, variables serving as an input in the casual loop diagram are modeled as auxiliary variables (e.g., the buyer order rate in Figure 31), whereas variables with many interconnections to other variables in the casual loop diagram are modeled as a combination of stocks and flows (e.g., production rate of the supplier in Figure 31).

Symbol	**Interpretation**	**Mathematical formulation**
$\begin{tikzcd} X \arrow[r, bend left, "+"] & Y \end{tikzcd}$	If all else remains equal and X increases (decreases) then Y increases (decreases) above (below) what it would have been.	$\partial Y / \partial X > 0$
	In the case of accumulations, X adds to Y.	In the case of accumulations $Y = \int_{t_0}^{t} (X + ...)ds + Y_{t0}$
$\begin{tikzcd} X \arrow[r, bend left, "-"] & Y \end{tikzcd}$	If all else remains equal and X increases (decreases) then Y decreases (increases) below (above) what it would have been.	$\partial Y / \partial X < 0$
	In the case of accumulations, X adds to Y.	In the case of accumulations $Y = \int_{t_0}^{t} (-X + ...)ds + Y_{t0}$

Table 7: Link polarity in casual loop diagrams

As far as the most important criteria mentioned in section 6.4 are concerned, the following paragraphs elaborate on how the determinants are integrated into the design of the model. Furthermore, an explanation is given for how the model can be used to assess the current state of the supplier's manufacturing system and how potential improvement measures can be tested.

7.3 Description of the Developed SD Model

7.3.1 Model Elements

The determinant set, defined in Section 6.2, is composed of three categories: exchanged good, associated enterprises, and the entities' fit. To assess the performance of the supplier, only the determinants that are relevant to the manufacturing system of the supplier are modeled (Table 8).

Category	Determinant	Characteristics					
Exchanged good	Demand variation	constant	fluctuant	heavily fluctuant			
	Yearly demand	$<10^2$	$<10^3$	$<10^4$	$<10^5$	$<10^6$	$>10^6$
	Variants	none	<5	<50	≥50	>500	
Associated enterprises	CODP – suppl.	make to stock	make to order	purchase to order			
	Org. prin. – suppl.	fixed-site	jop-shop	cellular	flow line		
	Volume flexibility	none	limited	unlimited			
Entitie's fit	Repl. prin. – suppl.	pull	push				

Table 8: Determinants modeled in System Dynamics for the assessment of suppliers

Firstly, it must be shown how the manufacturing system of the supplier reacts to the order profile of the buyer, which is related to one single product exchanged within the dyad. To model this profile, two of the determinants in the category "exchanged good" must be specified: the yearly demand and the variation of demand (section 7.3.2).

The value and the shelf life of the exchanged good are only required to evaluate the inventory on the supplier side, in terms of holding cost and age, which is not explicitly modeled to assess the delivery reliability of the supplier. The number of variants of the supplied product has great effect on the organization's principle and is discussed in Section 7.3.4. Similarly, the modeling of the CODP (section 7.3.3), volume flexibility (section 7.3.5), and replenishment principle (section 7.3.6) are elaborated upon in their respective sections.

7.3.2 Demand

Demand and demand variation can be defined in three different ways within the developed model. First, historical demand for the relevant product can be entered into the model via a demand list (in which the mean demand and demand variation are implicitly defined). The list should encompass the number of units to be delivered to the buyer by the supplier on a daily basis.

Second, a value for the mean demand and a value for the standard deviation may be directly defined, and can be calculated from historical data. This information is then utilized by the model to draw a value for the daily demand from a normal distribution.

Finally, the order profile of the buyer can be calculated by simulating the buyer's manufacturing system with the supplier assessment tool, which uses the end-customer order data as an input. Thus the model itself is utilized in this case to derive the order data.

7.3.3 Customer Order Decoupling Point

Turning to the determinant model, the most important characteristic of the supplier's system is the Customer Order Decoupling Point (REINHART et al. 2006, p. 6). According to Section 6.2, three different forms exist: make-to-stock, make-to-order, and purchase-to-order. For each of these possible CODPs, a separate System Dynamics model was created, which makes use of the definition of the buyer's order profile, as described in the previous section. The code (ithink$^{©}$) for the three developed models can be obtained from the appendix.

7.3.3.1 Make-to-Stock Suppliers

The diagram for the SD model of the make-to-stock supplier is shown in Figure 31. As depicted, the buyer's order rate flows into the system of the supplier and increases the orders on hand of the supplier. In turn, a change in the orders on hand immediately reduces the available inventory of the final product of the supplier. As in make-to-stock systems, the buyer is served directly from available inventory when orders arise.

As the missing inventory increases, orders that are dispatched from the replenishment system (see Section 7.3.6) are added to the order backlog in the production of the supplier. Depending on the level of backlog, actual capacity may be increased, if volume flexibility is built into the supplier's manufacturing system (see Section 7.3.5) and the minimal fabrication time demanded by the customer cannot be met. If excess capacity is still available, the fabrication rate of the supplier also rises with the increased backlog, which, in turn, reduces the orders on hand of the supplier, conditional that buyer demand is zero.

In summary, the main parameters governing the delivery reliability of the make-to stock supplier are the availability of inventory, which depends on the stability of fabrication lead time, the organization principle of the supplier's fabrication system (see Section 7.3.4), and the inventory replenishment system.

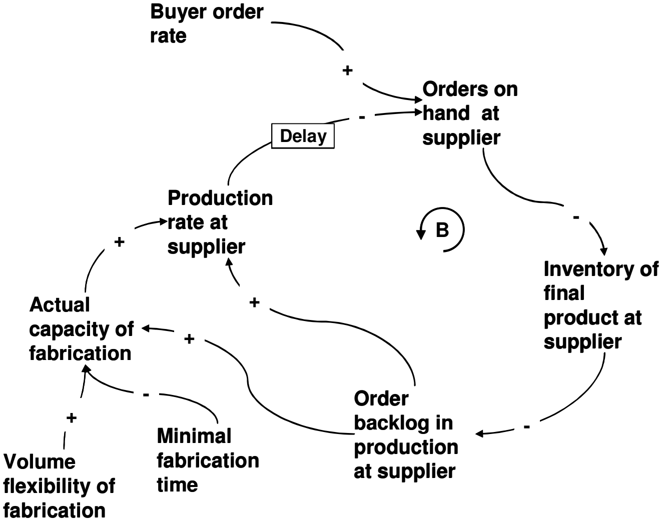


Figure 31: Casual loop diagram for a make-to-stock system

7.3.3.2 Make-to-Order Suppliers

When considering the make-to-order system, two different cases must be differentiated. The first is a system where no finished good inventory exisits and parts are assembled to the order of the buyer based on components or sub-assembly groups are drawn from inventory.

The second is a system, where the product requested by the buyer is built from raw material stock, which is transformed into the final product in production. As the second case resembles the purchase-to-order-system, with a raw material supplier lead time of zero, this case is addressed by the model described in the following section.

In the first case, which is depicted in Figure 32, inflowing orders increase the orders on hand at the supplier. As the orders increase, actual assembly capacity (see Section 7.3.5 for volume flexibility) and the supplier's assembly rate increase as far as possible. The high assembly rate causes a greater number of orders to be released by the replenishment system, which increases the order backlog in fabrication, which is translated, as in the case of assembly, to higher fabrication capacity and a higher fabrication rate. Increased production results in higher component inventory, which enables the reduction of orders from the buyer through assembly.

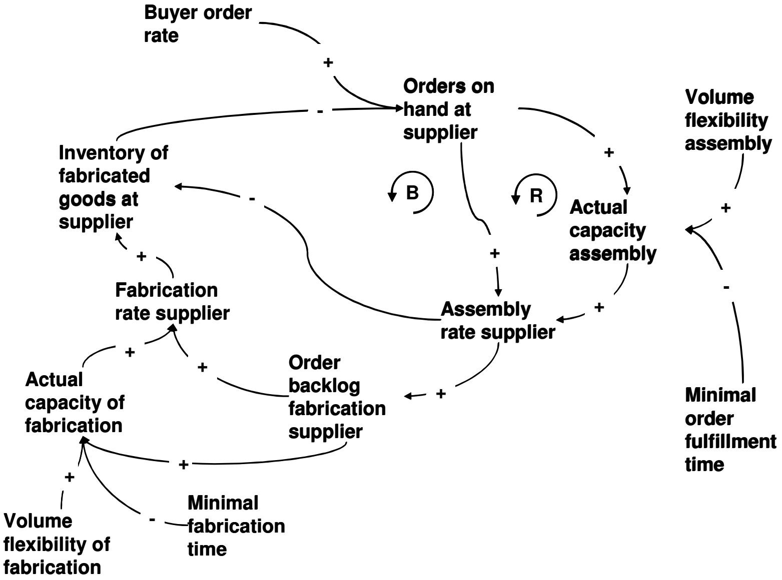


Figure 32: Casual loop diagram for a make-to-order system

Similar to the previous case, the availability of component inventory is of significance to the delivery reliability of a make-to-order supplier. Second, the stability of assembly lead time is a governing factor of this system.

7.3.3.3 Purchase-to-Order Suppliers

As for the other models, the orders of the buyer increase the orders on hand of the supplier, as there exisits no finished goods inventory. This increase results in a higher backlog in the production of the supplier as well as in the production of the supplier's supplier from whom the raw material (or components/assembly groups) is purchased.

These increases in backlog cause increased production rates for both parties, as well as a potential capacity increase on the supplier side (see Section 7.3.5 for volume flexibility). The higher production rates then lead to a reduction of the orders on hand, again, considering the case of no additional buyer orders.

In contrast to the previously described system, the delivery reliability of the purchase-to-order system (shown in Figure 33) depends mostly on the lead time stability of the supplier and the suppliers' supplier, which is very dependent on the employed organization principle. As no inventory buffers are present to assure lead time stability in this system (accept maybe at the supplier's supplier), the replenishment system is always a push system.

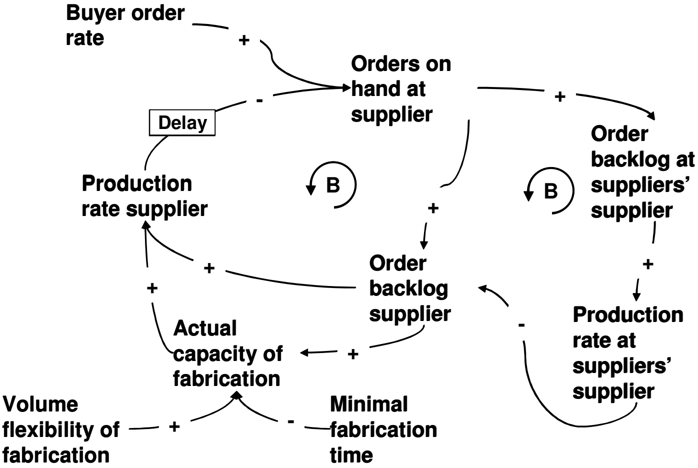


Figure 33: Casual loop diagram for a purchase-to-order system

7.3.4 Organization Structure and Variants

As mentioned in the previous section, the organization principle of the supplier's manufacturing system has great effect on the lead time stability of the system. According to Section 6.2, four different options are available for organizing the manufacturing system: flow line, job shop, cellular system, and fixed site.

Generally, all types of manufacturing system organizations are modeled through an inflow, a stock acting as a conveyor, and an outflow. The inflow has a defined capacity of parts that can flow into the conveyor per time unit, which vary in accordance to the volume flexibility (elaborated in Section 7.3.5). The time that a group of parts spends inside the conveyor (i.e., a stock with a delayed outflow) is determined by the through-put time distribution inherent to the organization principle of the manufacturing system of the supplier.

In considering the flow line, the number of parts that can be produced within a certain time is fairly constant, and varies only according to the mix of variants scheduled on the line, if the process times for the variants are different. Thus, by keeping the number of parts flowing into the conveyor constant, the throughput time varies for different combinations of variants, which can be easily calculated from the process times of the variants and the buyer's order profile. Hence, for a flow line, the production rate is determined by the average number of parts that can be produced during one day and the throughput time distribution that results from the variant mix, which has a mean of one day and a standard deviation that depends on the parameters mentioned above.

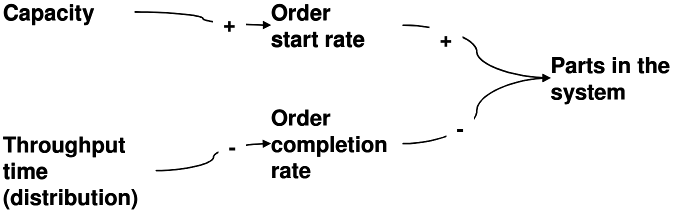


Figure 34: Casual loop diagram of the organization principle

In terms of the casual loop diagram, an example of the flow line can be described as shown in Figure 34. The capacity of the system regulates the order start rate into the manufacturing system. The throughput time distribution governs the order completion rate and therefore the outflow from the manufacturing system.

In the case of the job shop, the calculation of the throughput time distribution is more complex, since this calculation considers every possible path through production for all products that are produced in the job shop, all queues in front of every machine and assembly station, and all the different process times that are relevant for a product. Thus, the estimation of the mean throughput time and the variation may be done more efficiently using historical order data. Nevertheless, the results from queuing theory can be applied to the calculation of the throughput time distribution. Examples of such methods have been provided by ASKIN (1993) or SAINIS (1975) and are summarized in the appendix.

In terms of the System Dynamics model, two parameters must be specified to ensure that the flow and stock structure resembles the behavior of the job shop. First, the inflow must be set to the average number of parts that are released to the shop floor during a day. Second, the throughput time distribution for such a batch must be specified according to the methods discussed above.

The cellular system can be treated as either a flow line or a simple job shop, depending on the process time variation within the system. A cellular system with synchronized process times resembles the case of the flow line, whereas a system with varying process times must be treated as a job shop.

Fixed site production is difficult to model, since the organization form in this industry ranges from highly standardized (as in aircraft manufacturing) to very loosely organized (as in construction). Thus, in the view of this thesis, the most beneficial method to model fixed site systems is to determine the number of products for which production is initiated per unit time (e.g., day) and, as in the case of the job shop, to analyze the throughout time distribution based on historical data. As in the previous systems, these parameters can then be entered into the System Dynamics model.

7.3.5 Capacity Volume Flexibility

One characteristic, that is common to all organization forms, is that the level of capacity can be adapted to situations with increased or decreased buyer demand. The casual loop diagram (Figure 35) may be interpreted as follows:

The actual capacity of the system is determined by the base capacity and the volume flexibility, which is specified as a percentage of the base capacity that can be maximally added or subtracted from the base capacity. The actual capacity, which must lie between the upper and lower bounds, is then determined by considering the desired capacity, which can be calculated from the order backlog and the minimal order fulfillment time accepted by the buyer. Actual volume flexibility is based on measures such as varying work times and the utilization of external capacities.

This means that the number of products entered into the system varies on a daily basis, depending on the order backlog, the minimal order fulfillment time required by the buyer, and the level of volume flexibility.

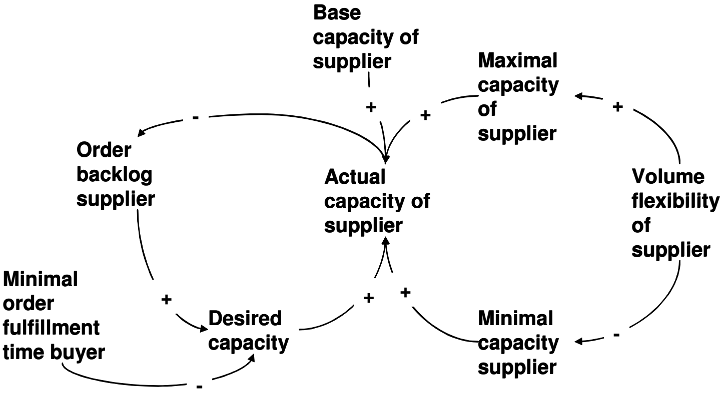


Figure 35: *Casual loop diagram for capacity volume flexibility*

In the model, the effect of capacity volume flexibility is approximated by increasing the inflow of orders to the system while keeping the throughput time of the system constant for all organization types.

7.3.6 Replenishment System

As discussed in previous sections, the replenishment system is a crucial part of the manufacturing system, as it can greatly affect the availability of parts in make-to-stock and assemble-to-order systems.

7.3.6.1 Demand-Oriented Replenishment

The casual loop diagram for the System Dynamics model of the demand-oriented replenishment system (i.e., push system), was mostly adapted from STERMAN 2000, p. 363) (Figure 36). The starting point for the replenishment decision is the order rate of the buyer, which is translated into an expected order rate via a first order delay[16], which dampens temporary demand shocks. The expected order rate and the minimal inventory coverage (in days) then determine the desired inventory. Considering the actual inventory, together with the desired inventory, the amount of missing stock is assessed.

The amount of missing inventory is again dampened by a first order delay and the resulting inventory adjustment rate together with the buyer order rate adds up to the desired delivery rate of the manufacturing system into the inventory. The desired delivery rate multiplied by the expected manufacturing system lead time results in the desired supply line, which is equal to the sum of the order backlog and the orders in the manufacturing system. By comparing the desired to the existing supply line, the missing supply line can be assessed, which, in turn, is dampened by a first order delay. The resulting supply line adjustment rate is added to the supply line, which is reduced by the delivery rate of material exiting production.

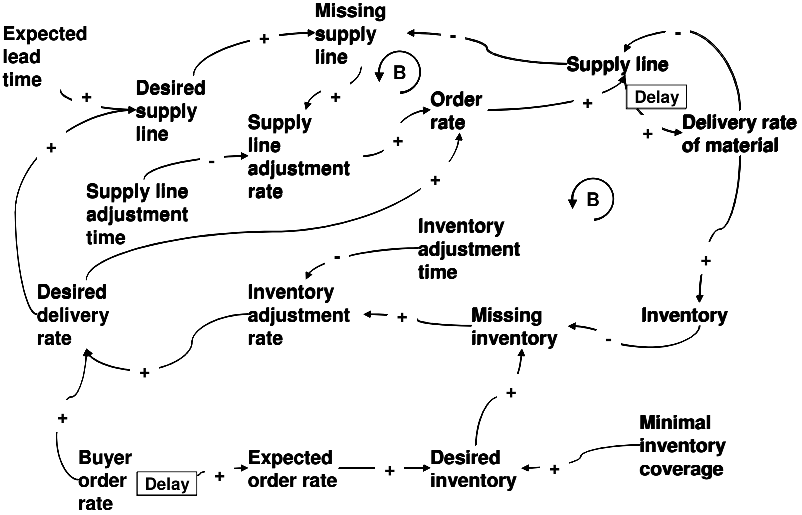


Figure 36: Casual loop diagram for the push system

In summary, the demand-oriented replenishment system is based on various dampening factors, that resemble the expectation of production planning and control personnel in regards to future orders. Another prevalent factor is the de-

---

[16] see STERMAN 2000, p. 415

sired inventory coverage, which is also decided upon by the product planning personnel.

7.3.6.2 Consumption-Oriented Replenishment

In contrast, the consumption-oriented (i.e., pull system) is based on statistical data and the real amount of parts consumed from inventory. As shown in Figure 37, the mean order rate of the buyer and the standard deviation of the order rate translate into the expected order rates and the expected standard deviation, respectively. This process is delayed, as these statistical values are calculated from the data of the last 30 days, which means that step changes only take effect after a certain number of periods.

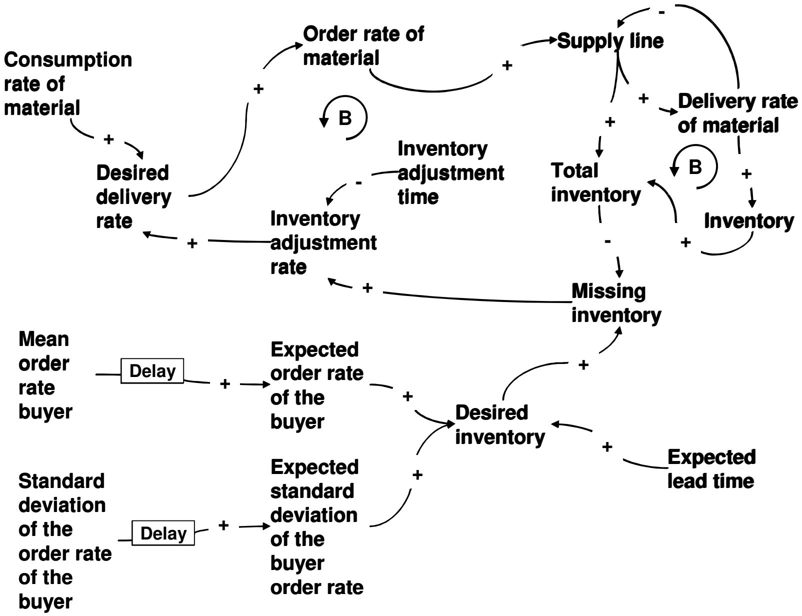


Figure 37: Casual loop diagram for the pull system

The order rate, standard deviation, and expected lead time are entered into a reduced version of formula (28), to obtain the desired inventory. This value is compared with actual inventory and the supply line, to assess the missing inventory, which is dampened via a first order delay and translated into the inventory adjustment rate. The actual demand drawn from the inventory in a certain period and the inventory adjustment rate then add up to the material order rate, by which the supply line is increased. As for the demand-oriented replenishment system, the supply line is reduced by the material that is delivered into the inventory from production.

To ensure the functionality of the System Dynamics model of the replenishment system and the remaining model components, the relevant tests for model evaluation (as suggested by STERMAN 2000, pp. 858) were successfully applied. These include the dimensional consistency and the extreme condition tests, where the first eliminates unit conversion errors and the second assures that the model still behaves as designed, under extreme conditions such as high demand (e.g., 10^7 per day) or very long lead times (e.g., 200 periods).

7.4 Model Application

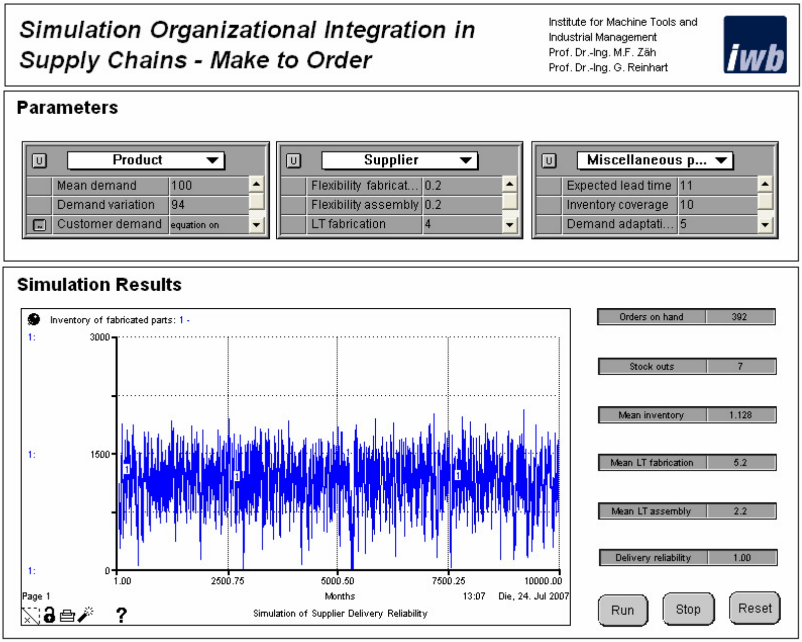
To provide an intuitive understanding of how the developed System Dynamics models are to be applied in industry, the user interface (Figure 38) is elaborated upon in the following section.

The interface consists of two segments. The first contains the parameter input list, which is divided into lists for the demand data, the supplier data, and miscellaneous parameters as required for the model. The parameters that are included in the product specification list are identical for all models (make-to-stock, make-to-order, or purchase-to-order) and include: mean demand, demand variation, and buyer's expected lead time.

The definition of the supplier parameters encompasses: volume flexibility, mean lead time, lead time variation of the supplier's production (or assembly and fabrication, as in the case of the assemble-to-order model), and replenishment principle (except for the purchase-to-order model).

The parameters to be specified in the miscellaneous section are mostly related to the replenishment principle for the make-to-stock and the make-to-order system. They include the expected lead time from the placement of an order to the arrival in the inventory, which is used for both push and pull systems, as well as the dampening factors mentioned above for the push system. In the case of the purchase-to-order system, the relevant parameters are the lead time for an average order and the lead time variation for the supplier's supplier.

The second segment of the user interface contains the model control, and performance measures that result from a simulation run. In Figure 38, for the make-to-order system, the graph displays the inventory level between assembly and fabrication. Similarly, in the case of the make-to-order system, the level of the final inventory is shown, since it is the most relevant measure for delivery reliability. For the purchase-to-order system, the order backlog is displayed, as this metric provides information on irregularities in delivery. In addition, for all models, the numeric values of the following key performance indicators are shown: orders on hand, stock-outs, mean lead time of production, and most importantly, delivery reliability. For make-to-stock and make-to-order systems, the mean inventory value in also displayed.



Simulation Organizational Integration in Supply Chains - Make to Order

Institute for Machine Tools and Industrial Management
Prof. Dr.-Ing. M.F. Zäh
Prof. Dr.-Ing. G. Reinhart

Parameters

Product
Mean demand 100
Demand variation 94
Customer demand equation on

Supplier
Flexibility fabricat... 0.2
Flexibility assembly 0.2
LT fabrication 4

Miscellaneous p...
Expected lead time 11
Inventory coverage 10
Demand adaptati... 5

Simulation Results

Orders on hand 392
Stock outs 7
Mean inventory 1.128
Mean LT fabrication 5.2
Mean LT assembly 2.2
Delivery reliability 1.00

Figure 38: User interface of the supplier assessment tool

To assess the number of periods the simulation model must be run to obtain reliable results, the simulation is considered to be based on a number of randomly generated number streams drawn from different distributions (e.g., customer demand or fabrication throughput time). To ensure that the mean value and deviation of the generated streams are correlated with the desired values, a minimum sample size must be defined. This can be calculated for every stream using the following formula (HARTUNG et al. 1998, p. 181):

$$n \geq \left(\frac{\left(u_{1-\frac{\alpha}{2}} + u_{1-\beta} \right) \sigma}{\mu_1 - \mu_0} \right)^2 \tag{36}$$

where μ_0 is the desired mean value of the distribution, σ is the desired standard deviation of the distribution, α and β are error levels, and μ_1 is the mean value, where the beta error is met. To ensure that this relation is satisfied for all random variables, the formula should be applied to all variables and the simulation run time should be set to the highest obtained value. Also, the calculation of the minimum sample size should be considered to be valid for steady simulation. As the simulation begins with an "empty factory", the number of periods that are required to reach steady state should be added to the run time of the simulation model.

When all parameters have been specified, the model can be run and results may be evaluated. As the number of streams generated for the random variables are differentiated in each simulation run, multiple runs of the model can enable the identification of effects that only occur under certain parameter combinations (e.g., high demand and high lead time occurring in parallel).

Measures for improving the supplier's manufacturing system can be found by testing different parameter combinations. An example of how this is achieved is given in the next chapter.

8 Industrial Assessment of Delivery Reliability

8.1 Supplier of Magnetic Valves

To evaluate the applicability of the ideas developed in the preceding chapter, an industrial system was analyzed by means of the standardized System Dynamics models, and guidelines were derived for improving the system.

The investigated plant supplies various parts, including magnetic valves to an inter-company-buyer who produces train equipment. These valves are essential components of the pneumatic brake control system of track vehicles. In order to enable a deeper understanding on the analyzed Supply Chain, the value stream (refer to ROTHER & SHOOK 2003) of the analyzed dyad is depicted in Figure 39.

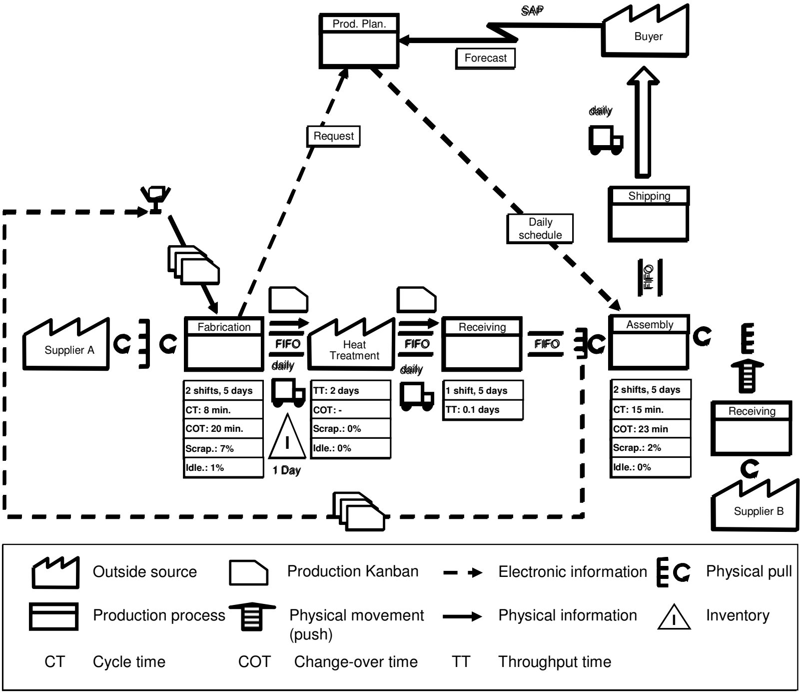


Figure 39: Value stream map of the supply chain for the magnetic valve

The buyer orders the parts via the common ERP system (SAP$^{©}$) and also provides a forecast to the supplier to enable a timely response to demand peaks. The orders are converted to a daily production schedule by the supplier's production planning and control department.

Accordingly, magnetic valves, consisting of an aluminium body and a certain number of standard parts, are assembled, tested, and packaged in one of the assembly department's cells, which is also dedicated to other products. Assembly cells operate five days a week, two shifts a day.

Standard parts are drawn from a supermarket that is situated in the assembly and replenished by the vendor-managed inventory principle by supplier B. Similarly, the valve bodies are picked from the stock that is available in the assembly area. Empty containers are conveyed to the fabrication department together with a Kanban.

During fabrication, the Kanban enters the production queue and the sequence in which orders are processed is determined by the production manager. The machining center, for the fabrication, is responsible for an entire product group, which differs from the products processed in the assembly cell. It operates an equal number of shifts for the assembly. The cycle time for the magnetic valve is 8 minutes and the required changeover time for setting up production for the magnetic valve is 20 minutes. When the valves are fabricated, the necessary raw material is picked from a supermarket as aluminium blocks that are replenished by supplier A based on the same principle employed by supplier B.

After production, parts are collected and transferred to a supplier for heat treatment at the end of each day. After 48 hours, the parts are then returned to the site of the supplier, irrespective of the quantity, where they are accepted by the receiving department and transferred to the material stock in assembly.

Once orders have been completed, they are forwarded to the shipping department, where the required documents are attached to the orders. Finally, orders are conveyed to the buyer via a truck that commutes between the supplier and the buyer on a daily basis.

8.2 Simulative Investigation

As delivery reliability of the supplier varied between 80 and 85%, under the buyer's order profile, a simulative investigation was conducted utilizing the make-to-order simulation model. For the specification of the simulation parameters, the buyer's order profile was calculated from the order data for 105 days, which is depicted in Figure 40. As illustrated, the mean demand is 102 parts per day and the standard deviation of demand was calculated to be 94 parts. The last parameter in the product segment, the buyer's expected lead time, was determined to be 10 days.

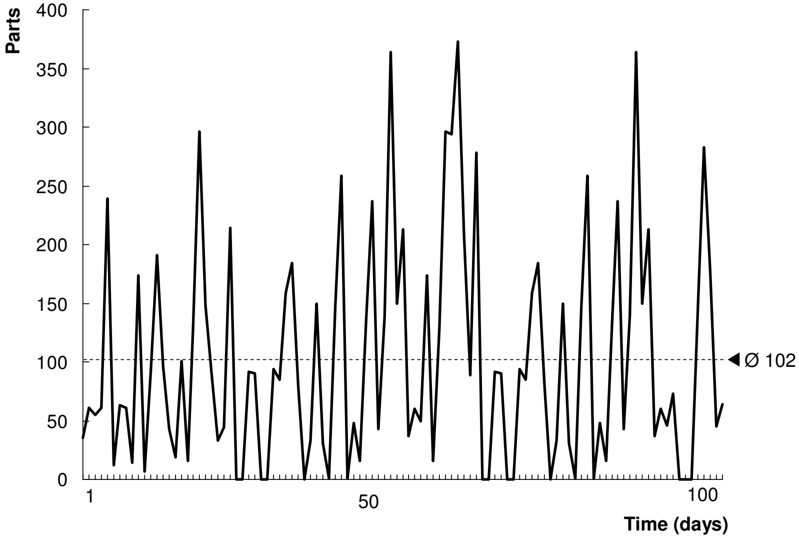


Figure 40: Buyer demand for magnetic valves based on historical data

In the supplier segment, volume flexibility was set to zero for both fabrication and assembly, as both departments work 2 shifts, when they can produce around 112 parts per day, assuming an average of 3 changeovers per day and a shift duration of 8 hours. For the simulation of the organization principle, the mean lead time of the fabrication cells for an average batch of 102 parts was assessed to be 4 days on the basis of historical data, with a standard deviation of 2 days, considering that various products are produced in the fabrication cell. The lead time of the assembly cell for a batch of 102 parts was determined to be 2 days, with a standard deviation of 2 days. The replenishment principle applied by the supplier is a consumption-oriented system, as discussed in the previous section. The expected replenishment lead time for parts drawn from inventory, which is a required input for calculating the maximal amount of inventory, was set to 6 days.

The number of simulation periods was calculated to be 7.638, using formula (36) with α and β error levels of 0,0001, $\mu_0 = 102$, $\sigma = 94$, and $\mu_1 = 110$.

The results of the simulations for the current state of the supplier's system, which was simulated to be 10,000 periods in each run, yielded delivery reliability values of around 85%. Furthermore, the average inventory was calculated to be around 400 parts in each run, which matches the actual value range. Thus, the simulation of the supplier's manufacturing system had a good resemblance with the real system.

To find measures that increase the delivery reliability of the supplier, three system adaptations were tested. The first is the increase of volume flexibility from 0 to 0.1, which would mean that fabrication would work up to 2 more hours every day, if required, for the current backlog situation. This measure could be implemented without additional cost by introducing work hour banks, to allow workers to accumulate and borrow hours within defined intervals. The simulation results (Table 9), that are based on 10 simulation runs, show that the delivery reliability increases to a value between 0.97 (i.e., 97%) and 0.99, and the stock level rises above the current state level by 21 to 47 parts. Additional simulation runs, however, prove that the inventory level can be reduced to the current level by reducing the expected lead time in fabrication, which is permitted, since this parameter is reduced by the volume flexibility.

	Measure		
Results	Increased volume flexibility from 0 to 0.1	Increased inventory in Kanban cycle by 50%	Reduced buyer order variation from 94 to 75
Delivery reliability	0.97 – 0.99	0.85 – 0.90	0.96 – 0.98
Inventory level	421 – 447	928 – 1.050	444 – 481

Table 9: Results of simulative investigation of magnetic valve supplier performance

The second measure that was selected was to increase the amount of inventory in the Kanban cycle by 50%, which would mean that the cost of additional inventory would arise. The simulation results depicted in Table 9, demonstrate that a slight increase in delivery reliability can be achieved with this measure. Nevertheless, perfect delivery reliability cannot be reached by increasing the inventory level within the consumption-oriented system because the highly variable demand of the buyer cannot be served with the capacity available in the system.

The third measure tested during the simulative investigation was a decrease of the buyer demand variation, which could be realized at no cost, if the buyer differently manages customer orders. The standard deviation of the buyer's orders was thus reduced from 94 to 75. Ten simulation runs showed that the effect of reducing the demand variation entered into the system of the supplier (by the buyer) can increase the delivery reliability to a value between 0.96 and 0.98. The increase in inventory, as in the previous case, can be reduced by lowering the number of parts in the Kanban cycle.

8.3 Managerial Implications

The simulative investigation demonstrated that simple measures can enable a significant improvement in supplier performance. Thus, in the view of this thesis, the selection of the supplier should include a number of dimensions such as technical capabilities of the supplier or personal relations, but should also include a thorough analysis of the supplier's manufacturing system.

In the example described above, system analysis can bring forth measures that must be implemented on the supplier side. Nevertheless, the analysis can also help to assess the impact that a change in the buyer's order profile can have on the delivery reliability of the supplier, to illustrate that a buyer-supplier relationship is, and must be, a cooperative venture.

Hence, the integration of a supplier manufacturing system simulation should be added to the standard supplier selection procedures for manufacturing enterprises. As the industrial example reveals, a supplier assessment tool can reduce the time and qualifications required for such an analysis.

9 Summary and Outlook

9.1 Summary

The complexity of products is continuously rising, and product life-cycles are becoming increasingly shorter. Thus, Original Equipment Manufacturers increasingly rely on their suppliers. In turn, these vendors supply a large percentage of the components and sub-assembly groups constituting the final product. From the results of the survey conducted in the course of this research, however, supplier quality and on-time delivery rates are considerable concerns of the buyers and the Original Equipment Manufacturers.

In today's industry, supplier quality is mostly addressed by supplier certification programs that are to ensure the suppliers’ technical capabilities of producing high quality products. These programs have limited effectiveness. The quality problems that remain are often addressed through prescribing costly measures such as high inspection frequencies on the supplier side or increasing incoming quality checks on the buyer side. Additionally, suppliers sometimes must incur the buyer's cost of poor supplier quality and pay penalties.

To provide a means through which the quality of suppliers can be increased in a sustainable manner, which would be beneficial for both parties, incentive structures were derived in this thesis. Under certain circumstances, these offer a financial incentive to suppliers when high quality is delivered. These structures were found by applying repeated games to the quality management problem and are based on Grimm-Trigger and Limited Retaliation strategies. The results were tested in two case studies and the industrial application showed that the offering of a higher part price can enable the supplier to invest in technology that results in higher quality while, at the same time, reduces the buyer's overall cost. This is explained by the fact that the price increase is less costly to the buyer than is the cost for incoming inspection to ensure high supplier quality.

Hence, the first objective of this thesis, to assist the management of supplier quality through deriving conditions under which a supplier is at least indifferent to delivering perfect or imperfect quality, to enhance the quality levels in industry, has been fulfilled.

In terms of insufficient delivery reliability of suppliers, a review of quantitative models for supply chain management showed that a great number of measures have been proposed and adopted by industry to increase the effectiveness of demand information sharing between the buyer and the supplier. For instance, the bullwhip effect, or more precisely, the effects of demand signaling and order batching are mitigated through the use of real time information technology. Furthermore, information asymmetry, with regards to demand information on the supplier and the buyer side, can be addressed by applying the capacity reservation or the buy back contracts.

In any case, research concepts aimed at the manufacturing system design of the suppliers do not seem to be very effective. Measures such as the quantity flexibility contract are often applied, but the consequences are seldom initiated when agreements are not followed, since any form of punishment will not be beneficial to the buyer-supplier relationship. Echelon and queuing systems are excellent means for suppliers to analyze the characteristics of their manufacturing systems, yet they are not often utilized in industry due to their complexity. Finally, discrete event simulation models for assessing the supplier's manufacturing system are costly and require a large degree of expert know-how when adapted or extended.

The hypothesis of this research is that the root cause for insufficient supplier delivery reliability is that the supplier’s manufacturing system is often not organized optimally in regards to the buyer's order profile. To prove the hypothesis, a determinant model was derived, which fully describes the operational elements of bilateral buyer-supplier relationships. This model was subsequently used as the basis for the design of an empirical investigation. The statistical results of the survey suggest that the initial hypothesis is confirmed, as the design of the supplier’s manufacturing system was found to infrequently match with the requirements of the buyer. To enable the upfront assessment of suppliers, System Dynamics models were developed on the basis of the determinant model, that enable a rapid assessment of the supplier’s performance, when subjected to the buyer’s order profile. In addition, measures for increasing delivery reliability can be tested quickly with the System Dynamics models, as demonstrated by the case study in industry.

The second objective of this thesis, to provide a means for buyers to efficiently and effectively ascertain the delivery reliability of potential suppliers, taking into account the organizational integration of the production systems of the supply chain, has been achieved.

9.2 Outlook

As shown in the introduction to this thesis, the price of the procured product is the third most important priority when a buyer selects a supplier. To address this aspect, and as a consequent step for improving quality and delivery reliability, two issues must be investigated in future research.

First, a means must be provided to allow for the assessment of the cost of manufacturing system flexibility, to show the buyer the effect that the buyer's delivery promises to the end-customer can have on the cost of the supplier’s manufacturing system. Hence, research is needed to quantify the cost of volume, routing, machine, and process flexibilities (see BROWNE et al. 1984). In the case of volume flexibility, this could be straightforward, since the only parameter is working time with respect to labor cost. This could be more complicated in cases where volume flexibility also depends on technical features of production equipment. Similarly, the cost of routing, machine, and process flexibility are mostly connected with technical details of the machines employed in production. Thus, a method must be derived for the financial assessment of supplier flexibility levels that are cost-optimal for the buyer.

The second step is to arrive at a method that allows for the quantification of the cost for the supplier when short-term delivery dates are changed by the buyer (i.e., cost from increased numbers of change-overs, higher stock levels, etc.). In this way, the supplier could present to the buyer a price menu that would depend on delivery dates, and the buyer, in turn, could evaluate whether or not a change in the order date would be worth an increased part price.

10 References

ACCENTURE 2005

Accenture GmbH: The buying organization of the future – 2002 European procurement survey. <www.accenture.com/xdoc/nl/locations/nederland/our_work/service_lines/buyer_future.pdf> (04.02.2005).

AEROJET 2005

Aerojet GmbH: Aerojet Purchase Order Quality Clauses. <http://www.aerojet.com/supplier/Sac/QAClauses12-2002.pdf> (04.02.2005).

ALICKE 2003

Alicke, K.: Planung und Betrieb von Logistiknetzwerken – Unternehmensübergreifendes Supply Chain Management. Berlin: Springer (2003).

ANDERNACH 2005

Andernach, K.: Modell zur Bewertung und Steuerung der Qualitätsverbesserung im Rahmen von Qualitätsmanagementsystemen. Doctoral Thesis Technische Universität Berlin (2005).

ANDREß et al. 1997

Andreß, H.-J.; Hagenaars, J. A.; Kühnel, S.: Analyse von Tabellen und kategorialen Daten: log-lineare Modelle, latente Klassenanalyse, logistische Regression und GSK-Ansatz. Berlin: Springer (1997).

ANGERHOFER & ANGELIDES 2000

Angerhofer, B. J.; Angelides, M. C.: System dynamics modelling in supply chain management: research review. In: Joines, J. A. et al. (Eds.): Proceedings of the 2000 Winter Simulation Conference; Orlando, FL, December 10-13, 2000, pp. 342-351.

ASKIN 1993

Askin, R. G.: Modelling and analysis of manufacturing systems. New York, NY: John Wiley & Sons (1993).

AVIBANK 2005

Avibank: Supplier Quality Clauses. <http://www.avibank.com/admin/cotent/uploaded_files/Avibank/Supplier/Quality/Clauses/2-8-05.pdf> (04.02.2005).

BACKHAUS et al. 2003
Backhaus, K.; Erichson, B.; Plinke, W.; Weiber, R.: Multivariate Analysemethoden: eine anwendungsorientierte Einführung. 10th ed. Berlin: Springer (2003).

BAUMGARTEN et al. 2003
Baumgarten, H.; Strommel, H.; Beyer, I.: Fit for Collaboration. PPS Management 8 (2003) 2, pp. 9-12.

BEAMON & CHEN 2001
Beamon, B. M.; Chen, V. C.: Performance analysis of conjoined supply chains. International Journal of Production Research 39 (2001) 14, pp. 3195-3218.

BHUSHI & JAVALAGI 2004
Bhushi, U. M.; Javalagi, C. M.: System dynamics application to supply chain management: a review. International Engineering Management Conference, 2004. Proceedings. IEEE International (2004), pp. 1244-1248.

BOSCH 2005
Bosch GmbH: Einkaufsbedingungen. <http://purchasing.bosch.com/download/Bosch_Einkaufsbedingungen.pdf> (04.02.2005).

BROSER 2002
Broser, W.: Methode zur Definition und Bewertung von Anwendungsfeldern für Kompetenznetzwerke. Doctoral Thesis Technische Universität München (2002). München: Utz 2002. (Forschungsberichte *iwb* 176).

BROWNE et al. 1984
Browne, J.; Dubois, D.; Rathmill, K.; Sethi, S.; Stecke, K.: Classification of flexible manufacturing systems. The FMS Magazine 2 (1984) 4, pp. 114-117.

BULLINGER & KÜHNER 2002
Bullinger, H.-J.; Kühner, M.: Supply Chain Management. Zeitschrift für wirtschaftlichen Fabrikbetrieb (ZWF) 97 (2002) 5, pp. 254-258.

BURLAT et al. 2003
Burlat, P.; Besombes, B.; Deslandres, V.: Constructing a typology for networks of firms. Production Planning and Control 14 (2003) 5, pp. 399-409.

CACHON 2003
Cachon, G.: Supply chain coordination with contracts. In: Graves, S. et al. (Eds.): Handbooks in operations research and management science (volume 11): supply chain management: design, coordination and operation. Amsterdam, NY: North-Holland (2003).

CACHON & LARIVIERE 2005
Cachon, G.; Lariviere, M.: Supply chain coordination with revenue sharing contracts. Management Science 51 (2005) 1, pp. 33-44.

CAPS-RESEARCH 2005
CAPS-Research, Inc.: Purchasing Performance Benchmarking Report for the Aerospace / Defense Industry. <http://www.capsresearch.org/ publications/pdfs-protected/Aerospace2004.pdf> (04.02.2005).

CHASE et al. 1998
Chase, R. B.; Aquilano, N. J.; Jacobs, F. R.: Production and operations management: manufacturing and services. Boston, MA: Irwin / McGraw-Hill (1998).

CHEN 2003
Chen, F.: Information sharing and supply chan coordination. In: Graves, S. et al. (Eds.): Handbooks in operations research and management science (volume 11): supply chain management: design, coordination and operation. Amsterdam, NY: North-Holland (2003).

CHILD 1998
Child, S. J.: The extended enterprise – a concept of co-operation. Production Planning & Control 9 (1998) 4, pp. 320-327.

CHRISTOPHER 2005
Christopher, M.: Creating the Agile Supply Chain. <http://www.martin-christopher.info/downloads/downloads/creating_the_agile_suply_chain.pdf> (18.02.2005).

CISEK et al. 2002
Cisek, R.; Habicht, C.; Neise, P.: Gestaltung wandlungsfähiger Produktionssysteme. Zeitschrift für wirtschaftlichen Fabrikbetrieb 97 (ZWF) 9 (2002) 9, pp. 441-445.

CORSTEN & GÖSSINGER 2001
Corsten, H.; Gössinger, R.: Auftragsdekompostion und -allokation in Unternehmensnetzwerken. PPS Management 6 (2001) 1, pp. 35-41.

CRAVENS et al. 1996
Cravens, D. W.; Piercy, N. F.; Shipp, S. H.: New organizational forms for competing in highly dynamics environments: the network paradigm. British Journal of Management 7 (1996) 3, pp. 203-218.

DARBY & KARNI 1973
Darby, M. R.; Karni, E.: Free competition and the optimal amount of fraud. Journal of Law and Economics 16 (1973) 1, pp. 67-88.

DATHE 1998
Dathe, J.: Kooperationen - Leitfaden für Unternehmen. München: Carl Hanser (1998).

DAVIES 2000
Davies, W.: Partner risk: managing the downside of strategic alliances. West Lafayette, IN: Purdue University Press (2000).

DELOITTE 2005
Deloitte: The challenge of complexity. <http://www.deloitte.com/dtt/cda/doc/content/The%20challenge%20of%20complexity%20final%20proof%200804.pdf> (03.03.2005).

DYER 2004
Dyer, J.: Toyotas Geheimnis. Wirtschaftswoche (2004) 20, pp. 76-79.

EATON 2005
Eaton, Inc.: Supplier Quality Manual. <http://www.aerospace.eaton.com/pdfs/aerospace/supplier_quality_manual.pdf> (04.02.2005).

EVERITT 2000
Everitt, B.: The analysis of contingency tables. 2nd ed. London: Chapman & Hall (2000). (Monographs on statistics and applied probability 45).

FEDERGRUEN 1993
Federgruen, A.: Centralized planning models for multi-echelon inventory systems under uncertainty. In: Graves, S. et al. (Eds.): Handbooks in operations research and management sciecne (Vol. 4): Logistics of production and inventory. Amsterdam, NY: Elsevier science publishing (1993), pp. 133-173.

FEITZINGER & LEE 1997
Feitzinger, E.; Lee, H.: Mass customization at Hewlett Packar: the power of postponement. Harvard Business Rewiev 75 (1997) 1 / 2, pp. 116-121.

FIALA 2005

Fiala, P.: Information sharing in supply chains. Omega – The international Journal of Management Science (forthcoming).

FISHER 1997

Fisher, M. L.: What is the right supply chain for your product? Harvard Business Review 75 (1997) 3 / 4, pp. 105-116.

FLEISCHMANN et al. 2000

Fleischmann, B.; Meyr, H.; Wagner, M.: Advanced Planning. In: Stadtler, H. et al. (Eds.): Supply chain management and advanced planning - concepts, models and case studies. Berlin: Springer (2000), pp. 59-71.

FORRESTER 1958

Forrester, J. W.: A major breakthrough for decision makers. Harvard Business Review 36 (1958) 4, pp. 37-66.

FORRESTER 1996

Forrester, J. W.: Industrial dynamics. Portland, OR: Productivity Press 1996.

FRESE 1999

Frese, E.: Organisationstrukturen und Managementsysteme. In: Schuh, G. et al. (Eds.): Integriertes Management. Berlin: Springer (1999). (Betriebshütte Teil 1)

FROHLICH & WESTBROOK 2001

Frohlich, M. T.; Westbrook, R.: Arcs of integration: an internationla study of supply chain strategies. Journal of Operations Management 19 (2001) 2, pp. 185-200.

FUDENBERG & TIROLE 2000

Fudenberg, D.; Tirole, J.: Game theory. 7th ed. Cambridge, MA: MIT Press (2000).

GANESHAN et al. 1999

Ganeshan, R. M.; Jack, E.; Magazine, M. J.; Stephens, P.: A Taxonomic review of supply chain management research. In: Tayur, S. et al. (Eds.): Quantitative Models for Supply Chain Management. Norwell, MA: Kluwer Academic Publishers 1999, pp. 841-873. (International Series in Operations Research and Management Science 17).

GEIGER 1994

Geiger, W.: Qualitätslehre. 2nd ed. München: Vieweg (1994).

GEIMER & BECKER 2001
Geimer, H.; Becker, T.: Mit dem Supply Chain Operations Reference-Modell (SCOR) Prozesse optimieren. In: Lawrenz, O. et al. (Eds.): Supply Chain Management – Konzepte, Erfahrungsberichte und Strategien auf dem Weg zu digitalen Wertschöpfungsnetzen. 2nd ed. Wiesbaden: Vieweg (2001).

GIBBONS 2004
Gibbons, R.: A primer in game theory. New York: Prentice Hall (2004).

GILBERT 1993
Gilbert, N.: Analyzing tabular data. London: ULC Press (1993).

GRABAN 1999
Graban, M.: An inventory planning methodology for a semiconductor manufacturer with significant sources of variability. Diploma Thesis Massachusetts Institute of Technology, Boston, MA (1999).

GUDEHUS 1999
Gudehus, T.: Logistik. Berlin: Springer (1999).

GÜNTHER & LAAKMANN 2002
Günther, S.; Laakmann, F.: Efficient evaluation and selection of IT-support based on the supply chain management task reference model. In: 6th International Conference on Engineering Design and Automation. Proceedings. Mauii, Hawaii 4.-7. April. (2002).

Bhushi, U. M.; Javalagi, C. M.: System dynamics application to supply chain management: a review. International Engineering Management Conference, 2004. Proceedings. IEEE International (2004), pp. 1244-1248.

HABICHT & NEISE 2004
Habicht, C.; Neise, P.: Questionnaire for the survey "Gemeinsam Werte schaffen" of the Institute for Machine Tools and Industrial Management. <www.iwb.tum.de/Studie_Lieferantenbeziehungen> (04.02.2005).

HAMMER 2001
Hammer, M.: The super efficient company. Harvard Business Rewiev (2001) 9, pp. 81-91.

HAMPRECHT 2003
Hamprecht, H.: Positionskämpfe an der Werkbank. Automobilwoche 4 (2003) 17.2.2003, p. 12.

HANDFIELD & NICHOLS 1999

Handfield, R. B.; Nichols, E. L.: Introduction to supply chain management. Upper Saddle River, NJ: Prentice-Hall (1999).

HARLAND et al. 2002

Harland, C. M.; Lamming, R. C.; Zheng, J.; Johnson, T. E.: A Taxonomy of Supply Networks. IEEE Engineering Managment Review 30 (2002) 4, pp. 79-85.

HARTUNG et al. 1998

Hartung, J.; Elpelt, B.; Klösener, K.-H.: Statistik : Lehr- und Handbuch der angewandten Statistik. 11th ed. München: Oldenbourg (1998).

HECKMANN et al. 2003

Heckmann, P.; Shorten, D.; Engel, H.: Supply Chain Management at 21. <http://www.boozallen.de/content/ downloads/scm_21.pdf> (24.02.2005).

HEYMAN & SOBEL 1984

Heyman, D.; Sobel, M.: Statistic Models in Operations Research (Volume 1). New York, NY: McGraw Hill (1984).

HIEBER 2005

Hieber, R.: Trends und Entwicklungen im Supply Chain Management. <http://www.competence-site.de/pps.nsf/0/ed9e2f1bab1ea9a8c1256b 88004f880f?OpenDocument> (10.03.2005).

HIRSCHMANN 1998

Hirschmann, P.: Kooperative Gestaltung unternehmensübergreifender Geschäftsprozesse. Doctoral Thesis Universität des Saarlandes (1998). Wiesbaden: Gabler (1998).

HUANG 2004

Huang, C.-K.: An optimal policy for a single-vendor single-buyer integrated production-inventory problem with process unreliability consideration. International Journal of Production Economics (2004) 91, pp. 91-98.

JAGDEV & THOBEN 2001

Jagdev, H. S.; Thoben, K. D.: Anatomy of enterprise collaborations. Production Planning & Control 12 (2001) 5, pp. 437-451.

KALMBACH & KEINHANS 2004

Kalmbach, R.; Keinhans, C.: Zulieferer auf der Gewinnerseite. Automobil Produktion (2004) 4, pp. 4-8. (http://www.mercermc.de/fast_2015/ FAST2015.pdf)

KALUZA et al. 2003

Kaluza, B.; Dullnig, H.; Malle, F.: Principal-Agent-Probleme in Supply Chains - Problemanalyse und Diskussion von Lösungsvorschlägen. Diskussionsbeiträge des Instituts für Wirtschaftswissenschaften Nr. 2003/03. Universität Klagenfurt (2003).

KLEER 2005

Kleer, M.: Supply Chain Management – Entwicklungsstufen, Gestaltungselemente und -ansätze. <http://www.adlittle.de/downloads/artikel/scm_entwicklungsstufen_gestaltungselemente_g-ansaetze.pdf> (10.03.2005).

KOPCZAK 1997

Kopczak, L. R.: Logistics partnership and supply chain restructuring: survey results from the US computer industry. Production and Operations Management 6 (1997) 3, pp. 226-247.

KREUTZER 2004

Kreutzer, B.: Deutsche Automobilbranche nicht in allen Bereichen gut aufgestellt. ASU-BUJ-News 2004 (2004) September.

KUHN & HELLINGRATH 2002

Kuhn, A.; Hellingrath, B.: Supply Chain Management: optimierte Zusammenarbeit in der Wertschöpfungskette. Berlin: Springer (2002).

LAMMING et al. 2000

Lamming, R. C.; Johnson, T. E.; Zheng, J.; Harland, C. M.: An initial classification of supply networks. International Journal of Production and Operations Management 20 (2000) 6, pp. 675-691.

LEE et al. 1997a

Lee, H.; Padmanabhan, V.; Whang, S.: Information distortion in a supply chain: the bullwhip effect. Management Science 43 (1997) 4, pp. 546-558.

LEE et al. 1997b

Lee, H.; Padmanabhan, V.; Whang, S.: The bullwip effect in supply chains. Sloan Management Review 38 (1997) 3, pp. 98-102.

LEEDY 1985

Leedy, P.: Practical research: planning and design. 3rd ed. New York, NY: Macmillan (1985).

LIM 2001

Lim, W. S.: Producer-supplier contracts with incomplete information. Management Science 47 (2001) 5, pp. 709-715.

LINCK 2001

Linck, J.: A decomposition-based approach for manufacturing system design. Doctoral Thesis Massachusetts Institute of Technology, Boston, MA (2001).

LODE 2002

Lode, L.: Information sharing in a supply chain with horizontal competion. Management Science 48 (2002) 9, pp. 1196-1212.

LUTZE & ÖZER 2007

Lutze, H.; Özer, Ö. Promised lead time contracts under asymmetric information. Operations Research forthcoming (2007).

MEYR et al. 2000

Meyr, H.; Rohde, J.; Stadtler, H.; Sürie, C.: Supply Chain Analysis. In: Stadtler, H. et al. (Eds.): Supply Chain Management and Advanced Planning. Concepts, Models, Software and Case Studies. Berlin: Springer (2000), pp. 29-56.

MILBERG 2000

Milberg, J.: Unternehmenspolitik im Wandel. In: Reinhart, G. et al. (Eds.): ... nur der Wandel bleibt - Wege jenseits der Flexibilität. München: Utz (2000).

MILBERG & NEISE 2006

Milberg, J.; Neise, P.: Organizational design of supply chains. Annals of the German Academic Society for Production Engineering 13 (2006) 2, pp. 181-186.

MOINZADEH 2002

Moinzadeh, K.: A multi-echelon inventory system with information exchange. Management Science 48 (2002) 3, pp. 414-426.

MORECROFT 1979

Morecroft, J.: Influences from information technology on industry cycles. Doctoral Thesis Massachusetts Institute of Technology, Boston, MA (1979).

MYERSON 1981

Myerson, R.: Optimal auction design. Mathematics of Operations Research 6 (1981) 1, pp. 58-73.

NEISE 2002

Neise, P.: Globalisierung in Kompetenznetzwerken. In: von Behr, M. (Ed.): Erhöhung der Globalisierungsfähigkeit kleiner und mittlerer Unternehmen. München: ISF München aktuell (2002), pp. 160 -172.

NELSON 1970

Nelson, P.: Information and consumer behaviour. Journal of Political Economy 78 (1970) 2, pp. 311-329.

NIENHAUS et al. 2003

Nienhaus, J.; Schnetzler, M.; Sennheiser, A.; Weidemann, M.; Glaubitt, K.; Pierpaoli, F.; Heinzel, H.: Trends im Supply Chain Management - Ergebnisse einer Studie mit mehr als 200 Unternehmen. ETH-Zentrum für Unternehmenswissenschaften (2003).

OPTEK-TECHNOLOGIES 2005

Optek-Technologies, Inc.: Supplier Quality Requirements Manual. <www.optekinc.com/pdf/Supplier%20Quality%20Requirements%20Manual.pdf> (04.02.2005).

ÖZER & WEI 2006

Özer, Ö.; Wei, W.: Strategic commitment for optimal capacity decision under asymmetric forecast information. Management Science 52 (2006) 8, pp. 1238-1257.

PACIFIC-SCIENTIFIC 2005

Pacific-Scientific, Inc.: Supplier Quality Assurance Giudelines. <http://www.pacsci.com/> (04.02.2005).

PARK et al. 1996

Park, H. Y.; Reddy, C.; Shin, G.-C.; Eckerle, C.: Impact of the supplier certification program in US firms. European Journal of Purchasing & Supply Management 2 (1996) 2/3, pp. 107-118.

PASTERNACK 2002

Pasternack, B.: Using revenue sharing to achieve channel coordination for a newsboy type inventory model. In: Pardalos, P. et al. (Eds.): Supply Chain Management: Models, Applications and Research. Norwell, MA: Kluwer Academic Publishers (2002).

PEARSON 1904

Pearson, K.: On the theory of contingency and its relation to association and normal correlation. London: Drapers Co. (1904). (Biometric series)

PFOHL et al. 1998

Pfohl, H.-C.; Häusler, P.; Müller, K.: Logistikmanagement kleiner und mittlerer Unternehmen in wandelbaren regionalen Produktionsnetzwerken. Industrie Management 14 (1998) 6, pp. 29-33.

POIRIER & QUINN 2003

Poirier, C.; Quinn, F. J.: A survey of supply chain progress. Supply Chain Management Review 7 (2003) 5, pp. 40-74.

POIRIER & QUINN 2004

Poirier, C.; Quinn, F. J.: How are we doing - A survey of supply chain progress. Supply Chain Management Review 8 (2004) 8, pp. 24-31.

RAGHUNATHAN 2001

Raghunathan, S.: Information sharing in a supply chain: a note its value when demand is non-stationary. Management Science 47 (2001) 4, pp. 605-610.

RATLIFF 2004

Ratliff, J.: Graduate-level course in game theory. <http://www.virtual-perfection.com/gametheory/> (31.12.2004).

REFA 1990

REFA: Planung und Gestaltung komplexer Produktionssysteme. München: Carl Hanser (1990).

REINHART 2003

Reinhart, G.: Mit der Digitalen Fabrik zur Virtuellen Produktion. In: Zäh, M. F. et al. (Eds.): Grenzen überwinden - Wachstum der neuen Art. München: Utz (2003), pp. 139-158.

REINHART & ZÄH 2007

Reinhart, G.; Zäh, M. F. (Eds.): Lecture notes factory planning. München: TU München (2007).

REINHART et al. 2006

Reinhart, G.; Neise, P.; Sudhoff, W.; von Bredow, M.: Produzieren in globalen Netzwerken. In: Zaeh, M. F. et al. (Eds.): 8. Münchener Kolloquium. München: Utz (2006), pp. 175-192.

REYNIERS & TAPIERO 1995

Reyniers, D. J.; Tapiero, C. S.: Delivery and control of quality in supplier-producer contracts. Management Science 41 (1995) 10, pp. 1581-1589.

RICE & HOPPE 2001

Rice, J. B.; Hoppe, R. M.: Supply chain vs. supply chain: the hype and reality. Supply Chain Management Review 5 (2001) 5, pp. 47-54.

ROHDE et al. 2000

Rohde, J.; Meyr, H.; Wagner, M.: Die Supply Chain Planning Matrix. PPS Management 5 (2000) 1, pp. 10-15.

ROTHER & SHOOK 2003

Rother, M.; Shook, J.: Sehen lernen: mit Wertstromdesign die Wertschöpfung erhöhen und Verschwendung beseitigen. Stuttgart: Log X (2003).

SAINIS 1975

Sainis, P.: Ermittlung von Durchlaufzeiten in der Werkstattfertigung aus Daten des Fertigungsprogrammes mit Hilfe der Warteschlangentheorie. Doctoral Thesis Universität Hannover (1975).

SALANIÉ 1997

Salanié, B.: The economics of contracts: a primer. Cambridge, MA: MIT Press (1997).

SATURNEE 2005

Saturnee, Inc.: Supplier Guidelines. <http://www.saturnee.com/sreqhome.htm #9.0> (04.02.2005).

SCHLIFFENBACHER 2000

Schliffenbacher, K.: Konfiguration virtueller Wertschöpfungsketten in dynamischen, heterarchischen Kompenetenznetzwerken. Doctoral Thesis Technische Universität München (2000). München: Utz (2000). (Forschungsberichte *iwb* 140).

SCHÖNSLEBEN 2004

Schönsleben, P.: Integrales Logistikmanagement: Planung und Steuerung der umfassenden Supply Chain. 4th ed. Berlin: Springer (2004).

SCM-COMPETENCE-AND-TRANSFER-CENTER 2005

SCM-Competence-and-Transfer-Center: scm-CTC Reference Model. <http://portal.lfo.unidormund.de/jsp/epctrl.jsp?mod=scm000028&cat=scm000098&pri=scm&lng=1> (08.03.2005).

SELKE 2004

Selke, C.: Entwicklung von Methoden zur automatischen Modellgenerierung. Doctoral Thesis Technische Universität München (2004). München: Utz (2004). (Forschungsberichte *iwb* 193).

SEMINI et al. 2006

Semini, M.; Fauske, H.; Strandhagen, J. O.: Applications of discrete-event simulation to support manufacturing logistics decision-making: a survey. In: Proceedings of the 38th conference on Winter simulation, Monterey, CA. (2006).

SEURING 2001

Seuring, S.: Die Produkt-Kooperations-Matrix im Supply Chain Management – Konzeption und instrumentelle Ausgestaltung. EcoMTex-Diskussionspapier Nr. 02 der Universität Oldenburg. (2001).

SHAPIRO & STIGLITZ 1984

Shapiro, C.; Stiglitz, J. E.: Equilibrium Unemployment as a Worker Discipline Device. American Economic Review 74 (1984) 3, pp. 433-441.

SIMCHI-LEVI et al. 2003

Simchi-Levi, D.; Kaminsky, P.; Simchi-Levi, E.: Designing and managing the supply chain: concepts, strategies, and case studies. Boston, MA: Irwin / McGraw-Hill (2003).

SOUTHCO 2005

Southco, Inc.: Supplier Quality Statement of Requirements. <http://www.southco.com/suppliers/pdf/Form1058SouthcoQualityRequirements.pdf> (04.02.2005).

SPENGLER 1950

Spengler, J.: Vertical integration and antitrust policy. Journal of Political Economy 58 (1950) 4, pp. 347-352.

STARBIRD 1997

Starbird, S. A.: Acceptance sampling, imperfect production, and the optimality of zero defects. Naval Research Logistics 44 (1997) 6, pp. 515-530.

STERMAN 1989

Sterman, J. D.: Modelling managerial behaviour: misperceptions of feedback in a dynamic decision making experiment. Management Science 35 (1989) 3, pp. 321-339.

STERMAN 2000

Sterman, J. D.: Business dynamics: systems thinking and modeling for a complex world. Boston, MA: Irwin / McGraw-Hill (2000).

STEVENS 1989

Stevens, G. C.: Integrating the Supply Chain. International Journal of Physical Distribution and Logistics Management 19 (1989) 8, pp. 3-8.

SUPPLY-CHAIN-COUNCIL 2005
Supply-Chain-Council: Supply-Chain Operations Reference-model: overview of SCOR version 6.1. <http://www.supply-chain.org/SCOR/SCOR_Overview_6.1.pdf> (14.03.2005).

SYDOW 1992
Sydow, J.: Strategische Netwerke, Evolution und Organisation. Wiesbaden: Gabler (1992).

TAGARAS & LEE 1996
Tagaras, G.; Lee, H.: Economic models for vendor evaluatiuon with quality cost analysis. Management Science 42 (1996) 11, pp. 1531-1543.

THOMPSON 1967
Thompson, J. D.: Organizations in Actions. New York, NY: McGraw-Hill (1967).

TIROLE 2003
Tirole, J.: The theory of industrial organizations. Cambridge, MA: MIT Press (2003).

TOMLIN 2000
Tomlin, B. T.: Supply chain design: capacity, flexibility and wholesale price strategies. Doctoral Thesis Sloan School of Management, Boston, MA (2000).

TOWER-AUTOMOTIVE 2005
Tower-Automotive, Inc.: Achieving Supplier Quality Excellence. <http://www.towerautomotive.com/pdf/00_asqe.pdf> (04.02.2005).

TSAY 1999
Tsay, A. A.: Quantity flexibility contract and supplier-customer incentives. Management Science 45 (1999) 10, pp. 1339-1358.

TSAY & LOVEJOY 1999
Tsay, A. A.; Lovejoy, W. S.: Quantity flexibility contracts und supply chain performance. Manufacturing and Service Operations Management 1 (1999) 2, pp. 89-111.

TSAY et al. 1999
Tsay, A. A.; Nahmias, S.; Agrawal, N.: Modeling supply chain contracts: a review. In: Tayur, S. et al. (Eds.): Quantitative Models for Supply Chain Management. Norwell, MA: Kluwer Academic Publishers (1999), pp. 299-336. (International Series in Operations Research and Management Science 17).

VDI-4400 2000
VDI-4400: Blatt 2: Logistikkennzahlen für die Produktion. (2000). (Standard of the German Associaion of Engineers (VDI)).

VINCENT et al. 1999
Vincent, L.; Besombes, B.; Boudarel, M. R.: Paradoxes et Management des groupements d'enterprises. In: Actes et Proceedings 3ème Congrès International Franco-Québècois de Génie Industriel. Montreal: Presses Internationales Polytechnique (1999), pp. 495-504.

VON STEINÄCKER & KÜHNER 2001
von Steinäcker, J.; Kühner, M.: Supply Chain Management - Revolution oder Modewort? In: Lawrenz, O. et al. (Eds.): Supply Chain Management – Konzepte, Erfahrungsberichte und Strategien auf dem Weg zu digitalen Wertschöpfungsnetzen. Wiesbaden: Vieweg (2001).

WEBASTO 2005
Webasto, GmbH: Qualitätsrichtlinien für Lieferanten. <http://www.bobelle.de/Download/customerspecifics/QW1_Ausgabe_11.pdf> (04.02.2005).

WIENDAHL 1997
Wiendahl, H.-P.: Fertigungsregelung - Logistische Beherrschung von Fertigungsabläufen auf Basis des Trichtermodells. München: Carl Hanser (1997).

WIENDAHL 2002
Wiendahl, H.-P.: Erfolgsfaktor Logistikqualität. Berlin: Springer (2002).

WIENDAHL et al. 2005
Wiendahl, H.-P.; Reinsch, S.; Ouali, K.: Simulationsgestützte Planung und Steuerung von Lieferketten. wt Werkstattstechnik online 95 (2005) 4, pp. 242-247.

WILDEMANN 2004
Wildemann, H.: Leitfaden zur Konzipierung, Berechnung und Einführung von Betreibermodellen. 3rd ed. München: TCW-Verlag (2004).

YIN 1994
Yin, R. K.: Case study research: design and methods. 2nd ed. Thousand Oaks, CA: Sage Publications (1994). (Applied social research methods series

ZÄH 2003

Zäh, M. F.: Kooperationsmanagement: Ein Überblick. In: Zaeh, M. F. et al. (Eds.): Kooperationsmanagement in der Produktion. München: Utz 2003. (*iwb* Seminarberichte 69).

ZÄH & MÖLLER 2007

Zäh, M. F.; Möller, N.: Dimensionierung von Kanban-Regelkreisen. In: Dickmann, P. (Ed.): Schlanker Materialfluss mit Lean Production, Kanban und Innovationen. Berlin: Springer 2007, pp. 126-133.

ZÄH et al. 2004a

Zaeh, M. F.; Habicht, C.; Neise, P.: Classification and parameterization of bilateral supply chain cooperations. In: Proceedings of CIRP Design Seminar; Cairo. 2004.

ZÄH et al. 2004b

Zäh, M. F.; Habicht, C.; Neise, P.: Modeling supply networks by means of building blocks. In: 4. Chemnitzer Tagung "Vernetzt Planen und Produzieren" (VPP); Chemnitz 27th-28th of September. 2004.

ZÄH et al. 2005

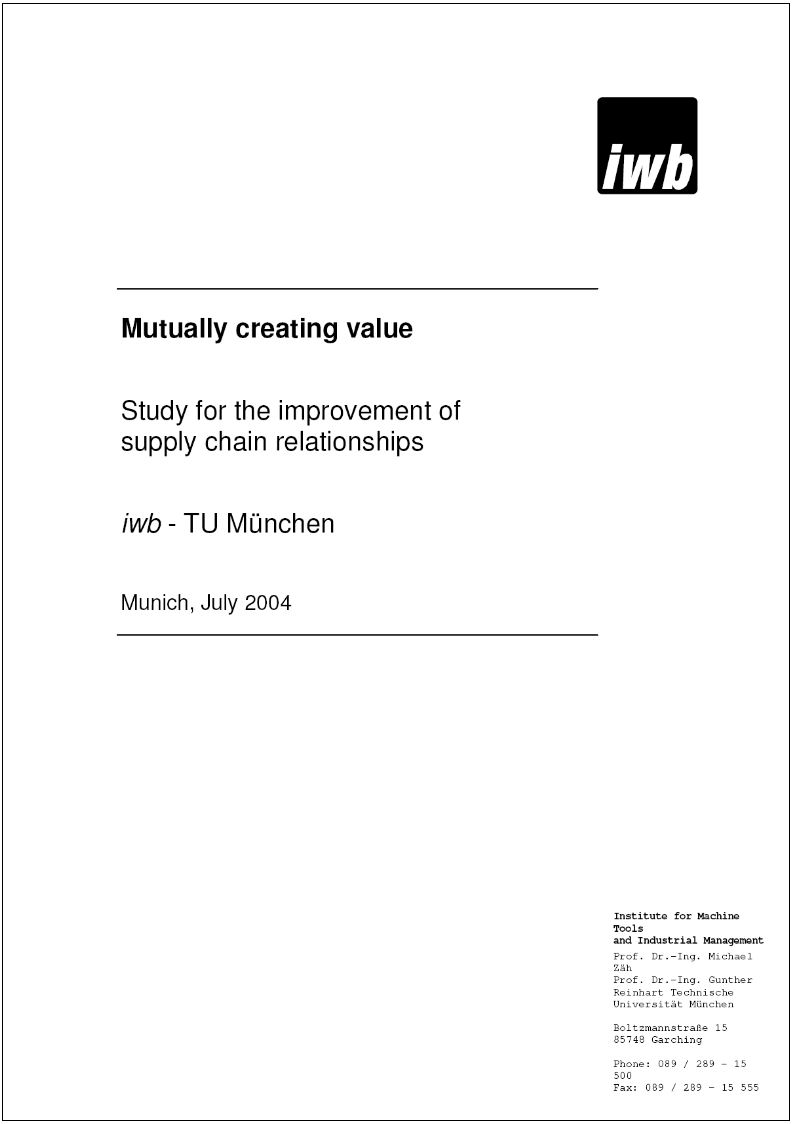
Zäh, M. F.; Özer, Ö.; Neise, P.: An Incentive Structure for the Management of Supplier Quality. In: Reinhart, G. et al. (Eds.): Proceedings of the 1st International Conference on Changeable, Agile, Reconfigurable and Virtual Production; 22nd-23rd of September. Munich: Utz 2005, pp. 123-133.

ZSIDISIN 2003

Zsidisin, G. A.: Managerial perceptions of supply risk. Journal of Supply Chain Management 39 (2003) 4, pp. 14-25.

11 Appendix

11.1 Questionnaire



Mutually creating value

Study for the improvement of
supply chain relationships

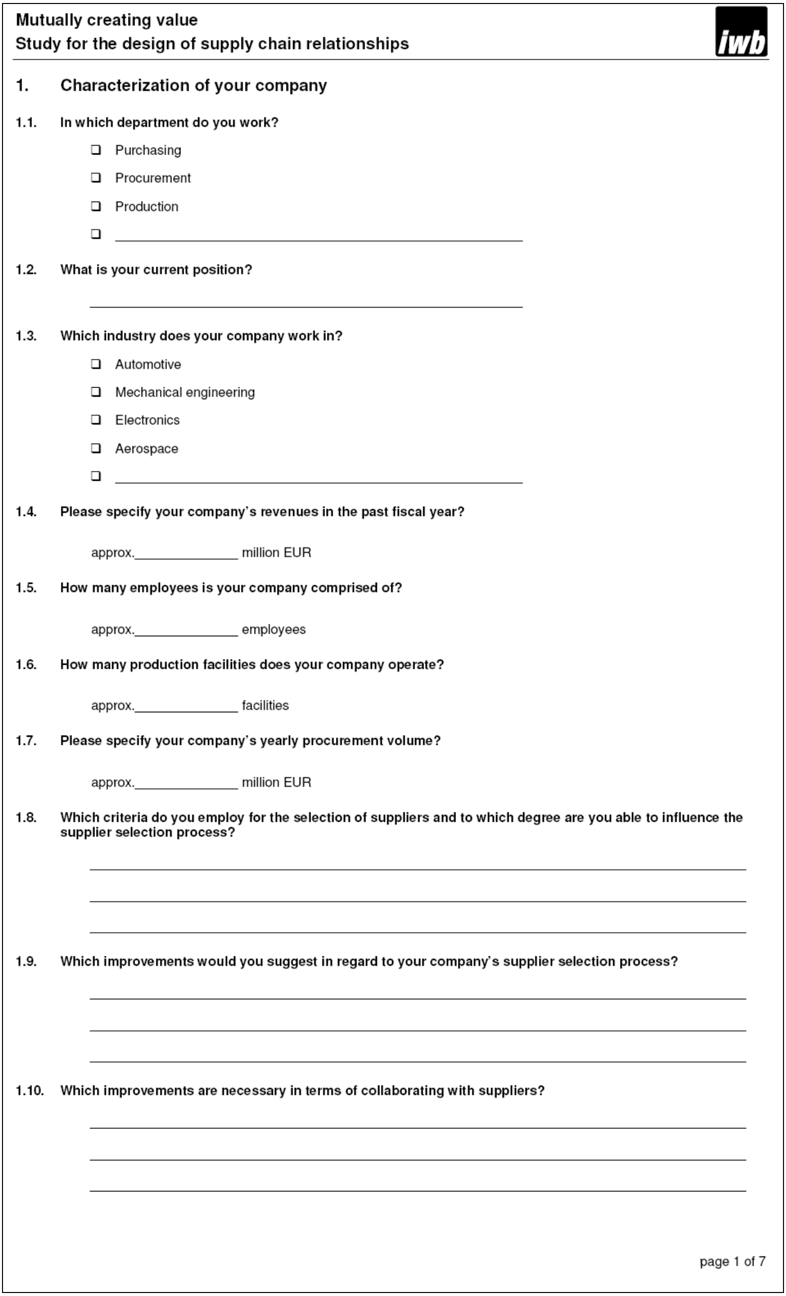
iwb - TU München

Munich, July 2004

Institute for Machine Tools
and Industrial Management
Prof. Dr.-Ing. Michael Zäh
Prof. Dr.-Ing. Gunther Reinhart Technische Universität München

Boltzmannstraße 15
85748 Garching

Phone: 089 / 289 - 15 500
Fax: 089 / 289 - 15 555



Mutually creating value
Study for the design of supply chain relationships

1. Characterization of your company

1.1. In which department do you work?

- ☐ Purchasing
- ☐ Procurement
- ☐ Production
- ☐ ____

1.2. What is your current position?

____

1.3. Which industry does your company work in?

- ☐ Automotive
- ☐ Mechanical engineering
- ☐ Electronics
- ☐ Aerospace
- ☐ ____

1.4. Please specify your company's revenues in the past fiscal year?

approx.______________ million EUR

1.5. How many employees is your company comprised of?

approx.______________ employees

1.6. How many production facilities does your company operate?

approx.______________ facilities

1.7. Please specify your company's yearly procurement volume?

approx.______________ million EUR

1.8. Which criteria do you employ for the selection of suppliers and to which degree are you able to influence the supplier selection process?

____

____

____

1.9. Which improvements would you suggest in regard to your company's supplier selection process?

____

____

____

1.10. Which improvements are necessary in terms of collaborating with suppliers?

____

____

____

page 1 of 7

2. Characterization of a specific product

In the following we would like to concentrate on a single product (or product family), which is produced by your company or business unit. Your selection should focus a product that is characteristic for and relevant to your company (thus not a low runner). Furthermore, you should be somewhat familiar with suppliers that deliver at least one of the constituent parts of this product.

2.1. Which position does your company have within the product's supply chain?

☐ Original Equipment Manufacturer (OEM)

☐ Supplier (1st tier)

☐ Supplier (nth tier)

2.2. Which of the following supply chain elements does the product pass through?

☐ Distribution center ☐ Wholesaler ☐ Retailer *or* ☐ none

2.3. Which category does the product belong to?

☐ Capital good

☐ Consumer good

2.4. Which of the following alternatives best characterizes the product?

☐ raw material

☐ standard part

☐ drawing part

☐ component / module

☐ final product

2.5. In which yearly quantity is the product produced?

approx.______________ parts / units

2.6. How much does the monthly demand vary from the average monthly demand per year?

approx. ± ____________ %

2.7. How long is he product's shelf life (e. g. in terms of corrosion, etc.)?

☐ days

☐ weeks

☐ months

☐ unlimited

2.8. Is the real demand of the final customer conveyed to your company?

☐ yes

☐ no

2.9. How many relevant variants of the product exist?

approx.______________ variants

2.10. What is the product's sales price?

approx.______________ EUR

Mutually creating value
Study for the design of supply chain relationships

2.11. Which customer order decoupling point has been selected for the product?

☐ Make to Stock (MTS)
Products are produced to stock, delivered to customers when demanded and then replenished.

☐ Make to Order (MTO)
Products are produced when customers have placed an order and then delivered to the customer. The required material for production is mostly in stock.

☐ Purchase to Order (PTO)
Material for production is procured from suppliers once customers have placed an order. Upon arrival of the material products are produced and delivered to the customer.

2.12. Which principle of organization applies to your company's <u>fabrication</u> facilities?

☐ Project shop
Personnel and fabrication equipment are moved towards the product when needed and the fabrication object (product) rests.

☐ Job shop
Fabrication equipment is grouped according to technologies and mostly universal.

☐ Cellular layout
Fabrication equipment is arranged according to the process sequence, dedicated to product families and loosely connected.

☐ Flow shop
Fabrication equipment is arranged according to the process sequence and rigidly connected.

2.13. Which principle of organization applies to your company's <u>assembly</u> facilities?

☐ Project shop
Personnel and assembly equipment are moved towards the product when needed and the assembly object (product) rests.

☐ Job shop
Assembly equipment is grouped according to technologies and mostly universal.

☐ Cellular layout
Assembly equipment is arranged according to the process sequence, dedicated to product families and loosely connected.

☐ Flow shop
Assembly equipment is arranged according to the process sequence and rigidly connected.

2.14. How is the fabrication of the product controlled <u>internally</u>?

☐ Push
Fabrication orders are conveyed to the shop floor when actual demand exists (customer orders or forecasted demand)

☐ Pull
Fabrication orders are conveyed to the shop floor once parts have been consumed in assembly.

2.15. How is the assembly of the product controlled <u>internally</u>?

☐ Push
Assembly orders are conveyed to the shop floor when actual demand exists (customer orders or forecasted demand)

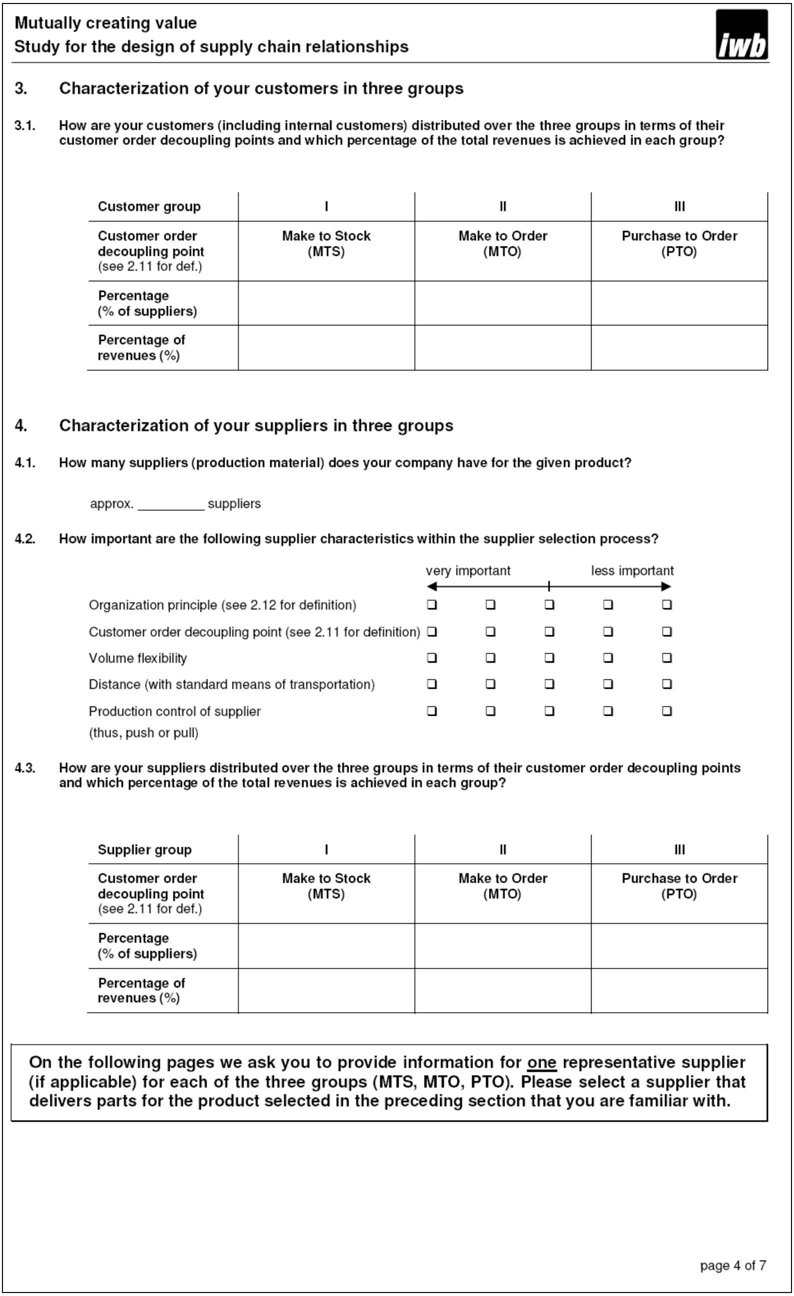
☐ Pull
Assembly orders are conveyed to the shop floor once parts have been consumed by customers.

2.16. How volume flexible are your production facilities?

☐ not at all

☐ limited

☐ unlimited



Mutually creating value
Study for the design of supply chain relationships

3. Characterization of your customers in three groups

3.1. How are your customers (including internal customers) distributed over the three groups in terms of their customer order decoupling points and which percentage of the total revenues is achieved in each group?

Customer group	**I**	**II**	**III**
Customer order decoupling point (see 2.11 for def.)	**Make to Stock (MTS)**	**Make to Order (MTO)**	**Purchase to Order (PTO)**
Percentage (% of suppliers)			
Percentage of revenues (%)			

4. Characterization of your suppliers in three groups

4.1. How many suppliers (production material) does your company have for the given product?

approx. _________ suppliers

4.2. How important are the following supplier characteristics within the supplier selection process?

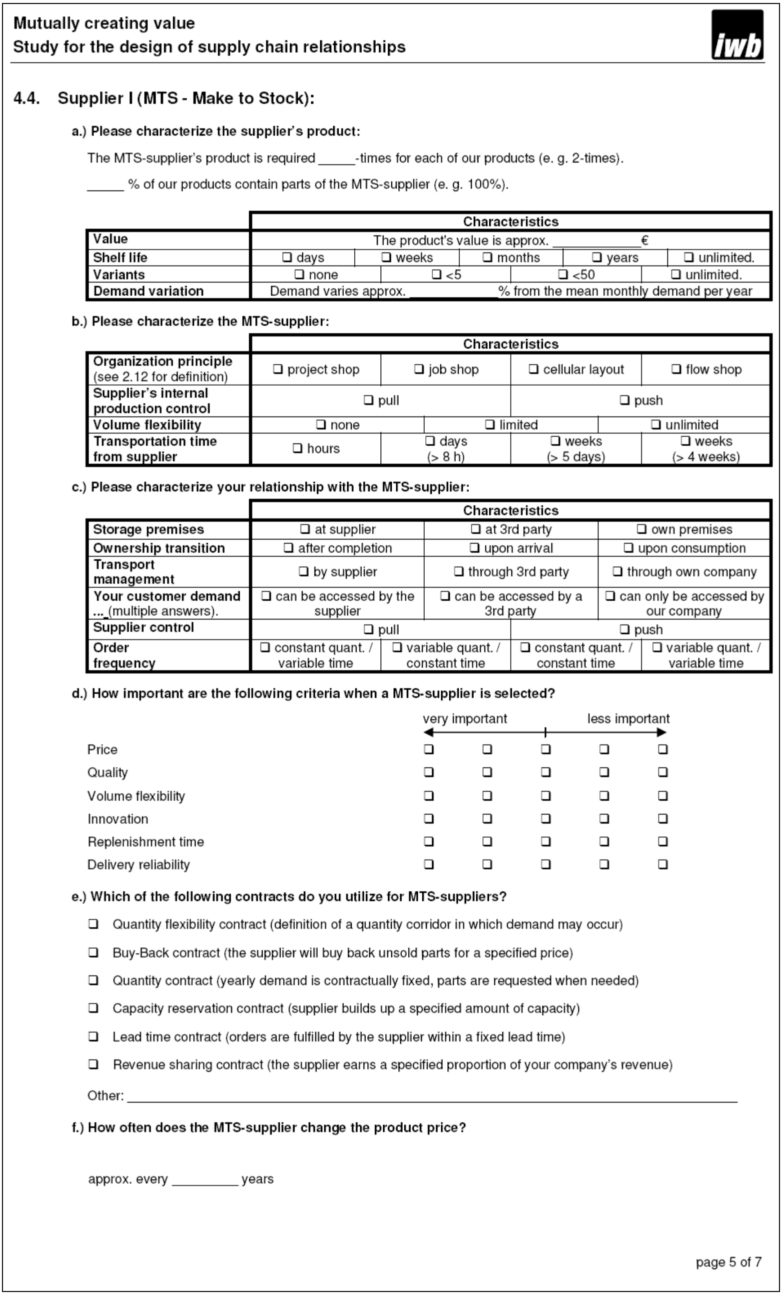
	very important				less important
Organization principle (see 2.12 for definition)	☐	☐	☐	☐	☐
Customer order decoupling point (see 2.11 for definition)	☐	☐	☐	☐	☐
Volume flexibility	☐	☐	☐	☐	☐
Distance (with standard means of transportation)	☐	☐	☐	☐	☐
Production control of supplier (thus, push or pull)	☐	☐	☐	☐	☐

4.3. How are your suppliers distributed over the three groups in terms of their customer order decoupling points and which percentage of the total revenues is achieved in each group?

Supplier group	**I**	**II**	**III**
Customer order decoupling point (see 2.11 for def.)	**Make to Stock (MTS)**	**Make to Order (MTO)**	**Purchase to Order (PTO)**
Percentage (% of suppliers)			
Percentage of revenues (%)			

On the following pages we ask you to provide information for <u>one</u> representative supplier (if applicable) for each of the three groups (MTS, MTO, PTO). Please select a supplier that delivers parts for the product selected in the preceding section that you are familiar with.

page 4 of 7



Mutually creating value
Study for the design of supply chain relationships

4.4. Supplier I (MTS - Make to Stock):

a.) Please characterize the supplier's product:

The MTS-supplier's product is required _____-times for each of our products (e. g. 2-times).

_____ % of our products contain parts of the MTS-supplier (e. g. 100%).

	Characteristics				
Value	The product's value is approx. ___________€				
Shelf life	☐ days	☐ weeks	☐ months	☐ years	☐ unlimited.
Variants	☐ none	☐ <5	☐ <50	☐ unlimited.	
Demand variation	Demand varies approx. ___________% from the mean monthly demand per year				

b.) Please characterize the MTS-supplier:

	Characteristics			
Organization principle (see 2.12 for definition)	☐ project shop	☐ job shop	☐ cellular layout	☐ flow shop
Supplier's internal production control	☐ pull		☐ push	
Volume flexibility	☐ none	☐ limited	☐ unlimited	
Transportation time from supplier	☐ hours	☐ days (> 8 h)	☐ weeks (> 5 days)	☐ weeks (> 4 weeks)

c.) Please characterize your relationship with the MTS-supplier:

	Characteristics			
Storage premises	☐ at supplier	☐ at 3rd party	☐ own premises	
Ownership transition	☐ after completion	☐ upon arrival	☐ upon consumption	
Transport management	☐ by supplier	☐ through 3rd party	☐ through own company	
Your customer demand ... (multiple answers).	☐ can be accessed by the supplier	☐ can be accessed by a 3rd party	☐ can only be accessed by our company	
Supplier control	☐ pull		☐ push	
Order frequency	☐ constant quant. / variable time	☐ variable quant. / constant time	☐ constant quant. / constant time	☐ variable quant. / variable time

d.) How important are the following criteria when a MTS-supplier is selected?

	very important				less important
Price	☐	☐	☐	☐	☐
Quality	☐	☐	☐	☐	☐
Volume flexibility	☐	☐	☐	☐	☐
Innovation	☐	☐	☐	☐	☐
Replenishment time	☐	☐	☐	☐	☐
Delivery reliability	☐	☐	☐	☐	☐

e.) Which of the following contracts do you utilize for MTS-suppliers?

☐ Quantity flexibility contract (definition of a quantity corridor in which demand may occur)

☐ Buy-Back contract (the supplier will buy back unsold parts for a specified price)

☐ Quantity contract (yearly demand is contractually fixed, parts are requested when needed)

☐ Capacity reservation contract (supplier builds up a specified amount of capacity)

☐ Lead time contract (orders are fulfilled by the supplier within a fixed lead time)

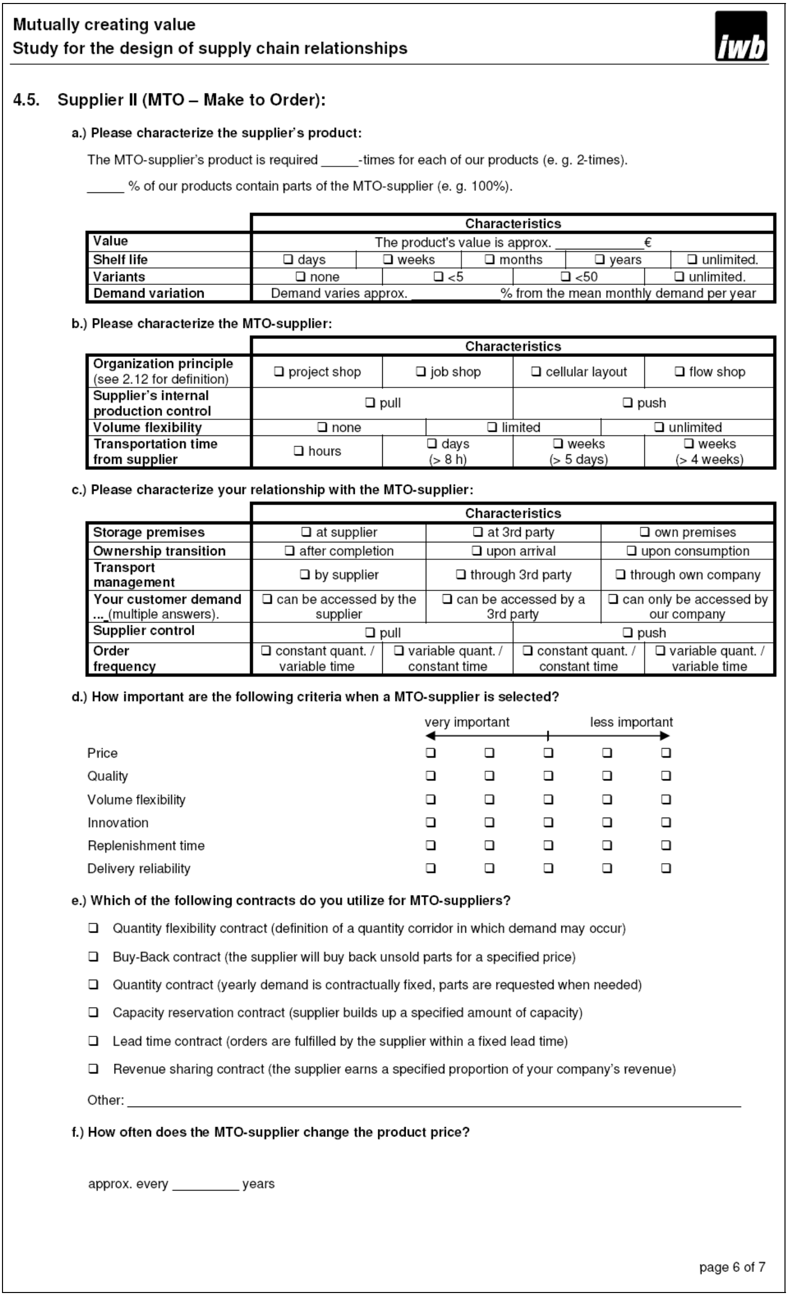
☐ Revenue sharing contract (the supplier earns a specified proportion of your company's revenue)

Other: ____

f.) How often does the MTS-supplier change the product price?

approx. every _________ years

page 5 of 7



Mutually creating value
Study for the design of supply chain relationships

4.5. Supplier II (MTO – Make to Order):

a.) Please characterize the supplier's product:

The MTO-supplier's product is required _____-times for each of our products (e. g. 2-times).

_____ % of our products contain parts of the MTO-supplier (e. g. 100%).

	Characteristics				
Value	The product's value is approx. ___________ €				
Shelf life	☐ days	☐ weeks	☐ months	☐ years	☐ unlimited.
Variants	☐ none	☐ <5	☐ <50	☐ unlimited.	
Demand variation	Demand varies approx. __________% from the mean monthly demand per year				

b.) Please characterize the MTO-supplier:

	Characteristics			
Organization principle (see 2.12 for definition)	☐ project shop	☐ job shop	☐ cellular layout	☐ flow shop
Supplier's internal production control	☐ pull	☐ push		
Volume flexibility	☐ none	☐ limited	☐ unlimited	
Transportation time from supplier	☐ hours	☐ days (> 8 h)	☐ weeks (> 5 days)	☐ weeks (> 4 weeks)

c.) Please characterize your relationship with the MTO-supplier:

	Characteristics			
Storage premises	☐ at supplier	☐ at 3rd party	☐ own premises	
Ownership transition	☐ after completion	☐ upon arrival	☐ upon consumption	
Transport management	☐ by supplier	☐ through 3rd party	☐ through own company	
Your customer demand … (multiple answers).	☐ can be accessed by the supplier	☐ can be accessed by a 3rd party	☐ can only be accessed by our company	
Supplier control	☐ pull	☐ push		
Order frequency	☐ constant quant. / variable time	☐ variable quant. / constant time	☐ constant quant. / constant time	☐ variable quant. / variable time

d.) How important are the following criteria when a MTO-supplier is selected?

	very important				less important
Price	☐	☐	☐	☐	☐
Quality	☐	☐	☐	☐	☐
Volume flexibility	☐	☐	☐	☐	☐
Innovation	☐	☐	☐	☐	☐
Replenishment time	☐	☐	☐	☐	☐
Delivery reliability	☐	☐	☐	☐	☐

e.) Which of the following contracts do you utilize for MTO-suppliers?

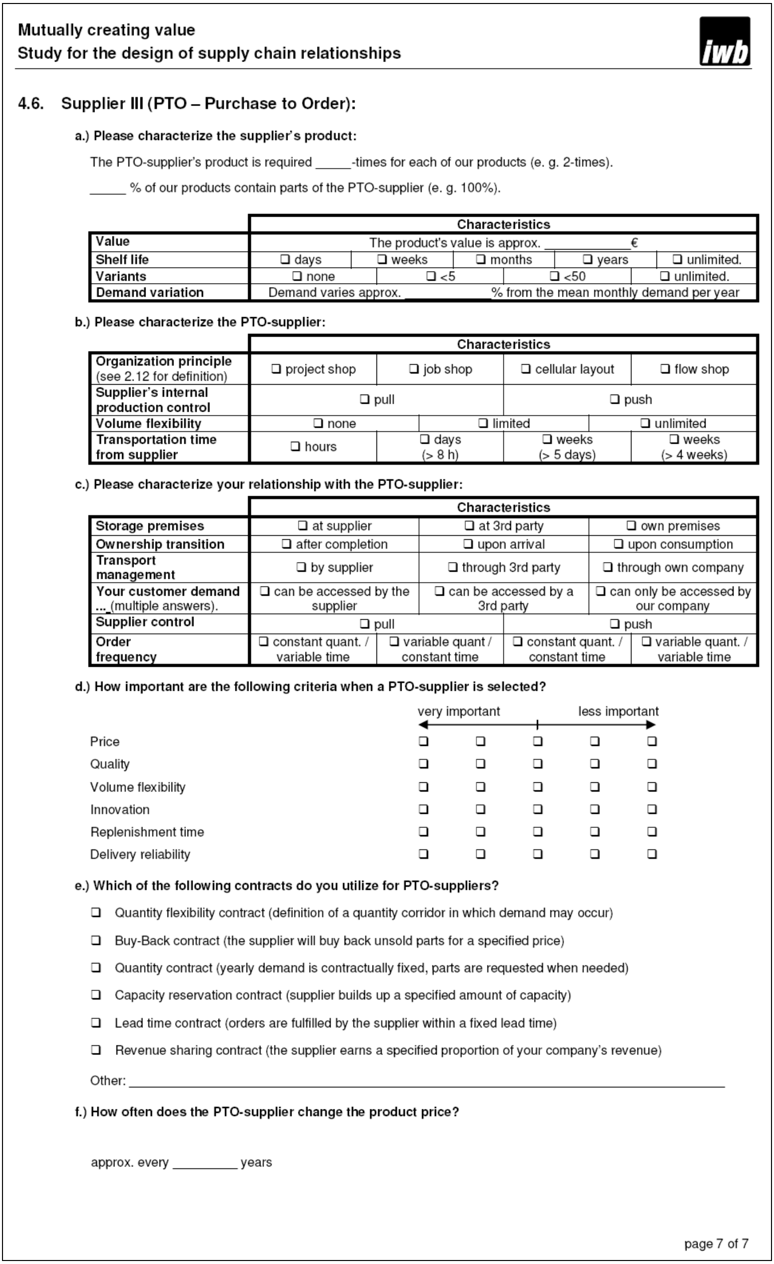
- ☐ Quantity flexibility contract (definition of a quantity corridor in which demand may occur)
- ☐ Buy-Back contract (the supplier will buy back unsold parts for a specified price)
- ☐ Quantity contract (yearly demand is contractually fixed, parts are requested when needed)
- ☐ Capacity reservation contract (supplier builds up a specified amount of capacity)
- ☐ Lead time contract (orders are fulfilled by the supplier within a fixed lead time)
- ☐ Revenue sharing contract (the supplier earns a specified proportion of your company's revenue)

Other: ____

f.) How often does the MTO-supplier change the product price?

approx. every _________ years

page 6 of 7



Mutually creating value
Study for the design of supply chain relationships

4.6. Supplier III (PTO – Purchase to Order):

a.) Please characterize the supplier's product:

The PTO-supplier's product is required _____-times for each of our products (e. g. 2-times).

_____ % of our products contain parts of the PTO-supplier (e. g. 100%).

	Characteristics				
Value	The product's value is approx. ____________€				
Shelf life	☐ days	☐ weeks	☐ months	☐ years	☐ unlimited.
Variants	☐ none	☐ <5	☐ <50	☐ unlimited.	
Demand variation	Demand varies approx. ____________% from the mean monthly demand per year				

b.) Please characterize the PTO-supplier:

	Characteristics			
Organization principle (see 2.12 for definition)	☐ project shop	☐ job shop	☐ cellular layout	☐ flow shop
Supplier's internal production control	☐ pull		☐ push	
Volume flexibility	☐ none	☐ limited	☐ unlimited	
Transportation time from supplier	☐ hours	☐ days (> 8 h)	☐ weeks (> 5 days)	☐ weeks (> 4 weeks)

c.) Please characterize your relationship with the PTO-supplier:

	Characteristics			
Storage premises	☐ at supplier	☐ at 3rd party	☐ own premises	
Ownership transition	☐ after completion	☐ upon arrival	☐ upon consumption	
Transport management	☐ by supplier	☐ through 3rd party	☐ through own company	
Your customer demand ... (multiple answers).	☐ can be accessed by the supplier	☐ can be accessed by a 3rd party	☐ can only be accessed by our company	
Supplier control	☐ pull		☐ push	
Order frequency	☐ constant quant. / variable time	☐ variable quant / constant time	☐ constant quant. / constant time	☐ variable quant. / variable time

d.) How important are the following criteria when a PTO-supplier is selected?

	very important				less important
Price	☐	☐	☐	☐	☐
Quality	☐	☐	☐	☐	☐
Volume flexibility	☐	☐	☐	☐	☐
Innovation	☐	☐	☐	☐	☐
Replenishment time	☐	☐	☐	☐	☐
Delivery reliability	☐	☐	☐	☐	☐

e.) Which of the following contracts do you utilize for PTO-suppliers?

☐ Quantity flexibility contract (definition of a quantity corridor in which demand may occur)

☐ Buy-Back contract (the supplier will buy back unsold parts for a specified price)

☐ Quantity contract (yearly demand is contractually fixed, parts are requested when needed)

☐ Capacity reservation contract (supplier builds up a specified amount of capacity)

☐ Lead time contract (orders are fulfilled by the supplier within a fixed lead time)

☐ Revenue sharing contract (the supplier earns a specified proportion of your company's revenue)

Other: ____

f.) How often does the PTO-supplier change the product price?

approx. every _________ years

page 7 of 7

11.2 Survey Determinants

Case Nr.	Value	Yearly demand	Demand variation	Variants	Shelf life	CODP supplier	Organization principle supplier	Volume flexibility supplier	CODP buyer	Organization principle buyer (fab.)	Organization principle buyer (assy.)	Distance	Replenishment principle (buyer/ fabrication)	Replenishment principle (buyer / assembly)	Replenishment principle (supplier)
1	200	2000	50	2	4	1	2	2	2	2	3	2	1	1	2
2	1000	1000	100	2	4	2	3		2	2	3	2	1	1	2
3	3800	1000	50	1	5	3	2	2	2	2	3	2	1	1	1
4	25	5000000	7,5	2	5	1	4	2	1	3	4	2	1	1	2
5		2500000	10	2	5	1	4	2	1	3	3	2	2	2	2
6		50000	10	1	5	2	4	2	1	3	3	2	2	2	2
7		5000	30	1	5	2	4	2	2	4	2	2	1	1	
8	20	65	10	1	3	2	4	2	3	2	3	3	1	1	1
9	700	1000	55	2	4	1	4	3	3	3	3	2	1	1	1
10	1050	500	50	2	5	3	3	3	3	3	3	2	1	1	2
11	7	10000	40	2	5	1	3	2	2	3	3	3	2	1	2
12			30		3	1	4	2	1	2	3	2	1	1	1
13		700	30	2	3	2	3	2	1	2	3	2	1	1	2
14		700	30	2	3	3	3	2	1	2	3	1	1	1	2
15		960		2	4	1	3	2	1	3	3	2	1	1	2
16	500	42000	10	3	4	1	4	2	1	4	4	2	2	2	1
17	150	6000	15	3	4	2	3	2	1	4	4	2	2	2	2
18	45	18000	10	2	4	3	4	2	1	4	4	1	2	2	2
19		100	50	2	4	3	3		3	1	1	2	1	1	
20	300	2000	40	3	4	2	3	2	1	3	3	2	1	1	2
21	300	125			5	3		2	2	2	3	1	1	1	2
22	100	840000	5	3	2	2	4	2	2	4	4	1	1	1	2
23	50	900	30	2	4	1	3	2	2	3	3	3	1	1	2
24	500	400			4	2	3	3	2	3	3	2	1	1	2
25	100	360	4	2	5	1	4	2	3	4	4	2	1	1	1

Case Nr.	Value	Yearly demand	Demand variation	Variants	Shelf life	CODP supplier	Organization principle supplier	Volume flexibility supplier	CODP buyer	Organization principle buyer (fab.)	Organization principle buyer (assy.)	Distance	Replenishment principle (buyer/ fabrication)	Replenishment principle (buyer / assembly)	Replenishment principle (supplier)
26	1000	1800	100	2	4	2	2	2	3	4	4	2	1	1	2
27	4000	6480	20	2	4	3	3	2	3	4	4	3	1	1	2
28	6	1800000	70	4	3	3	4	2	3	4		1	1		2
29	20	100000	35	3	4	1	3		3	3	3	2	1	1	2
30		100000	35	2	3	2	3	2	3	3	3	2	1	1	1
31		100000		3	3	3	3	2	3	3	3	1	1	1	2
32			20	1	3	1	4	2	2	2	2	2	1	1	1
33			20	1	3	2	4	2	2	2	2	3	1	1	1
34			20	3	3	3	4	2	2	2	2	1	1	1	2
35	5	500	10	3	5	1	4	2	3	3	3	1	1	1	1
36	15000	50	10	4	3	2	3	2	3	3	3	2	1	1	2
37	200000	50	10	4	3	3	4	2	3	3	3	2	1	1	1
38		4508000	5	1	3	1	4	2	1	4	3	2	1	1	2
39		1127000	25	3	3	2	4	2	1	4	3	2	1	1	1
40			30	3	3	3	4	2	1	4	3	2	1	1	1
41	300	14000	15	1	5	1	3	2	3	3	3	2	1	1	2
42	80	14000	20	3	5	2	3	2	3	3	3	2	1	1	1
43	250	14000	20	3	5	3	3	2	3	3	3	3	1	1	2
44	100	60000	100	2	4	2	4	2	3	3	3	2	1	1	2
45	150	40000	100		4	3	3	2	3	3	3	1	1	1	2
46			20	1	3	1	4	2	2	3	3	2	1	1	1
47		300	20	2	3	2	3	2	2	3	3	2	1	1	2
48		300	50	3	3	3	3	2	2	3	3	1	1	1	2
49		15000	15	3	4	1	3	2	1	3	3	2	2	1	1
50		300000	15	3	4	2	3	2	1	3	3	2	2	1	2
51			10	3	4	3	3		1	3	3	2	2	1	2
52	10	50000	20	1	4	1	3	2	1	4	4	1	1	1	2
53	30	50000	20	1	3	2	3	2	1	4	4	1	1	1	2
54	2	50000	10	1	3	3	3	2	1	4	4	1	1	1	2

Case Nr.	Value	Yearly demand	Demand variation	Variants	Shelf life	CODP supplier	Organization principle supplier	Volume flexibility supplier	CODP buyer	Organization principle buyer (fab.)	Organization principle buyer (assy.)	Distance	Replenishment principle (buyer/ fabrication)	Replenishment principle (buyer / assembly)	Replenishment principle (supplier)
55	1500	32	25	2	3	2	1	2	2	1	1	3	1	1	2
56	2500	40	25	2	3	3	1	2	2	1	1	2	1	1	2
57	400	30000	0		4	2	4	3	2	4	4	2	1	1	2
58		1000000	10	2	5	1	2	2	1	3	3	2	2	2	2
59		200000	10	2	5	2	3	2	1	3	3	2	2	2	1
60	3	72000	10	2	5	2	4	2	2	3	3	2	1	1	2
61		27000	10	2	3	1	4	2	3			2			2
62		27000	10	2	3	3	4	2	3			1			2
63	1	3000000	5	1	3	2	4	2	2	4	4	2	1	1	2
64		2700000	20	1	3	1	4	2	2	3	3	3	1	1	2
65		900000	20	2	2	2	3	1	2	3	3	2	1	1	2
66	0,2	40000000	15	1	5	2	4	2	2	4		2	1		2
67	125	4000	15	2	3	1	4	2	2	4	4	1	1	1	1
68	250	4000	15	3	5	2	4	2	2	4	4	1	1	1	2
69	3750	4000	15	3	5	3	4	2	2	4	4	1	1	1	2
70	1000	40000	10	4	4	1	4	2	2	3	3	2	1	1	1
71	19000	900000	10	3	4	2	3	2	2	3	3	2	1	1	2
72			100	3	4	3	1	2	3	1	1	1	1	1	2
73	1	160	60	2	3	1	4	2	2	3	3	2	1	1	1
74	30	4800	60	3	3	2	3	2	2	3	3	3	1	1	2
75	3	480	60	3	3	3	3	2	2	3	3	1	1	1	1
76	350	300	50	3	4	1	4	2	2	2	1	2	1	1	1
77	900	720		2	4	2	3	2	2	2	1	1	1	1	2
78	20000	120	50	4	4	3	1	2	2	2	1	2	1	1	2
79	25000	200	10	2	4	2	3	2	2	3	3	3	1	1	2
80	4500	64	20	2	4	1	4	2	3	2	2	2	1	1	1
81	10500	100	15	2	4	2	3	2	3	2	2	2	1	1	2
82	8000	40	5	1	4	3	2	2	3	2	2	3	1	1	2
83	40000	21		1	3	1	4	2	3	3	3	2	1	1	2

Case Nr.	Value	Yearly demand	Demand variation	Variants	Shelf life	CODP supplier	Organization principle supplier	Volume flexibility supplier	CODP buyer	Organization principle buyer (fab.)	Organization principle buyer (assy.)	Distance	Replenishment principle (buyer/ fabrication)	Replenishment principle (buyer / assembly)	Replenishment principle (supplier)
84	70000	16,8		1	3	3	4	2	3	3	3	1	1	1	2
85	0,5	8000	5	1	2	1	4	2	2	3	3	2	1	2	2
86	20	80000	5	1	3	2	2	2	2	3	3	2	1	2	2
87	4000	0,04	5	1	4	3	4	2	3	4	4	1	1	1	2
88	30	6000	20	3	4	1	2	2	1	3	3	2	1	2	2
89	3	700	20	2	5	2	2	2	1	3	3	2	1	2	1
90	1	500	20	2	5	3	2	2	1	3	3	1	1	2	1
91	80		5	3	4	1	3	2				1			2
92	5		5	3	4	2	3	2				1			2
93	3		5	3	4	3	4	2				1			1
94	70000	16,8		1	3	3	4	2	3	3	3	1	1	1	2
95	0,5	8000	5	1	2	1	4	2	2	3	3	2	1	2	2

Explanation of metric and nominal variables:

Value: price of the part procured by the buyer [€]

Yearly demand: number of parts procured by the buyer within one year [parts]

Demand variation: percentage of the buyer’s average monthly demand variation from the monthly mean [%]

Variants: number of variants of the product procured by the buyer (1 = none, 2 = <5, 3 = <50, 4 = >50, 5 = >500)

Shelf life: time the product procured by the buyer may be stored (1 = days, 2 = weeks, 3 = months, 4 = years, 5 = unlimited)

CODP (supplier / buyer): customer order decoupling point (1 = MTS, 2 = MTO, 3 = PTO)

Organization principle (supplier / buyer, fabrication / assembly): principle according to which production is organized (1 = project shop, 2 = job shop, 3 = group techn., 4 = flow line)

Volume flexibility (supplier): range in which the supplier’s output may be profitably varied (1 = none, 2 = limited, 3 = unlimited):

Distance: transportation time between the supplier’s and the buyer’s facilities (1 = hours, 2 = days, 3 = weeks, 4 = months)

Replenishment principle (buyer / supplier): principle employed for initiating factory orders (1 = push / pull, 2 = pull / push)

11.3 Statistical Results

11.3.1 Kruskal-Wallis Tests Results

11.3.1.1 Grouping Variable Variants

Ranks

Metric variables	Variants	N	Mean rank
Value	none	15	30.40
	<50	24	31.73
	<50	18	28.03
	unlimited	5	46.20
	Total	62	
Demand variation	none	19	31.18
	<50	34	48.50
	<50	26	42.77
	unlimited	5	43.30
	Total	84	
Yearly demand	none	19	42.39
	<50	36	37.01
	<50	20	47.10
	unlimited	5	32.00
	Total	80	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	4.051	6.284	3.221
DoF	3	3	3
Asymp. sig.	0.256	0.099**	0.359

Legend for all following SPSS analyses: * = significant at the 95%-level; ** = significant at the 90%-level

11.3.1.2 Grouping Variable Shelf Life

Ranks

Metric variables	Shelf life	N	Mean rank
Value	weeks	2	15.50
	months	18	33.39
	years	30	38.43
	unlimited	16	26.63
	Total	66	
Demand variation	weeks	3	21.17
	months	31	47.89
	years	33	45.79
	unlimited	20	38.45
	Total	87	
Yearly demand	weeks	3	65.17
	months	29	38.84
	years	31	39.34
	unlimited	21	48.98
	Total	84	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	5.799	4.399	5.245
DoF	3	3	3
Asymp. sig.	0.122	0.221	0.155

11.3.1.3 Grouping Variable CODP – Supplier

Ranks

Metric variables	CODP – supplier	N	Mean rank
Value	MTS	21	28.40
	MTO	26	33.85
	PTO	19	38.66
	Total	66	
Demand variation	MTS	29	41.38
	MTO	33	41.68
	PTO	25	50.10
	Total	87	
Yearly demand	MTS	27	46.17
	MTO	34	46.47
	PTO	23	32.33
	Total	84	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	2.863	2.087	5.515
DoF	2	2	2
Asymp. sig.	0.239	0.352	0.063**

11.3.1.4 Grouping Variable Organization Principle – Supplier

Ranks

Metric variables	Organization principle – supplier	N	Mean rank
Value	project shop	4	48.50
	job shop	8	27.00
	group technology	25	33.66
	flow shop	28	31.91
	Total	65	
Demand variation	project shop	5	66.90
	job shop	9	46.22
	group technology	34	49.59
	flow shop	39	35.68
	Total	87	
Yearly demand	project shop	4	10.25
	job shop	9	39.17
	group technology	35	42.73
	flow shop	35	45.63
	Total	83	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	3.621	10.269	7.894
DoF	3	3	3
Asymp. sig.	0.305	0.016*	0.048*

11.3.1.5 Grouping Variable Volume Flexibility – Supplier

Ranks

Metric variables	Volume flexibility – supplier	N	Mean rank
Value	none	0	-
	limited	60	31.81
	unlimited	4	42.88
	Total	64	
Demand variation	none	1	47.50
	limited	79	41.66
	unlimited	3	49.17
	Total	83	
Yearly demand	none	1	71.50
	limited	76	40.97
	unlimited	4	33.88
	Total	81	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	1.326	0.340	2.049
DoF	1	2	2
Asymp. sig.	0.249	0.844	0.359

11.3.1.6 Grouping Variable CODP – Buyer

Ranks

Metric variables	CODP – buyer	N	Mean rank
Value	MTS	11	19.68
	MTO	29	30.14
	PTO	23	40.24
	Total	63	
Demand variation	MTS	24	35.94
	MTO	35	45.01
	PTO	25	45.28
	Total	84	
Yearly demand	MTS	22	56.02
	MTO	34	40.96
	PTO	28	33.75
	Total	84	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	9.923	2.483	10.506
DoF	2	2	2
Asymp. sig.	0.007*	0.289	0.005*

11.3.1.7 Grouping Variable Organization Principle – Buyer

Ranks

Metric variables	Organization principle – buyer (assembly)	N	Mean rank
Value	project shop	6	42.00
	job shop	3	52.00
	group technology	35	29.03
	flow shop	17	27.47
	Total	61	
Metric variables	Organization principle buyer (assembly)	N	Mean rank
Demand variation	project shop	7	62.79
	job shop	7	37.71
	group technology	49	43.32
	flow shop	17	24.35
	Total	80	
Yearly demand	project shop	7	15.07
	job shop	4	18.25
	group technology	52	42.47
	flow shop	17	50.18
	Total	80	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	7.613	15.767	15.379
DoF	3	3	3
Asymp. sig.	0.055**	0.001*	0.002*

11.3.1.8 Grouping Variable Distance

Ranks

Metric variables	Distance	N	Mean rank
Value	hours	20	26.88
	days	37	36.08
	weeks	9	37.61
	Total	66	
Demand variation	hours	22	40.86
	days	54	44.65
	weeks	11	47.09
	Total	87	
Yearly demand	hours	21	41.60
	days	53	44.42
	weeks	10	34.25
	Total	84	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	3.468	.550	1.500
DoF	2	2	2
Asymp. sig.	0.177	0.760	0.472

11.3.1.9 Grouping Variable Replenishment Principle – Buyer

Ranks

Metric variables	Replenishment principle – buyer (assembly)	N	Mean Rank
Value	push	53	33.25
	pull	8	16.06
	Total	61	
Demand variation	push	68	43.51
	pull	12	23.42
	Total	80	
Yearly demand	push	68	38.08
	pull	12	54.21
	Total	80	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	6.526	7.778	4.916
DoF	1	1	1
Asymp. sig.	0.011*	0.005*	0.027*

11.3.1.10 Grouping Variable Replenishment Principle – Supplier

Ranks

Metric variables	Replenishment principle – supplier	N	Mean rank
Value	pull	17	29.44
	push	49	34.91
	Total	66	
Demand variation	pull	26	45.54
	push	59	41.88
	Total	85	
Yearly demand	pull	20	35.98
	push	62	43.28
	Total	82	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	1.025	0.404	1.424
DoF	1	1	1
Asymp. sig.	0.311	0.525	0.233

11.3.1.11 Grouping Variable Dyad

Ranks

Metric variables	Dyad	N	Mean rank
Value	MTS-MTS	4	22.88
	MTS-MTO	4	23.25
	MTS-PTO	3	10.67
	MTO-MTS	9	21.28
	MTO-MTO	14	31.00
	MTO-PTO	6	41.42
	PTO-MTS	7	34.71
	PTO-MTO	7	40.14
	PTO-PTO	9	44.61
	Total	63	
Demand variation	MTS-MTS	9	28.78
	MTS-MTO	9	42.06
	MTS-PTO	6	37.50
	MTO-MTS	12	49.71
	MTO-MTO	16	34.69
	MTO-PTO	7	60.57
	PTO-MTS	7	37.00
	PTO-MTO	7	49.43
	PTO-PTO	11	47.91
	Total	84	

Metric variables	Dyad	N	Mean rank
Yearly demand	MTS-MTS	9	63.78
	MTS-MTO	9	54.11
	MTS-PTO	4	42.88
	MTO-MTS	10	40.00
	MTO-MTO	17	49.24
	MTO-PTO	7	22.21
	PTO-MTS	8	34.06
	PTO-MTO	8	32.00
	PTO-PTO	12	34.71
	Total	84	

Test Statistics

Results	Value	Demand variation	Yearly demand
Chi-square	16.482	11.320	18.804
DoF	8	8	8
Asymp. sig.	0.036*	0.184	0.016*

11.3.2 Cross Tables and Chi-Square-Tests

11.3.2.1 Variants

Cross table variants vs. shelf life

		Shelf life				Total
		weeks	months	years	unlimited	
	none	1	13	3	5	22
	<50	1	11	14	10	36
	<50	1	7	14	5	27
	unlimited	0	3	2	0	5
Total		3	34	33	20	90

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	11.832	9	0.223
N of valid cases	90		

Cross table variants vs. CODP – supplier

		CODP – supplier			Total
		MTS	MTO	PTO	
Variants	none	8	9	5	22
	<50	14	14	8	36
	<50	7	10	10	27
	unlimited	1	1	3	5
Total		30	34	26	90

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	4.735	6	0.578
N of valid cases	90		

Cross table variants vs. organization principle – supplier

		Organization principle – supplier				Total
		project shop	job shop	group technology	flow shop	
Variants	none	0	3	4	15	22
	<50	3	5	16	12	36
	<50	1	1	15	10	27
	unlimited	1	0	1	3	5
Total		5	9	36	40	90

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	15.496	9	0.078
N of valid cases	90		

Cross table variants vs. volume flexibility – supplier

		Volume flexibility – supplier			Total
		none	limited	unlimited	
Variants	none	0	22	0	22
	<50	1	31	2	34
	<50	0	25	0	25
	unlimited	0	5	0	5
Total		1	83	2	86

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	4.754	6	0.576
N of valid cases	86		

Cross table variants vs. CODP – buyer

		CODP – buyer			Total
		MTS	MTO	PTO	
Variants	none	5	10	7	22
	<50	10	14	12	36
	<50	9	9	6	24
	unlimited	0	2	3	5
Total		24	35	28	87

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	4.236	6	0.645
N of valid cases	87		

Cross table variants vs. organization principle – buyer

		Organization principle – buyer (assembly)				Total
		project shop	job shop	group technology	flow shop	
Variants	none	0	4	12	5	21
	<50	5	2	21	6	34
	<50	2	1	16	5	24
	unlimited	1	0	3	0	4
Total		8	7	52	16	83

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	9.212	9	0.418
N of valid cases	83		

Cross table variants vs. distance

		Distance			Total
		hours	days	weeks	
Variants	none	5	13	4	22
	<50	6	25	5	36
	<50	12	13	2	27
	unlimited	1	4	0	5
Total		24	55	11	90

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	8.064	6	0.233
N of valid cases	90		

Cross table variants vs. replenishment principle – buyer

		Replenishment principle – buyer (assembly)		Total
		push	pull	
Variants	none	18	3	21
	<50	28	6	34
	<50	21	3	24
	unlimited	4	0	4
Total		71	12	83

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	1.031	3	0.794
N of valid cases	83		

Cross table variants vs. replenishment principle – supplier

		Replenishment principle – supplier		Total
		pull	push	
Variants	none	5	16	21
	<50	9	26	35
	<50	9	18	27
	unlimited	2	3	5
Total		25	63	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	0.996	3	0.802
N of valid cases	88		

Cross table variants vs. Dyad

		Dyad									
		MTS-MTS	MTS-MTO	MTS-PTO	MTO-MTS	MTO-MTO	MTO-PTO	PTO-MTS	PTO-MTO	PTO-PTO	Total
Variants	none	2	2	1	4	5	1	2	2	3	22
	<50	4	3	3	6	7	1	4	4	4	36
	<50	3	4	2	1	4	4	2	1	3	24
	unlim.	0	0	0	1	0	1	0	1	2	5
Total		9	9	6	12	16	7	8	8	12	87

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	15.928	24	0.891
N of valid cases	87		

11.3.2.2 Shelf life

Cross table shelf life vs. CODP – supplier

		CODP – supplier			
		MTS	MTO	PTO	Total
Shelf life	weeks	1	2	0	3
	months	10	13	12	35
	years	13	13	10	36
	unlimited	7	8	6	21
Total		31	36	28	95

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	2.205	6	0.900
N of valid cases	95		

Cross table shelf life vs. organization principle – supplier

		Organization principle – supplier				
		project shop	job shop	group technology	flow shop	Total
Shelf life	weeks	0	0	1	2	3
	months	3	1	11	20	35
	years	2	4	20	10	36
	unlimited	0	4	6	10	20
Total		5	9	38	42	94

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	13.503	9	0.141
N of valid cases	94		

Cross table shelf life vs. volume flexibility – supplier

		Volume flexibility			Total
		none	limited	unlimited	
Shelf life	weeks	1	2	0	3
	months	0	35	0	35
	years	0	29	3	32
	unlimited	0	20	1	21
Total		1	86	4	91

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	33.225	6	0.000*
N of valid cases	91		

Directional measures

Measures			Value	Asymp. Std. Error	Approx. T	Approx. sig.
Nominal by Nominal	Lambda	Symmetric	0.066	0.030	2.045	0.041
		Shelf life dependent	0.071	0.034	2.045	0.041
		Volume flexibility dependent	0.000	0.000		
	Goodman and Kruskal tau	Shelf life dependent	0.042	0.012		0.080
		Volume flexibility dependent	0.090	0.090		0.012

Cross table shelf life vs. CODP – buyer

		CODP – buyer			Total
		MTS	MTO	PTO	
Shelf life	weeks	0	3	0	3
	months	8	16	11	35
	years	10	11	12	33
	unlimited	7	8	6	21
Total		25	38	29	92

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	5.944	6	0.430
N of valid cases	92		

Cross table shelf life vs. Organization principle – buyer

		Organization principle – buyer (assembly)				Total
		project shop	job shop	group technology	flow shop	
Shelf life	weeks	0	0	2	1	3
	months	3	3	22	4	32
	years	5	3	17	8	33
	unlimited	0	1	15	4	20
Total		8	7	56	17	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	6.818	9	0.656
N of valid cases	88		

Cross table shelf life vs. distance

		Distance			Total
		hours	days	weeks	
Shelf life	weeks	1	2	0	3
	months	11	19	5	35
	years	9	23	4	36
	unlimited	5	14	2	21
Total		26	58	11	95

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	1.507	6	0.959
N of valid cases	95		

Cross table shelf life vs. replenishment principle – buyer

		Replenishment principle – buyer (assembly)		Total
		push	pull	
Shelf life	weeks	2	1	3
	months	31	1	32
	years	29	4	33
	unlimited	14	6	20
Total		76	12	88

Chi-square-test and symmetric measures

Measures		Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square		8.602	3	0.035
Nominal by	Phi	0.313		0.035
Nominal	Cramer’s V	0.313		0.035
N of valid cases		88		

Directional measures

Measures			Value	Asymp. Std. Error	Approx. T	Approx. sig.
Nominal by Nominal	Lambda	Symmetric	0.060	0.121	0.479	0.632
		Shelf life dependent	0.073	0.146	.479	0.632
		Volume flexibility dependent	0.000	0.000		
	Goodman and Kruskal tau	Shelf life dependent	0.037	0.023		0.022
		Volume flexibility dependent	0.098	0.065		0.037

Cross table shelf life vs. replenishment principle – supplier

		Replenishment principle – supplier		Total
		pull	push	
Shelf life	weeks	0	3	3
	months	12	23	35
	years	7	28	35
	unlimited	7	13	20
Total		26	67	93

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	3.453	3	0.327
N of valid cases	93		

Cross table shelf life vs. dyad

		Dyad									Total
		MTS-MTS	MTS-MTO	MTS-PTO	MTO-MTS	MTO-MTO	MTO-PTO	PTO-MTS	PTO-MTO	PTO-PTO	
Shelf life	weeks	0	0	0	1	2	0	0	0	0	3
	months	2	3	3	6	6	4	2	4	5	35
	years	5	3	2	4	6	1	3	3	6	33
	unlimited	3	3	1	1	4	3	3	1	2	21
Total		10	9	6	12	18	8	8	8	13	92

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	15.336	24	0.911
N of valid cases	92		

11.3.2.3 CODP – Supplier

Cross table CODP – supplier vs. organization principle – supplier

		Organization principle – supplier				Total
		project shop	job shop	group technology	flow shop	
CODP – supplier	MTS	1	3	8	19	31
	MTO	1	3	19	13	36
	PTO	3	3	11	10	27
Total		5	9	38	42	94

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	8.377	6	0.212
N of valid cases	94		

Cross table CODP – supplier vs. volume flexibility

		Volume flexibility			Total
		none	limited	unlimited	
CODP – supplier	MTS	0	29	1	30
	MTO	1	32	2	35
	PTO	0	25	1	26
Total		1	86	4	91

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	1.891	4	0.756
N of valid cases	91		

Cross table CODP – supplier vs. CODP – buyer

		CODP – buyer			Total
		MTS	MTO	PTO	
CODP – supplier	MTS	10	12	8	30
	MTO	9	18	8	35
	PTO	6	8	13	27
Total		25	38	29	92

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	5.888	4	0.208
N of valid cases	92		

Cross table CODP - supplier vs. organizational principle – buyer

		Organization principle – buyer (assembly)				Total
		project shop	job shop	group technology	flow shop	
CODP – supplier	MTS	2	2	20	5	29
	MTO	2	3	22	7	34
	PTO	4	2	14	5	25
Total		8	7	56	17	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	2.388	6	0.881
N of valid cases	88		

Cross table CODP - supplier vs. distance

		Distance			Total
		hours	days	weeks	
CODP – supplier	MTS	4	24	3	31
	MTO	5	26	5	36
	PTO	17	8	3	28
Total		26	58	11	95

Chi-square-test and symmetric measures

Measures		Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square		23.351	4	0.00*
Nominal by	Phi	0.496		0.00*
Nominal	Cramer's V	0.351		0.00*
N of valid cases		95		

Directional measures

Measures			Value	Asymp. Std. Error	Approx. T	Approx. sig.
Nominal by Nominal	Lambda	Symmetric	0.219	0.083	2.403	0.016
		CODP supplier dependent	0.203	0.071	2.651	0.008
		Distance dependent	0.243	0.118	1.832	0.067
	Goodman and Kruskal tau	CODP supplier dependent	0.116	0.046		0.000
		Distance dependent	0.170	0.069		0.000

Cross table CODP – supplier vs. replenishment principle – buyer

		Replenishment principle buyer (assembly)		Total
		push	pull	
CODP – supplier	MTS	24	5	29
	MTO	29	5	34
	PTO	23	2	25
Total		76	12	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	1.027	2	0.598
N of valid cases	88		

Cross table CODP – supplier vs. replenishment principle – supplier

		Replenishment principle – supplier		Total
		pull	push	
CODP – supplier	MTS	13	18	31
	MTO	7	28	35
	PTO	6	21	27
Total		26	67	93

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	4.549	2	0.103
N of valid cases	93		

11.3.2.4 Organizational principle – Supplier

Cross table organizational principle – supplier vs. volume flexibility

		Volume flexibility			Total
		none	limited	unlimited	
Organization principle – supplier	project shop	0	5	0	5
	job shop	0	9	0	9
	group technology	1	31	2	34
	flow shop	0	40	2	42
Total		1	85	4	90

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	2.524	6	0.866
N of valid cases	90		

Cross table organizational principle - supplier vs. CODP – buyer

		CODP – buyer			Total
		MTS	MTO	PTO	
Organization principle – supplier	project shop	0	4	1	5
	job shop	4	3	2	9
	group technology	12	12	12	36
	flow shop	9	18	14	41
Total		25	37	29	91

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	6.400	6	0.380
N of valid cases	91		

Cross table organizational principle – supplier vs. – buyer

		Organization principle – buyer (assembly)				Total
		project shop	job shop	group technology	flow shop	
Organization principle – supplier	project shop	5	0	0	0	5
	job shop	0	1	7	1	9
	group technology	2	1	28	5	36
	flow shop	1	5	20	11	37
Total		8	7	55	17	87

Chi-square-test and symmetric measures

Measures		Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square		60.021	9	0.00*
Nominal by	Phi	0.831		0.00*
Nominal	Cramer's V	0.480		0.00*
N of valid cases		87		

Directional measures

Measures			Value	Asymp. Std. Error	Approx. T	Approx. sig.
Nominal by	Lambda	Symmetric	0.207	0.090	2.098	0.036
Nominal		Organization principle supplier dependent	0.240	0.128	1.659	0.097
		Organization principle buyer dependent	0.156	0.064	2.303	0.021
	Goodman and Kruskal tau	Organization principle supplier dependent	0.124	0.052		0.000
		Organization principle buyer dependent	0.182	0.036		0.000

Cross table organizational principle – supplier vs. distance

		Distance			Total
		hours	days	weeks	
Organization	project shop	1	3	1	5
principle –	job shop	1	7	1	9
supplier	group technology	11	21	6	38
	flow shop	12	27	3	42
Total		25	58	11	94

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	3.299	6	0.770
N of valid cases	94		

Cross table organizational principle – supplier vs. repl. principle – buyer

		Replenishment principle – buyer (assembly)		Total
		push	pull	
Organization	project shop	5	0	5
principle –	job shop	4	5	9
supplier	group technology	34	2	36
	flow shop	32	5	37
Total		75	12	87

Chi-square-test and symmetric measures

Measures		Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square		16.058	3	0.001*
Nominal by	Phi	0.430		0.001*
Nominal	Cramer's V	0.430		0.001*
N of valid cases		87		

Directional measures

Measures			Value	Asymp. Std. Error	Approx. T	Approx. sig.
Nominal by Nominal	Lambda	Symmetric	0.048	0.154	0.308	0.758
		Organization principle supplier dependent	0.040	0.171	0.229	0.818
		Replenishment principle buyer (assembly) dependent	0.083	0.239	0.334	0.739
	Goodman and Kruskal tau	Organization principle supplier dependent	0.041	0.027		0.014
		Replenishment principle buyer (assembly) dependent	0.185	0.112		0.001

Cross table organizational principle – supplier vs. repl. principle – supplier

		Replenishment principle – supplier		Total
		pull	push	
Organization principle – supplier	project shop	0	5	5
	job shop	3	6	9
	group technology	5	32	37
	flow shop	18	23	41
Total		26	66	92

Chi-square-test and symmetric measures

Measures		Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square		11.001	3	0.012*
Nominal by Nominal	Phi	0.346		0.012*
	Cramer's V	0.346		0.012*
N of valid cases		92		

Directional measures

Measures			Value	Asymp. Std. Error	Approx. T	Approx. sig.
Nominal by Nominal	Lambda	Symmetric	0.117	0.091	1.223	0.221
		Organization principle supplier dependent	0.176	0.132	1.223	0.221
		Replenishment principle supplier dependent	0.000	0.000	.	.
	Goodman and Kruskal tau	Organization principle supplier dependent	0.068	0.040		0.000
		Replenishment principle supplier dependent	0.120	0.059		0.012

Cross table organizational principle – supplier vs. repl. principle – dyad

		Dyad									
		MTS - MTS	MTS - MTO	MTS -PTO	MTO - MTS	MTO - MTO	MTO -PTO	PTO- MTS	PTO- MTO	PTO- PTO	Tot.
Organization supplier – principle	project shop	0	0	0	1	1	2	0	0	1	5
	job shop	2	1	1	1	1	1	0	1	1	9
	group technology	3	6	3	2	8	2	2	4	6	36
	flow shop	5	2	2	8	8	2	6	3	5	41
Total		10	9	6	12	18	7	8	8	13	91

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	21.608	24	0.603
N of valid cases	91		

11.3.2.5 Volume Flexibility

Cross table volume flexibility vs. CODP – buyer

		CODP – buyer			
		MTS	MTO	PTO	Total
Volume flexibility	none	0	1	0	1
	limited	24	34	25	83
	unlimited	0	2	2	4
Total		24	37	27	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	3.130	4	0.536
N of valid cases	88		

Cross table volume flexibility vs. organizational principle – buyer

		Organization principle – buyer (assembly)				
		project shop	job shop	group technology	flow shop	Total
Volume flexibility	none	0	0	1	0	1
	limited	7	7	49	16	79
	unlimited	0	0	3	1	4
Total		7	7	53	17	84

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	1.453	6	0.963
N of valid cases	84		

Cross table volume flexibility vs. distance

		Distance			Total
		hours	days	weeks	
Volume flexibility	none	0	1	0	1
	limited	26	49	11	86
	unlimited	0	4	0	4
Total		26	54	11	91

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	3.625	4	0.459
N of valid cases	91		

Cross table volume flexibility vs. replenishment principle – buyer

		Replenishment principle – buyer (assembly)		Total
		push	pull	
Volume flexibility	none	1	0	1
	limited	67	12	79
	unlimited	4	0	4
Total		72	12	84

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	0.886	2	0.642
N of valid cases	84		

Cross table volume flexibility vs. replenishment principle – supplier

		Replenishment principle – supplier		Total
		pull	push	
Volume flexibility	none	0	1	1
	limited	25	60	85
	unlimited	1	3	4
Total		26	64	90

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	0.447	2	0.800
N of valid cases	90		

Cross table volume flexibility vs. dyad

		Dyad									Tot.
		MTS - MTS	MTS - MTO	MTS - PTO	MTO - MTS	MTO - MTO	MTO - PTO	PTO - MTS	PTO - MTO	PTO - PTO	
Volume flexibility	none	0	0	0	0	1	0	0	0	0	1
	limited	10	9	5	12	14	8	6	8	11	83
	unlimited	0	0	0	0	2	0	1	0	1	4
Total		10	9	5	12	17	8	7	8	12	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	10.829	16	0.820
N of valid cases	88		

11.3.2.6 CODP – Buyer

Cross table CODP – buyer vs. organizational principle – buyer

		Organization principle buyer (assembly)				Total
		project shop	job shop	group technology	flow shop	
CODP – buyer	MTS	0	0	18	7	25
	MTO	6	4	21	6	37
	PTO	2	3	17	4	26
Total		8	7	56	17	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	9.113	6	0.167
N of valid cases	88		

Cross table CODP – buyer vs. distance

		Distance			Total
		hours	days	weeks	
CODP – buyer	MTS	6	19	0	25
	MTO	9	22	7	38
	PTO	8	17	4	29
Total		23	58	11	92

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	5.428	4	0.246
N of valid cases	92		

Cross table CODP – buyer vs. replenishment principle – buyer

		Replenishment principle – buyer (assembly)		Total
		push	pull	
CODP – buyer	MTS	15	10	25
	MTO	35	2	37
	PTO	26	0	26
Total		76	12	88

Chi-square-test and symmetric measures

Measures		Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square		20.988	2	0.000*
Nominal by	Phi	0.488		0.000*
Nominal	Cramer’s V	0.488		0.000*
N of valid cases		88		

Directional measures

Measures			Value	Asymp. Std. Error	Approx. T	Approx. sig.
Nominal by Nominal	Lambda	Symmetric	0.127	0.047	2.383	0.017
		CODP buyer dependent	0.157	0.062	2.383	0.017
		Replenishment principle buyer (assembly) dependent	0.000	0.000	.	.
	Goodman and Kruskal tau	CODP buyer dependent	0.109	0.039		0.000
		Replenishment principle buyer (assembly) dependent	0.239	0.095		0.000

Cross table CODP – buyer vs. replenishment principle – supplier

		Replenishment principle – supplier		Total
		pull	push	
CODP – buyer	MTS	8	17	25
	MTO	9	28	37
	PTO	8	20	28
Total		25	65	90

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	0.451	2	0.798
N of valid cases	90		

11.3.2.7 Organizational Principle – Buyer

Cross table organizational principle – buyer vs. distance

		Distance			Total
		hours	days	weeks	
Organization principle – buyer	project shop	2	5	1	8
	job shop	1	4	2	7
	group technology	9	40	7	56
	flow shop	9	7	1	17
Total		21	56	11	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	11.693	6	0.069
N of valid cases	88		

Cross table organizational principle – buyer vs. replen. principle – buyer

		Replenishment principle – buyer (assembly)		Total
		push	pull	
Organization principle – buyer	project shop	8	0	8
	job shop	7	0	7
	group technology	47	9	56
	flow shop	14	3	17
Total		76	12	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	2.883	3	0.410
N of valid cases	88		

Cross table organizational principle – buyer vs. replen. principle – supplier

		Replenishment principle – supplier		Total
		pull	push	
Organization principle – buyer	project shop	1	6	7
	job shop	3	3	6
	group technology	18	38	56
	flow shop	3	14	17
Total		25	61	86

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	3.349	3	0.341
N of valid cases	86		

Cross table organizational principle – buyer vs. dyad

		Dyad									Tot.
		MTS - MTS	MTS - MTO	MTS -PTO	MTO - MTS	MTO - MTO	MTO -PTO	PTO-MTS	PTO-MTO	PTO - PTO	
Organization principle – buyer	project shop	0	0	0	2	2	2	0	0	2	8
	job shop	0	0	0	1	2	1	1	1	1	7
	group technology	7	7	4	8	9	4	5	6	6	56
	flow shop	3	2	2	1	4	1	1	1	2	17
Total		10	9	6	12	17	8	7	8	11	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	14.756	24	0.928
N of valid cases	88		

11.3.2.8 Distance

Cross table distance vs. replenishment principle – buyer

		Replenishment principle – buyer		Total
		push	pull	
Distance	hours	19	2	21
	days	46	10	56
	weeks	11	0	11
Total		76	12	88

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	2.886	2	0.236
N of valid cases	88		

Cross table distance vs. replenishment principle – supplier

		Replenishment principle – supplier		Total
		pull	push	
Distance	hours	5	21	26
	days	19	37	56
	weeks	2	9	11
	Total	26	67	93

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	2.496	2	0.287
N of valid cases	93		

Cross table distance vs. dyad

		Dyad									Tot.
		MTS - MTS	MTS - MTO	MTS - PTO	MTO - MTS	MTO - MTO	MTO - PTO	PTO - MTS	PTO - MTO	PTO - PTO	
Distance	hours	1	1	4	1	3	5	1	0	7	23
	days	9	8	2	8	11	3	7	7	3	58
	weeks	0	0	0	3	4	0	0	1	3	11
Total		10	9	6	12	18	8	8	8	13	92

Chi-square-test and symmetric measures

Measures		Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square		37.086	16	0.002*
Nominal by	Phi	0.635		0.002*
Nominal	Cramer's V	0.449		0.002*
N of valid cases		92		

Directional measures

Measures			Value	Asymp. Std. Error	Approx. T	Approx. sig.
Nominal by Nominal	Lambda	Symmetric	0.111	0.060	1.761	0.078
		Distance dependent	0.235	0.126	1.657	0.097
		Dyade dependent	0.054	0.042	1.276	0.202
	Goodman and Kruskal tau	Distance dependent	0.234	0.068		0.000
		Dyade dependent	0.050	0.013		0.002

11.3.2.9 Replenishment Principle – Buyer

Cross table replenishment principle – buyer vs. replen. principle – supplier

		Replenishment principle supplier		Total
		pull	push	
Replenishment principle – buyer	push	21	53	74
	pull	4	8	12
Total		25	61	86

Chi-square-test

Measures	Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square	0.123	2	0.726
N of valid cases	86		

Cross table replenishment principle – buyer vs. dyad

		Dyad									Tot.
		MTS - MTS	MTS - MTO	MTS -PTO	MTO - MTS	MTO - MTO	MTO -PTO	PTO-MTS	PTO-MTO	PTO-PTO	
Replenishment principle – buyer	push	6	5	4	11	16	8	7	8	11	76
	pull	4	4	2	1	1	0	0	0	0	12
Total		10	9	6	12	17	8	7	8	11	88

Chi-square-test and symmetric measures

Measures		Value	DoF	Asymp. sig. (2-sided)
Pearson chi-square		21.655	16	0.006*
Nominal by Nominal	Phi	0.496		0.006*
	Cramer's V	0.496		0.006*
N of valid cases		88		

Directional measures

Measures			Value	Asymp. Std. Error	Approx. T	Approx. sig.
Nominal by Nominal	Lambda	Symmetric	0.036	0.026	1.356	0.175
		Replenishment principle buyer dependent	0.000	0.000		
		Dyad dependent	0.042	0.031	1.356	0.175
	Goodman and Kruskal tau	Replenishment principle buyer dependent	0.246	0.094		0.006
		Dyad dependent	0.030	0.011		0.008

11.3.2.10 Replenishment Principle – Supplier

		Dyad									
		MTS - MTS	MTS - MTO	MTS - PTO	MTO - MTS	MTO - MTO	MTO - PTO	PTO - MTS	PTO - MTO	PTO - PTO	Tot.
Replenishment principle – supplier	pull	3	3	2	6	1	2	4	3	1	25
	push	7	6	4	6	16	6	4	5	11	65
Total		10	9	6	12	17	8	8	8	12	90

11.4 Methods for Throughput Time Calculation

11.4.1 General Introduction to Queing Theory

When considering queues in the context of queuing theory, one assumes a system with the following structure: Orders (also called customers) arrive with a certain arrival rate at the system, adding themselves to the queue, which might be empty or filled. The system has a certain number of capacities (e.g. machines, clerks) to fulfill those orders. Every time a capacity is finished with one order, it picks a new order out of the queue. The completion of an order takes a certain time, so there can only be one order at a capacity at the same time.

The wide field of queuing theory is usually structured by the mathematical characteristics of the queue, respectively the network of queues to be treated. There are three basic parameters treated in this model that determine the nature of a queue: type of arrival process at the queue, type of completion process at the capacities and number of capacities serving the single queue. The strategy for picking the next customer is always first-come-first-serve and the queues are not limited in length. These parameters are abbreviated with single letters and grouped together, to get a three letter code to identify the type of queue:

Type of arrival process / type of completion process / number of capacities

Here are now only a few possible parameter values listed: The arrival process is determined by its type of distribution: e.g. deterministic (D), Poisson distribution (M) or general independent distribution (GI). The distribution of the service time process can be e.g. deterministic (D), exponentially distributed (M) or generally distributed (G). For the number of capacities it is only important to distinguish between one single capacity and C capacities, since C can be a parameter inside the mathematical solution.

11.4.2 Askin's Method for Throughput Time Calculation

ASKIN (1993) assumes an open network (= unlimited queue capacity between machines) of GI/G/1 queues. The external arrival rate of new orders into the network is exponentially distributed. The following parameters determine completely the specific job-shop problem:

- M: number of capacities (single machines with queue) in the shop
- λ_j : mean external arrival rate of orders at each capacity
- P_{kj} : 2-dimensional array of probabilities for orders to go from one capacity to another after completion (including probability for rework at the same capacity or leaving the network)
- v_j : expected number of visits for one specific product at each capacity for an order before leaving the network
- service time distribution for all products: mean value μ_{j} and squared coefficient of variance $C_{S_j}^2$ at each capacity
- $\mu_{j,p}$: mean value of service time for one specific product at each capacity

An overview of the algorithm by ASKIN 1993 is given in Figure 41.

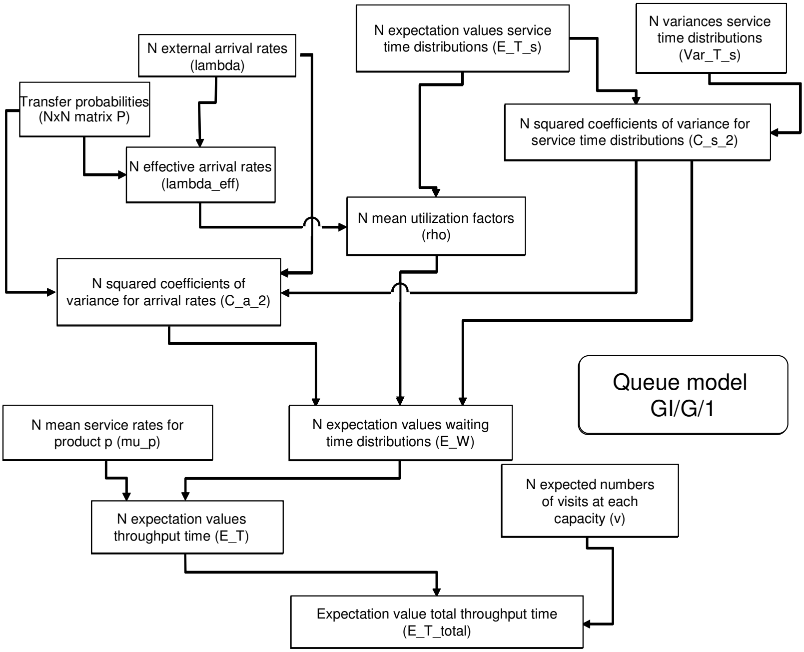


Figure 41: Throughput time calculation according to ASKIN *(1993)*

According to the sketched process, the first step is to calculate the effective arrival rate of orders at each capacity of the job-shop. The effective arrival rate includes the external arrival of new orders into the network and the transfer rate from other capacities with partially fulfilled orders. This is done by solving the equation system

$$\lambda_{eff,j} = \lambda_j + \sum_{k=1}^{M} \lambda_{eff,k}\, p_{k,j} \quad \text{for } 1 \le j \le M \tag{37}$$

The next step calculates the utilization factor of each capacity by

$$\rho_j = \frac{\lambda_{eff,j}}{\mu_j} \quad \text{for } 1 \le j \le M\ . \tag{38}$$

Next, the squared coefficient of variance for the arrival process at each capacity is calculated by solving the linear equation system

$$-\sum_{k=1}^{M}\lambda_{eff,k}\,p_{k,j}^2\left(1-\rho_k^2\right)\cdot C_{a,k}^2+\lambda_{eff,j}C_{a,j}^2=\sum_{k=1}^{M}\lambda_{eff,k}\,p_{k,j}\left(p_{k,j}\rho_k^2C_{S,k}^2+1-p_{k,j}\right)+\lambda_j \tag{39}$$

$$\text{for } 1\le j\le M\,.$$

So far the network as a whole was treated to obtain information about the characteristics of order flow between capacities. Now Jackson's Theorem is used (see ASKIN 1993, pp. 363) to prove that every capacity can be treated as an independent queue. This allows us to calculate the queue characteristics such as waiting time, throughput time or queue length for every capacity separately. For every capacity the expected waiting time in the queue and the throughput time at capacity *j* can be estimated using the approximation

$$E\left(W_q\right)\approx\frac{\rho^2\left(1+C_S^2\right)}{1+\rho^2C_S^2}\cdot\frac{C_a^2+\rho^2C_S^2}{2\lambda(1-\rho)} \tag{40}$$

$$\text{and }\; E(W)=E\left(W_q\right)+\frac{1}{\mu} \tag{41}$$

omitting the indices *j* at every variable in both formulae.

The last step in this procedure is to calculate the total throughput time for a specific order type. This is performed by connecting again the separately treated capacities to form a network. The total throughput time can be calculated by summing up all stations of an order on its route through the job-shop:

$$E\left(T_p\right)=\sum_{j=1}^{M}v_{j,p}\cdot\left(E_j\left(W_q\right)+\frac{1}{\mu_{j,p}}\right) \tag{42}$$

11.4.3 Sainis's Method for Throughput Time Calculation

As the variance of the throughput time can not be calculated using the previous method, a further, but more complex method by SAINIS (1975) is introduced. This method has similar assumptions for the job-shop model as ASKIN's method. An open network of independent capacities is assumed only for well disintegrated job-shops. This means, that the probabilities of order transfer between different capacities are equally distributed. For more details on these assumptions see (SAINIS 1975, chapter 2). The method also applies the Jackson's Theorem to treat the capacities of the network as single queues. The only difference in theory to ASKIN (1993) is, that the M/G/1 queue model is applied, which means that Poisson arrival processes are utilized instead of general processes. In addition, the model of SAINIS (1975) is more aiming for practical use in industrial environments, in contrast to the theoretical approach of ASKIN (1993).

As shown in Figure 42, the first step in this method is to define the mean arrival rate of orders at each capacity. This is simply done by analyzing the production plan for the next period and counting the visits at each capacity of each order, therefore getting $\lambda_{eff,j}$ directly. A similar procedure is used for getting the service time distribution. By coupling the production plan of orders with the work content plan for each product at each capacity, one obtains the service time histograms as explicit distributions for each capacity. From the histograms one can easily get the mean service rates μ_j. Now the mean utilization rates are calculated by

$$\rho_j = \frac{\lambda_j}{\mu_j} \text{ for } 1 \leq j \leq M \tag{43}$$

The next step is to perform a Laplace transformation on every service time distribution $f_s(t)$ to get $L[f_s(t)]$. This transformed distribution can be used to calculate the Laplace transformed distribution of the waiting time distribution at every capacity, assuming a M/G/1 queue model:

$$L\left[f_{w,j}(t)\right] = \frac{(1-\rho_j)\cdot s}{s-\lambda_j\left(1-L\left[f_{s,j}(t)\right]\right)} - (1-\rho_j) \text{ for } 1 \leq j \leq M \tag{44}$$

To get now the total waiting time distribution of the job-shop these single distributions must be convoluted. Inside the Laplace space this yields a simple multiplication of transformed distribution functions:

$$L\left[f_{w,ges}(t)\right] = \prod_{j=1}^{N} \frac{(1-\rho_j)\cdot s}{s-\lambda_j\left(1-L\left[f_{s,j}(t)\right]\right)} - \prod_{j=1}^{N}(1-\rho_j) \tag{45}$$

for N capacities on the route of a product through the job-shop.

This Laplace transformed distribution can now be transformed back, which is usually done numerically to get the true total waiting time distribution (histogram with absolute probabilities P_i for explicit waiting times $t_{w,i}$). From there the mean waiting time can be calculated and be added to the mean service times at every capacity on the job-shop route.

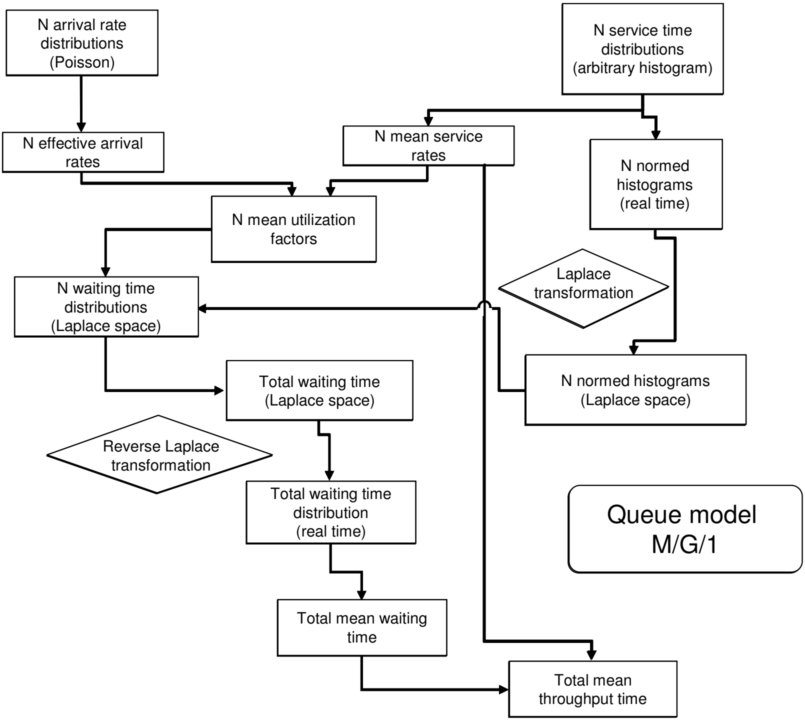


Figure 42: Throughput time calculation according to S*AINIS (1975)*

Mean waiting time:

$$E_W = \frac{\sum_{i=1}^{N} t_{w,i} \cdot P_i}{\sum_{i=1}^{N} P_i} \tag{46}$$

Mean throughput time:

$$E_T = E_W + \sum_{j=1}^{M} \frac{1}{\mu_j} \tag{47}$$

This yields the expected value for the total throughput time for a specific product on its way through fabrication. This value can be used for the System Dynamics model.

11.5 System Dynamics Code

11.5.1 MTS-Supplier

```
ccummulated_Stock(t) = Accummulated_Stock(t - dt) + (daily_Stock) * dt
INIT Accummulated_Stock = 0
daily_Stock = Inventory
Accumulated_LT(t) = Accumulated_LT(t - dt) + (Noname_1) * dt
INIT Accumulated_LT = 0
Noname_1 = LT_orders
Accumulated_TT_Fab_S(t) = Accumulated_TT_Fab_S(t - dt) + (TT_prod_in)
* dt
INIT Accumulated_TT_Fab_S = 0
TT_prod_in = TT_Prod_S
Max_TT(t) = Max_TT(t - dt) + (Diff_TT) * dt
INIT Max_TT = 0
Diff_TT = if LT_orders > Max_TT then (LT_orders-Max_TT) else 0
not_OT(t) = not_OT(t - dt) + (count_not_OT) * dt
INIT not_OT = 0
count_not_OT = if (LT_orders > desired_LT) and (TIME>500) then 1 else
0
Stock_outs(t) = Stock_outs(t - dt) + (Count_a__Stock_out) * dt
INIT Stock_outs = 0
Count_a__Stock_out = if Inventory = 0 then 1 else 0
Delivery_reliability = 1-(not_OT/TIME)
desired_LT = 10
Mean_inventory = Accummulated_Stock/TIME
Mean_LT = Accumulated_LT/TIME
Mean_LT_Production = Accumulated_TT_Fab_S/TIME
First_Order_Backlog_S(t) = First_Order_Backlog_S(t - dt) + (Cus-
tomer_order_rate - Orderfulfillment__Rate_S) * dt
INIT First_Order_Backlog_S = 0
Customer_order_rate = Customer_demand
Orderfulfillment__Rate_S =
max(Inventory/Minimal_Order_Fullfilment_Time_S,Inventory/Lead_time_buy
er)
IFulfilled_orders(t) = IFulfilled_orders(t - dt) + (Orderfulfill-
ment__Rate_S) * dt
INIT IFulfilled_orders = 0
Orderfulfillment__Rate_S =
max(Inventory/Minimal_Order_Fullfilment_Time_S,Inventory/Lead_time_buy
er)
Inventory(t) = Inventory(t - dt) + (End_Rate__Production_S - Deliv-
ery_Rate_S) * dt
INIT Inventory = Desired_Inventory__CO_S
End_Rate__Production_S = CONVEYOR OUTFLOW

      TRANSIT TIME = Throughput_time__distribution_Production
```

```
Delivery_Rate_S = Orderfulfillment__Rate_S
Order_Backlog__Fab_S(t) = Order_Backlog__Fab_S(t - dt) + (Inter-
nal_Order_Acceptance_Rate_S - Order__Rate_Fab_S) * dt
INIT Order_Backlog__Fab_S = 0
Internal_Order_Acceptance_Rate_S = Order_Rate_Components_S
Order__Rate_Fab_S = min(Actual_Capacity_Fab,Stock_Raw__Material_S)
Order_History(t) = Order_History(t - dt) + (Actual_Order_Rate_S - Out-
dated_Orders_S) * dt
INIT Order_History =
100,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100,10
0,100,100,100,100,100,100,100,100,100,100,100,100

      TRANSIT TIME = 30

      INFLOW LIMIT = INF

      CAPACITY = INF
Actual_Order_Rate_S = Delivery_Rate_S
Outdated_Orders_S = CONVEYOR OUTFLOW
Production(t) = Production(t - dt) + (Order__Rate_Fab_S -
End_Rate__Production_S) * dt
INIT Production = 0

      TRANSIT TIME = varies

      INFLOW LIMIT = INF

      CAPACITY = INF
Order__Rate_Fab_S = min(Actual_Capacity_Fab,Stock_Raw__Material_S)
End_Rate__Production_S = CONVEYOR OUTFLOW

      TRANSIT TIME = Throughput_time__distribution_Production
Stock_Raw__Material_S(t) = Stock_Raw__Material_S(t - dt) + (Receiv-
ing_Rate_Raw_Material_S - Consuption_Rate_Raw_Material_S) * dt
INIT Stock_Raw__Material_S = 10*Customer_demand
Receiving_Rate_Raw_Material_S = Consuption_Rate_Raw_Material_S
Consuption_Rate_Raw_Material_S = Order__Rate_Fab_S
Supply_Line_S(t) = Supply_Line_S(t - dt) + (Order_Rate_Components_S -
Delivery_Rate_Components_S) * dt
INIT Supply_Line_S = 0
Order_Rate_Components_S = if Replenishment_principle = 1 then
max(Desired_Internal__Order_Rate_CO_S,Minimal_Order_Rate_S) else if
Replenishment_principle = 2 then
max(Desired_Internal_Order_Rate_DO_S+Adjustment_RateSupply_Line,Minima
l_Order_Rate_S) else 0

Delivery_Rate_Components_S = End_Rate__Production_S
Actual_Capacity_Fab = if Desired_Capacity_Fab < Min_Capacity_Fab then
Min_Capacity_Fab else
if Desired_Capacity_Fab > Max_Capacity_Fab then Max_Capacity_Fab else
Desired_Capacity_Fab
```

```
Adjustment_RateSupply_Line = Missing_Supply__Line/Adustment_time_Supply_Line
Adjustment_Rate_Inventory_S = Missing__Inventory_CO_S/Inventory_adaptation_time
Adustment_time_Supply_Line = 5
Customer_demand = normal(Mean_demand,Demand_variation,1)
Demand_adaptation_time = 2
Demand_variation = 10
Desired_Capacity_Fab = Order_Backlog__Fab_S/LT_production
Desired_Internal_Order_Rate_DO_S = Expected_Order_Rate_S+Inventory_Adjustment_Rate_S
Desired_Internal__Order_Rate_CO_S = Delivery_Rate_S+Adjustment_Rate_Inventory_S
Desired_Inventory__CO_S = (Expected_lead_time*Mean_Order_Rate_S)+(3.09*Standard_Deviation_Order_Rate_S*SQRT(Expected_lead_time))
Desired_Supply_Line = Expected_lead_time*Desired_Internal_Order_Rate_DO_S
Desired__Inventory_DO_S = Expected_Order_Rate_S*Inventory_coverage
Expected_lead_time = 18
Expected_Order_Rate_S = SMTH1(Customer_order_rate,Demand_adaptation_time)
Flexibility__production = 0
Inventory_adaptation_time = 5
Inventory_Adjustment_Rate_S = Missing__Inventory_DO_S/Inventory_adaptation_time
Inventory_coverage = 14
Lead_time_buyer = 10
LT_orders = CYCLETIME(Orderfulfillment__Rate_S)+1
LT_production = 6
Maximal__Inventory_CO = Inventory + Supply_Line_S
Max_Capacity_Fab = (1+Flexibility__production)*Required_Capacity
Mean_demand = 100
Mean_Order_Rate_S = ARRAYMEAN(Order_Rate_History_Array_S[*])
Minimal_Order_Fullfilment_Time_S = 1
Minimal_Order_Rate_S = 0
Min_Capacity_Fab = (1-Flexibility__production)*Required_Capacity
Missing_Supply__Line = Desired_Supply_Line-Supply_Line_S
Missing__Inventory_CO_S = Desired_Inventory__CO_S-Inventory-Supply_Line_S
Missing__Inventory_DO_S = Desired__Inventory_DO_S-Inventory
Orders_on_hand = First_Order_Backlog_S
Order_Rate_History_Array_S[1] = qelem(Order_History,1)...
Order_Rate_History_Array_S[30] = qelem(Order_History,30)
Replenishment_principle = 2
Required_Capacity = Mean_demand
Sigma_LT_Production = 4
Standard_Deviation_Order_Rate_S = ARRAYSTDDEV(Order_Rate_History_Array_S[*])
```

```
Throughput_time__distribution_Production = normal(LT_production,Sigma_LT_Production)
TT_Prod_S = CYCLETIME(End_Rate__Production_S)
```

11.5.2 MTO-Supplier

```
Accumlated_TT_Assy(t) = Accumlated_TT_Assy(t - dt) + (daily_TT) * dtINIT Accumlated_TT_Assy = 0
daily_TT = TT_Assy_S
Accummulated_Stock(t) = Accummulated_Stock(t - dt) + (daily_Stock) * dt
INIT Accummulated_Stock = 0
daily_Stock = Inventory_of_fabricated_parts
Accumulated_TT_Fab_S(t) = Accumulated_TT_Fab_S(t - dt) + (TT_Fab_in) * dt
INIT Accumulated_TT_Fab_S = 0
TT_Fab_in = TT_Fab_S
Max_TT(t) = Max_TT(t - dt) + (Diff_TT) * dt
INIT Max_TT = 0
Diff_TT = if TT_Assy_S > Max_TT then (TT_Assy_S-Max_TT) else 0
not_OT(t) = not_OT(t - dt) + (count_not_OT) * dt
INIT not_OT = 0
count_not_OT = if (TT_Assy_S > desired_LT) and (TIME>500) then 1 else 0
Stock_outs(t) = Stock_outs(t - dt) + (Count_a__Stock_out) * dt
INIT Stock_outs = 0
Count_a__Stock_out = if Inventory_of_fabricated_parts = 0 then 1 else 0
Delivery_reliability = 1-(not_OT/TIME)
desired_LT = 10
Mean_inventory = Accummulated_Stock/TIME
Mean_LT_assembly = Accumlated_TT_Assy/TIME
Mean_LT_fabrication = Accumulated_TT_Fab_S/TIME
Assy_S(t) = Assy_S(t - dt) + (Order_Rate_Assy_S - Delivery_Rate_S) * dt
INIT Assy_S = 0

      TRANSIT TIME = varies

      INFLOW LIMIT = INF

      CAPACITY = INF
Order_Rate_Assy_S = Actual_Capacity_Assy
Delivery_Rate_S = CONVEYOR OUTFLOW

      TRANSIT TIME = Throughput_time_distribution_Assy_S
Fab_S(t) = Fab_S(t - dt) + (Order__Rate_Fab_S - End_Rate__Production_S) * dt
INIT Fab_S = 0
```

```
      TRANSIT TIME = varies
      INFLOW LIMIT = INF

      CAPACITY = INF
Order__Rate_Fab_S = min(Actual_Capacity_Fab,Stock_Raw__Material_S)
End_Rate__Production_S = CONVEYOR OUTFLOW

      TRANSIT TIME = Throughput_time__distribution_Fab_S
Finished_OrderS(t) = Finished_OrderS(t - dt) + (compelted_Order_S) *
dt
INIT Finished_OrderS = 0
compelted_Order_S = Delivery_Rate_S
First_Order_Backlog_S(t) = First_Order_Backlog_S(t - dt) + (Cus-
tomer_order_rate - OrderRelease__Rate_S) * dt
INIT First_Order_Backlog_S = 0
Customer_order_rate = Customer_demand
OrderRelease__Rate_S =
max(Inventory_of_fabricated_parts/Minimal_Order_Fullfilment_Time_S,Inv
entory_of_fabricated_parts/Lead_time_buyer)
Inventory_of_fabricated_parts(t) = Inventory_of_fabricated_parts(t -
dt) + (End_Rate__Production_S - Delivery__Rate_S) * dt
INIT Inventory_of_fabricated_parts = Desired_Inventory__CO_S
End_Rate__Production_S = CONVEYOR OUTFLOW

      TRANSIT TIME = Throughput_time__distribution_Fab_S
Delivery__Rate_S = OrderRelease__Rate_S
In_Process_Orders_S(t) = In_Process_Orders_S(t - dt) + (OrderRe-
lease__Rate_S - compelted_Order_S) * dt
INIT In_Process_Orders_S = 0
OrderRelease__Rate_S =
max(Inventory_of_fabricated_parts/Minimal_Order_Fullfilment_Time_S,Inv
entory_of_fabricated_parts/Lead_time_buyer)
compelted_Order_S = Delivery_Rate_S
Orders_on_hand(t) = Orders_on_hand(t - dt) + (Delivery__Rate_S - Or-
der_Rate_Assy_S) * dt
INIT Orders_on_hand = 0
Delivery__Rate_S = OrderRelease__Rate_S
Order_Rate_Assy_S = Actual_Capacity_Assy
Order_Backlog__Fab_S(t) = Order_Backlog__Fab_S(t - dt) + (Inter-
nal_Order_Acceptance_Rate_S - Order__Rate_Fab_S) * dt
INIT Order_Backlog__Fab_S = 0
Internal_Order_Acceptance_Rate_S = Order_Rate_Components_S
Order__Rate_Fab_S = min(Actual_Capacity_Fab,Stock_Raw__Material_S)
Order_History(t) = Order_History(t - dt) + (Actual_Order_Rate_S - Out-
dated_Orders_S) * dt
INIT Order_History =
100,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100,10
0,100,100,100,100,100,100,100,100,100,100,100,100

      TRANSIT TIME = 30
```

```
      INFLOW LIMIT = INF

      CAPACITY = INF
Actual_Order_Rate_S = Delivery__Rate_S
Outdated_Orders_S = CONVEYOR OUTFLOW
Stock_Raw__Material_S(t) = Stock_Raw__Material_S(t - dt) + (Receiv-
ing_Rate_Raw_Material_S - Consuption_Rate_Raw_Material_S) * dt
INIT Stock_Raw__Material_S = 10*Customer_demand
Receiving_Rate_Raw_Material_S = Consuption_Rate_Raw_Material_S
Consuption_Rate_Raw_Material_S = Order__Rate_Fab_S
Supply_Line_S(t) = Supply_Line_S(t - dt) + (Order_Rate_Components_S -
Delivery_Rate_Components_S) * dt
INIT Supply_Line_S = 0
Order_Rate_Components_S = if Replenishment_principle = 1 then
max(Desired_Internal__Order_Rate_CO_S,Minimal_Order_Rate_S) else if
Replenishment_principle = 2 then
max(Desired_Internal_Order_Rate_DO_S+Adjustment_RateSupply_Line,Minima
l_Order_Rate_S) else 0

Delivery_Rate_Components_S = End_Rate__Production_S
Actual_Capacity_Assy = if Desired_Capacity_Assy < Min_Capacity_Assy
then Min_Capacity_Assy else
if Desired_Capacity_Assy > Max_Capacity_Assy then Max_Capacity_Assy
else
Desired_Capacity_Assy
Actual_Capacity_Fab = if Desired_Capacity_Fab < Min_Capacity_Fab then
Min_Capacity_Fab else
if Desired_Capacity_Fab > Max_Capacity_Fab then Max_Capacity_Fab else
Desired_Capacity_Fab
Adjustment_RateSupply_Line = Miss-
ing_Supply__Line/Adustment_time_Supply_Line
Adjustment_Rate_Inventory_S = Miss-
ing__Inventory_CO_S/Inventory_adaptation_time
Adustment_time_Supply_Line = 5
Customer_demand = normal(Mean_demand,Demand_variation,1)
Demand_adaptation_time = 2
Demand_variation = 10
Desired_Capacity_Assy = Orders_on_hand/LT_assembly
Desired_Capacity_Fab = Order_Backlog__Fab_S/LT_fabrication
Desired_Internal_Order_Rate_DO_S = Ex-
pected_Order_Rate_S+Inventory_Adjustment_Rate_S
Desired_Internal__Order_Rate_CO_S = Deliv-
ery__Rate_S+Adjustment_Rate_Inventory_S
Desired_Inventory__CO_S = (Ex-
pected_lead_time*Mean_Order_Rate_S)+(3.09*Standard_Deviation_Order_Rat
e_S*SQRT(Expected_lead_time))
Desired_Supply_Line = Ex-
pected_lead_time*Desired_Internal_Order_Rate_DO_S
Desired__Inventory_DO_S = Expected_Order_Rate_S*Inventory_coverage
Expected_lead_time = 18
```

```
Expected_Order_Rate_S = SMTH1(Customer_order_rate,Demand_adaptation_time)
Flexibility_assembly = 0
Flexibility__fabrication = 0
Inventory_adaptation_time = 5
Inventory_Adjustment_Rate_S = Missing__Inventory_DO_S/Inventory_adaptation_time
Inventory_coverage = 14
Lead_time_buyer = 10
LT_assembly = 4
LT_fabrication = 6
Maximal__Inventory_CO = Inventory_of_fabricated_parts + Supply_Line_S
Max_Capacity_Assy = (1+Flexibility_assembly)*Required_Capacity
Max_Capacity_Fab = (1+Flexibility__fabrication)*Required_Capacity
Mean_demand = 100
Mean_Order_Rate_S = ARRAYMEAN(Order_Rate_History_Array_S[*])
Minimal_Order_Fullfilment_Time_S = 1
Minimal_Order_Rate_S = 0
Min_Capacity_Assy = (1-Flexibility_assembly)*Required_Capacity
Min_Capacity_Fab = (1-Flexibility__fabrication)*Required_Capacity
Missing_Supply__Line = Desired_Supply_Line-Supply_Line_S
Missing__Inventory_CO_S = Desired_Inventory__CO_S-Inventory_of_fabricated_parts-Supply_Line_S
Missing__Inventory_DO_S = Desired__Inventory_DO_S-Inventory_of_fabricated_parts
Order_Rate_History_Array_S[1] = qelem(Order_History,1)...
Order_Rate_History_Array_S[30] = qelem(Order_History,30)
Replenishment_principle = 2
Required_Capacity = 1.12*Mean_demand
Sigma_of_LT__assemby = 2
Sigma_WBZ__Fertigung = 4
Standard_Deviation_Order_Rate_S = ARRAYSTDDEV(Order_Rate_History_Array_S[*])
Throughput_time_distribution_Assy_S = normal(LT_assembly,Sigma_of_LT__assemby)
Throughput_time__distribution_Fab_S = normal(LT_fabrication,Sigma_WBZ__Fertigung)
TT_Assy_S = CYCLETIME(compelted_Order_S)
TT_Fab_S = CYCLETIME(End_Rate__Production_S)
```

11.5.3 PTO-Supplier

```
Accummulated_Stock(t) = Accummulated_Stock(t - dt) + (daily_Stock) * dt
INIT Accummulated_Stock = 0
daily_Stock = Stock_raw_material
Accumulated_LT(t) = Accumulated_LT(t - dt) + (LT_in) * dt
```

```
INIT Accumulated_LT = 0
LT_in = if LT_orders <> 1 then LT_orders else 0
Accumulated_TT_Fab_S(t) = Accumulated_TT_Fab_S(t - dt) + (TT_prod_in)
* dt
INIT Accumulated_TT_Fab_S = 0
TT_prod_in = TT_Prod_S
Cases(t) = Cases(t - dt) + (CAses_in) * dt
INIT Cases = 0
CAses_in = if TT_prod_in <> 0 then 1 else 0
Deliveries(t) = Deliveries(t - dt) + (Deliveries_in) * dt
INIT Deliveries = 0
Deliveries_in = if LT_in then 1 else 0
Max_TT(t) = Max_TT(t - dt) + (Diff_TT) * dt
INIT Max_TT = 0
Diff_TT = if LT_orders > Max_TT then (LT_orders-Max_TT) else 0
not_OT(t) = not_OT(t - dt) + (count_not_OT) * dt
INIT not_OT = 0
count_not_OT = if (LT_orders > Lead_time_buyer) and (TIME>500) then 1
else 0
Stock_outs(t) = Stock_outs(t - dt) + (Count_a__Stock_out) * dt
INIT Stock_outs = 0
Count_a__Stock_out = if Stock_raw_material = 0 then 1 else 0
Delivery_reliability = if Deliveries > 0 then 1-(not_OT/Deliveries)
else 1
Mean_LT = if Deliveries > 0 then Accumulated_LT/Deliveries else 0
Mean_LT_Production = if Cases > 0 then Accumulated_TT_Fab_S/Cases else
0
Mean_raw_material_inventory = Accummulated_Stock/TIME
Delay_SS(t) = Delay_SS(t - dt) + (Receiving_Rate_Raw_Material_S -
in_Production_SS) * dt
INIT Delay_SS = 10*Customer_demand
Receiving_Rate_Raw_Material_S = Customer_demand
in_Production_SS = DELAY(Receiving_Rate_Raw_Material_S,Transfer_delay)
First_Order_Backlog_S(t) = First_Order_Backlog_S(t - dt) + (Cus-
tomer_order_rate - Orderfulfillment__Rate_S) * dt
INIT First_Order_Backlog_S = 0
Customer_order_rate = Customer_demand
Orderfulfillment__Rate_S = End_Rate__Production_S
Fulfilled_orders(t) = Fulfilled_orders(t - dt) + (Orderfulfill-
ment__Rate_S) * dt
INIT Fulfilled_orders = 0
Orderfulfillment__Rate_S = End_Rate__Production_S
Order_Backlog__Prod_S(t) = Order_Backlog__Prod_S(t - dt) + (Inter-
nal_Order_Acceptance_Rate_S - Order__Rate_Fab_S) * dt
INIT Order_Backlog__Prod_S = 0
Internal_Order_Acceptance_Rate_S = Customer_demand
Order__Rate_Fab_S = min(Actual_Capacity_Fab,Stock_raw_material)
Production_S(t) = Production_S(t - dt) + (Order__Rate_Fab_S -
End_Rate__Production_S) * dt
```

```
INIT Production_S = 0

      TRANSIT TIME = varies

      INFLOW LIMIT = INF

      CAPACITY = INF
Order__Rate_Fab_S = min(Actual_Capacity_Fab,Stock_raw_material)
End_Rate__Production_S = CONVEYOR OUTFLOW

      TRANSIT TIME = Throughput_time__distribution_Production
Production_SS(t) = Production_SS(t - dt) + (in_Production_SS - En-
drate__Production_SS) * dt
INIT Production_SS = 0

      TRANSIT TIME = varies

      INFLOW LIMIT = INF

      CAPACITY = INF
in_Production_SS = DELAY(Receiving_Rate_Raw_Material_S,Transfer_delay)
Endrate__Production_SS = CONVEYOR OUTFLOW

      TRANSIT TIME = Throughput_time_distribution_production_SS
Stock_raw_material(t) = Stock_raw_material(t - dt) + (En-
drate__Production_SS - Cosumed_stock) * dt
INIT Stock_raw_material = 0
Endrate__Production_SS = CONVEYOR OUTFLOW

      TRANSIT TIME = Throughput_time_distribution_production_SS
Cosumed_stock = Order__Rate_Fab_S
Actual_Capacity_Fab = if Desired_Capacity_Production <
Min_Capacity_Fab then Min_Capacity_Fab else
if Desired_Capacity_Production > Max_Capacity_Fab then
Max_Capacity_Fab else
Desired_Capacity_Production
Customer_demand = normal(Mean_demand,Demand_variation,1)
Demand_variation = 10
Desired_Capacity_Production = Order_Backlog__Prod_S/LT_production
Flexibility__production = 0
Lead_time_buyer = 10
LT_orders = CYCLETIME(Orderfulfillment__Rate_S)+1
LT_production = 6
LT_production_SS = 2
Max_Capacity_Fab = (1+Flexibility__production)*Required_Capacity
Mean_demand = 100
Min_Capacity_Fab = (1-Flexibility__production)*Required_Capacity
Orders_on_hand = First_Order_Backlog_S
Required_Capacity = Mean_demand
Sigma_LT_Production = 4
```

```
Sigma_LT_Production_SS = 4
Throughput_time_distribution_production_SS = nor-
mal(LT_production_SS,Sigma_LT_Production_SS)
Throughput_time__distribution_Production = nor-
mal(LT_production,Sigma_LT_Production)
Transfer_delay = 1
TT_Prod_S = CYCLETIME(End_Rate__Production_S)
```

11.6 Utilized Software Products

ithink, version 8.a

isee systems, Inc.
Wheelock office park
31 Old Etna road, Suite 5N
Lebanon, NH 03766, USA
www.isseesystems.com

SPPS, version 14.0

SPPS GmbH Software
Theresienhöhe 13
80339 München, Germany
www.spss.com

iwb Forschungsberichte Band 1–121

Herausgeber: Prof. Dr.-Ing. J. Milberg und Prof. Dr.-Ing. G. Reinhart, Institut für Werkzeugmaschinen und Betriebswissenschaften der Technischen Universität München

Band 1–121 erschienen im Springer Verlag, Berlin, Heidelberg und sind im Erscheinungsjahr und den folgenden drei Kalenderjahren erhältlich im Buchhandel oder durch Lange & Springer, Otto-Suhr-Allee 26–28, 10585 Berlin

1 *Streifinger, E.*
Beitrag zur Sicherung der Zuverlässigkeit und Verfügbarkeit moderner Fertigungsmittel
1986 · 72 Abb. · 167 Seiten · ISBN 3-540-16391-3

2 *Fuchsberger, A.*
Untersuchung der spanenden Bearbeitung von Knochen
1986 · 90 Abb. · 175 Seiten · ISBN 3-540-16392-1

3 *Maier, C.*
Montageautomatisierung am Beispiel des Schraubens mit Industrierobotern
1986 · 77 Abb. · 144 Seiten · ISBN 3-540-16393-X

4 *Summer, H.*
Modell zur Berechnung verzweigter Antriebsstrukturen
1986 · 74 Abb. · 197 Seiten · ISBN 3-540-16394-8

5 *Simon, W.*
Elektrische Vorschubantriebe an NC-Systemen
1986 · 141 Abb. · 198 Seiten · ISBN 3-540-16693-9

6 *Büchs, S.*
Analytische Untersuchungen zur Technologie der Kugelbearbeitung
1986 · 74 Abb. · 173 Seiten · ISBN 3-540-16694-7

7 *Hunzinger, I.*
Schneiderodierte Oberflächen
1986 · 79 Abb. · 162 Seiten · ISBN 3-540-16695-5

8 *Pilland, U.*
Echtzeit-Kollisionsschutz an NC-Drehmaschinen
1986 · 54 Abb. · 127 Seiten · ISBN 3-540-17274-2

9 *Barthelmeß, P.*
Montagegerechtes Konstruieren durch die Integration von Produkt- und Montageprozeßgestaltung
1987 · 70 Abb. · 144 Seiten · ISBN 3-540-18120-2

10 *Reithofer, N.*
Nutzungssicherung von flexibel automatisierten Produktionsanlagen
1987 · 84 Abb. · 176 Seiten · ISBN 3-540-18440-6

11 *Diess, H.*
Rechnerunterstützte Entwicklung flexibel automatisierter Montageprozesse
1988 · 56 Abb. · 144 Seiten · ISBN 3-540-18799-5

12 *Reinhart, G.*
Flexible Automatisierung der Konstruktion und Fertigung elektrischer Leitungssätze
1988 · 112 Abb. · 197 Seiten · ISBN 3-540-19003-1

13 *Bürstner, H.*
Investitionsentscheidung in der rechnerintegrierten Produktion
1988 · 74 Abb. · 190 Seiten · ISBN 3-540-19099-6

14 *Groha, A.*
Universelles Zellenrechnerkonzept für flexible Fertigungssysteme
1988 · 74 Abb. · 153 Seiten · ISBN 3-540-19182-8

15 *Riese, K.*
Klipsmontage mit Industrierobotern
1988 · 92 Abb. · 150 Seiten · ISBN 3-540-19183-6

16 *Lutz, P.*
Leitsysteme für rechnerintegrierte Auftragsabwicklung
1988 · 44 Abb. · 144 Seiten · ISBN 3-540-19260-3

17 *Klippel, C.*
Mobiler Roboter im Materialfluß eines flexiblen Fertigungssystems
1988 · 86 Abb. · 164 Seiten · ISBN 3-540-50468-0

18 *Rascher, R.*
Experimentelle Untersuchungen zur Technologie der Kugelherstellung
1989 · 110 Abb. · 200 Seiten · ISBN 3-540-51301-9

19 *Heusler, H.-J.*
Rechnerunterstützte Planung flexibler Montagesysteme
1989 · 43 Abb. · 154 Seiten · ISBN 3-540-51723-5

20 *Kirchknopf, P.*
Ermittlung modaler Parameter aus Übertragungsfrequenzgängen
1989 · 57 Abb. · 157 Seiten · ISBN 3-540-51724-3

21 *Sauerer, Ch.*
Beitrag für ein Zerspanprozeßmodell Metallbandsägen
1990 · 89 Abb. · 166 Seiten · ISBN 3-540-51868-1

22 *Karstedt, K.*
Positionsbestimmung von Objekten in der Montage- und Fertigungsautomatisierung
1990 · 92 Abb. · 157 Seiten · ISBN 3-540-51879-7

23 *Peiker, St.*
Entwicklung eines integrierten NC-Planungssystems
1990 · 66 Abb. · 180 Seiten · ISBN 3-540-51880-0

24 *Schugmann, R.*
Nachgiebige Werkzeugaufhängungen für die automatische Montage
1990 · 71 Abb. · 155 Seiten · ISBN 3-540-52138-0

25 *Wrba, P.*
Simulation als Werkzeug in der Handhabungstechnik
1990 · 125 Abb. · 178 Seiten · ISBN 3-540-52231-X

26 *Eibelshäuser, P.*
Rechnerunterstützte experimentelle Modalanalyse mittels gestufter Sinusanregung
1990 · 79 Abb. · 156 Seiten · ISBN 3-540-52451-7

27 *Prasch, J.*
Computerunterstützte Planung von chirurgischen Eingriffen in der Orthopädie
1990 · 113 Abb. · 164 Seiten · ISBN 3-540-52543-2

28 *Teich, K.*
Prozeßkommunikation und Rechnerverbund in der Produktion
1990 · 52 Abb. · 158 Seiten · ISBN 3-540-52764-8

29 *Pfrang, W.*
Rechnergestützte und graphische Planung manueller und teilautomatisierter Arbeitsplätze
1990 · 59 Abb. · 153 Seiten · ISBN 3-540-52829-6

30 *Tauber, A.*
Modellbildung kinematischer Strukturen als Komponente der Montageplanung
1990 · 93 Abb. · 190 Seiten · ISBN 3-540-52911-X

31 *Jäger, A.*
Systematische Planung komplexer Produktionssysteme
1991 · 75 Abb. · 148 Seiten · ISBN 3-540-53021-5

32 *Hartberger, H.*
Wissensbasierte Simulation komplexer Produktionssysteme
1991 · 58 Abb. · 154 Seiten · ISBN 3-540-53326-5

33 *Tuczek, H.*
Inspektion von Karosseriepreßteilen auf Risse und Einschnürungen mittels Methoden der Bildverarbeitung
1992 · 125 Abb. · 179 Seiten · ISBN 3-540-53965-4

34 *Fischbacher, J.*
Planungsstrategien zur stömungstechnischen Optimierung von Reinraum-Fertigungsgeräten
1991 · 60 Abb. · 166 Seiten · ISBN 3-540-54027-X

35 *Moser, O.*
3D-Echtzeitkollisionsschutz für Drehmaschinen
1991 · 66 Abb. · 177 Seiten · ISBN 3-540-54076-8

36 *Naber, H.*
Aufbau und Einsatz eines mobilen Roboters mit unabhängiger Lokomotions- und Manipulationskomponente
1991 · 85 Abb. · 139 Seiten · ISBN 3-540-54216-7

37 *Kupec, Th.*
Wissensbasiertes Leitsystem zur Steuerung flexibler Fertigungsanlagen
1991 · 68 Abb. · 150 Seiten · ISBN 3-540-54260-4

38 *Maulhardt, U.*
Dynamisches Verhalten von Kreissägen
1991 · 109 Abb. · 159 Seiten · ISBN 3-540-54365-1

39 *Götz, R.*
Strukturierte Planung flexibel automatisierter Montagesysteme für flächige Bauteile
1991 · 86 Abb. · 201 Seiten · ISBN 3-540-54401-1

40 *Koepfer, Th.*
3D-grafisch-interaktive Arbeitsplanung - ein Ansatz zur Aufhebung der Arbeitsteilung
1991 · 74 Abb. · 126 Seiten · ISBN 3-540-54436-4

41 *Schmidt, M.*
Konzeption und Einsatzplanung flexibel automatisierter Montagesysteme
1992 · 108 Abb. · 168 Seiten · ISBN 3-540-55025-9

42 *Burger, C.*
Produktionsregelung mit entscheidungsunterstützenden Informationssystemen
1992 · 94 Abb. · 186 Seiten · ISBN 3-540-55187-5

43 *Hoßmann, J.*
Methodik zur Planung der automatischen Montage von nicht formstabilen Bauteilen
1992 · 73 Abb. · 168 Seiten · ISBN 3-540-5520-0

44 *Petry, M.*
Systematik zur Entwicklung eines modularen Programmbaukastens für robotergeführte Klebeprozesse
1992 · 106 Abb. · 139 Seiten · ISBN 3-540-55374-6

45 *Schönecker, W.*
Integrierte Diagnose in Produktionszellen
1992 · 87 Abb. · 159 Seiten · ISBN 3-540-55375-4

46 *Bick, W.*
Systematische Planung hybrider Montagesysteme unter Berücksichtigung der Ermittlung des optimalen Automatisierungsgrades
1992 · 70 Abb. · 156 Seiten · ISBN 3-540-55377-0

47 *Gebauer, L.*
Prozeßuntersuchungen zur automatisierten Montage von optischen Linsen
1992 · 84 Abb. · 150 Seiten · ISBN 3-540-55378-9

48 *Schrüfer, N.*
Erstellung eines 3D-Simulationssystems zur Reduzierung von Rüstzeiten bei der NC-Bearbeitung
1992 · 103 Abb. · 161 Seiten · ISBN 3-540-55431-9

49 *Wisbacher, J.*
Methoden zur rationellen Automatisierung der Montage von Schnellbefestigungselementen
1992 · 77 Abb. · 176 Seiten · ISBN 3-540-55512-9

50 *Garnich, F.*
Laserbearbeitung mit Robotern
1992 · 110 Abb. · 184 Seiten · ISBN 3-540-55513-7

51 *Eubert, P.*
Digitale Zustandesregelung elektrischer Vorschubantriebe
1992 · 89 Abb. · 159 Seiten · ISBN 3-540-44441-2

52 *Glaas, W.*
Rechnerintegrierte Kabelsatzfertigung
1992 · 67 Abb. · 140 Seiten · ISBN 3-540-55749-0

53 *Helml, H.J.*
Ein Verfahren zur On-Line Fehlererkennung und Diagnose
1992 · 60 Abb. · 153 Seiten · ISBN 3-540-55750-4

54 *Lang, Ch.*
Wissensbasierte Unterstützung der Verfügbarkeitsplanung
1992 · 75 Abb. · 150 Seiten · ISBN 3-540-55751-2

55 *Schuster, G.*
Rechnergestütztes Planungssystem für die flexibel automatisierte Montage
1992 · 67 Abb. · 135 Seiten · ISBN 3-540-55830-6

56 *Bomm, H.*
Ein Ziel- und Kennzahlensystem zum Investitionscontrolling komplexer Produktionssysteme
1992 · 87 Abb. · 195 Seiten · ISBN 3-540-55964-7

57 *Wendt, A.*
Qualitätssicherung in flexibel automatisierten Montagesystemen
1992 · 74 Abb. · 179 Seiten · ISBN 3-540-56044-0

58 *Hansmaier, H.*
Rechnergestütztes Verfahren zur Geräuschminderung
1993 · 67 Abb. · 156 Seiten · ISBN 3-540-56053-2

59 *Dilling, U.*
Planung von Fertigungssystemen unterstützt durch Wirtschaftssimulationen
1993 · 72 Abb. · 146 Seiten · ISBN 3-540-56307-5

60 *Strohmayr, R.*
Rechnergestützte Auswahl und Konfiguration von Zubringeeinrichtungen
1993 · 80 Abb. · 152 Seiten · ISBN 3-540-56652-X

61 *Glas, J.*
Standardisierter Aufbau anwendungsspezifischer Zellenrechnersoftware
1993 · 80 Abb. · 145 Seiten · ISBN 3.540-56890-5

62 *Stetter, R.*
Rechnergestütze Simulationswerkzeuge zur Effizienzsteigerung des Industrierobotereinsatzes
1994 · 91 Abb. · 146 Seiten · ISBN 3-540-56889-1

63 *Dirndorfer, A.*
Robotersysteme zur förderbandsynchronen Montage
1993 · 76 Abb. · 144 Seiten · ISBN 3-540-57031-4

64 *Wiedemann, M.*
Simulation des Schwingungsverhaltens spanender Werkzeugmaschinen
1993 · 81 Abb. · 137 Seiten · ISBN 3-540-57177-9

65 *Woenckhaus, Ch.*
Rechnergestütztes System zur automatisierten 3D-Layoutoptimierung
1994 · 81 Abb. · 140 Seiten · ISBN 3-540-57284-8

66 *Kummetsteiner, G.*
3D-Bewegungssimulation als integratives Hilfsmittel zur Planung manueller Montagesysteme
1994 · 62 Abb. · 146 Seiten · ISBN 3-540-57535-9

67 *Kugelmann, F.*
Einsatz nachgiebiger Elemente zur wirtschaftlichen Automatisierung von Produktionssystemen
1993 · 76 Abb. · 144 Seiten · ISBN 3-540-57549-9

68 *Schwarz, H.*
Simulationsgestützte CAD/CAM-Kopplung für die 3D-Laserbearbeitung mit integrierter Sensorik
1994 · 96 Abb. · 148 Seiten · ISBN 3-540-57577-4

69 *Viethen, U.*
Systematik zum Prüfen in flexiblen Fertigungssystemen
1994 · 70 Abb. · 142 Seiten · ISBN 3-540-57794-7

70 *Seehuber, M.*
Automatische Inbetriebnahme geschwindigkeitsadaptiver Zustandsregler
1994 · 72 Abb. · 155 Seiten · ISBN 3-540-57896-X

71 *Amann, W.*
Eine Simulationsumgebung für Planung und Betrieb von Produktionssystemen
1994 · 71 Abb. · 129 Seiten · ISBN 3-540-57924-9

72 *Schöpf, M.*
Rechnergestütztes Projektinformations- und Koordinationssystem für das Fertigungsvorfeld
1997 · 63 Abb. · 130 Seiten · ISBN 3-540-58052-2

73 *Welling, A.*
Effizienter Einsatz bildgebender Sensoren zur Flexibilisierung automatisierter Handhabungsvorgänge
1994 · 66 Abb. · 139 Seiten · ISBN 3-540-580-0

74 *Zetlmayer, H.*
Verfahren zur simulationsgestützten Produktionsregelung in der Einzel- und Kleinserienproduktion
1994 · 62 Abb. · 143 Seiten · ISBN 3-540-58134-0

75 *Lindl, M.*
Auftragsleittechnik für Konstruktion und Arbeitsplanung
1994 · 66 Abb. · 147 Seiten · ISBN 3-540-58221-5

76 *Zipper, B.*
Das integrierte Betriebsmittelwesen - Baustein einer flexiblen Fertigung
1994 · 64 Abb. · 147 Seiten · ISBN 3-540-58222-3

77 *Raith, P.*
Programmierung und Simulation von Zellenabläufen in der Arbeitsvorbereitung
1995 · 51 Abb. · 130 Seiten · ISBN 3-540-58223-1

78 *Engel, A.*
Strömungstechnische Optimierung von Produktionssystemen durch Simulation
1994 · 69 Abb. · 160 Seiten · ISBN 3-540-58258-4

79 *Zäh, M. F.*
Dynamisches Prozeßmodell Kreissägen
1995 · 95 Abb. · 186 Seiten · ISBN 3-540-58624-5

80 *Zwanzer, N.*
Technologisches Prozeßmodell für die Kugelschleifbearbeitung
1995 · 65 Abb. · 150 Seiten · ISBN 3-540-58634-2

81 *Romanow, P.*
Konstruktionsbegleitende Kalkulation von Werkzeugmaschinen
1995 · 66 Abb. · 151 Seiten · ISBN 3-540-58771-3

82 *Kahlenberg, R.*
Integrierte Qualitätssicherung in flexiblen Fertigungszellen
1995 · 71 Abb. · 136 Seiten · ISBN 3-540-58772-1

83 *Huber, A.*
Arbeitsfolgenplanung mehrstufiger Prozesse in der Hartbearbeitung
1995 · 87 Abb. · 152 Seiten · ISBN 3-540-58773-X

84 *Birkel, G.*
Aufwandsminimierter Wissenserwerb für die Diagnose in flexiblen Produktionszellen
1995 · 64 Abb. · 137 Seiten · ISBN 3-540-58869-8

85 *Simon, D.*
Fertigungsregelung durch zielgrößenorientierte Planung und logistisches Störungsmanagement
1995 · 77 Abb. · 132 Seiten · ISBN 3-540-58942-2

86 *Nedeljkovic-Groha, V.*
Systematische Planung anwendungsspezifischer Materialflußsteuerungen
1995 · 94 Abb. · 188 Seiten · ISBN 3-540-58953-8

87 *Rockland, M.*
Flexibilisierung der automatischen Teilbereitstellung in Montageanlagen
1995 · 83 Abb. · 168 Seiten · ISBN 3-540-58999-6

88 *Linner, St.*
Konzept einer integrierten Produktentwicklung
1995 · 67 Abb. · 168 Seiten · ISBN 3-540-59016-1

89 *Eder, Th.*
Integrierte Planung von Informationssystemen für rechnergestützte Produktionssysteme
1995 · 62 Abb. · 150 Seiten · ISBN 3-540-59084-6

90 *Deutschle, U.*
Prozeßorientierte Organisation der Auftragsentwicklung in mittelständischen Unternehmen
1995 · 80 Abb. · 188 Seiten · ISBN 3-540-59337-3

91 *Dieterle, A.*
Recyclingintegrierte Produktentwicklung
1995 · 68 Abb. · 146 Seiten · ISBN 3-540-60120-1

92 *Hechl, Chr.*
Personalorientierte Montageplanung für komplexe und variantenreiche Produkte
1995 · 73 Abb. · 158 Seiten · ISBN 3-540-60325-5

93 *Albertz, F.*
Dynamikgerechter Entwurf von Werkzeugmaschinen - Gestellstrukturen
1995 · 83 Abb. · 156 Seiten · ISBN 3-540-60608-8

94 *Trunzer, W.*
Strategien zur On-Line Bahnplanung bei Robotern mit 3D-Konturfolgesensoren
1996 · 101 Abb. · 164 Seiten · ISBN 3-540-60961-X

95 *Fichtmüller, N.*
Rationalisierung durch flexible, hybride Montagesysteme
1996 · 83 Abb. · 145 Seiten · ISBN 3-540-60960-1

96 *Trucks, V.*
Rechnergestützte Beurteilung von Getriebestrukturen in Werkzeugmaschinen
1996 · 64 Abb. · 141 Seiten · ISBN 3-540-60599-8

97 *Schäffer, G.*
Systematische Integration adaptiver Produktionssysteme
1996 · 71 Abb. · 170 Seiten · ISBN 3-540-60958-X

98 *Koch, M. R.*
Autonome Fertigungszellen - Gestaltung, Steuerung und integrierte Störungsbehandlung
1996 · 67 Abb. · 138 Seiten · ISBN 3-540-61104-5

99 *Moctezuma de la Barrera, J.L.*
Ein durchgängiges System zur computer- und rechnergestützten Chirurgie
1996 · 99 Abb. · 175 Seiten · ISBN 3-540-61145-2

100 *Geuer, A.*
Einsatzpotential des Rapid Prototyping in der Produktentwicklung
1996 · 84 Abb. · 154 Seiten · ISBN 3-540-61495-8

101 *Ebner, C.*
Ganzheitliches Verfügbarkeits- und Qualitätsmanagment unter Verwendung von Felddaten
1996 · 67 Abb. · 132 Seiten · ISBN 3-540-61678-0

102 *Pischeltsrieder, K.*
Steuerung autonomer mobiler Roboter in der Produktion
1996 · 74 Abb. · 171 Seiten · ISBN 3-540-61714-0

103 *Köhler, R.*
Disposition und Materialbereitstellung bei komplexen variantenreichen Kleinprodukten
1997 · 62 Abb. · 177 Seiten · ISBN 3-540-62024-9

104 *Feldmann, Ch.*
Eine Methode für die integrierte rechnergestützte Montageplanung
1997 · 71 Abb. · 163 Seiten · ISBN 3-540-62059-1

105 *Lehmann, H.*
Integrierte Materialfluß- und Layoutplanung durch Kopplung von CAD- und Ablaufsimulationssystem
1997 · 96 Abb. · 191 Seiten · ISBN 3-540-62202-0

106 *Wagner, M.*
Steuerungsintegrierte Fehlerbehandlung für maschinennahe Abläufe
1997 · 94 Abb. · 164 Seiten · ISBN 3-540-62656-5

107 *Lorenzen, J.*
Simulationsgestützte Kostenanalyse in produktorientierten Fertigungsstrukturen
1997 · 63 Abb. · 129 Seiten · ISBN 3-540-62794-4

108 *Krönert, U.*
Systematik für die rechnergestützte Ähnlichteilsuche und Standardisierung
1997 · 53 Abb. · 127 Seiten · ISBN 3-540-63338-3

109 *Pfersdorf, I.*
Entwicklung eines systematischen Vorgehens zur Organisation des industriellen Service
1997 · 74 Abb. · 172 Seiten · ISBN 3-540-63615-3

110 *Kuba, R.*
Informations- und kommunikationstechnische Integration von Menschen in der Produktion
1997 · 77 Abb. · 155 Seiten · ISBN 3-540-63642-0

111 *Kaiser, J.*
Vernetztes Gestalten von Produkt und Produktionsprozeß mit Produktmodellen
1997 · 67 Abb. · 139 Seiten · ISBN 3-540-63999-3

112 *Geyer, M.*
Flexibles Planungssystem zur Berücksichtigung ergonomischer Aspekte bei der Produkt- und Arbeitssystemgestaltung
1997 · 85 Abb. · 154 Seiten · ISBN 3-540-64195-5

113 *Martin, C.*
Produktionsregelung - ein modularer, modellbasierter Ansatz
1998 · 73 Abb. · 162 Seiten · ISBN 3-540-64401-6

114 *Löffler, Th.*
Akustische Überwachung automatisierter Fügeprozesse
1998 · 85 Abb. · 136 Seiten · ISBN 3-540-64511-X

115 *Lindermaier, R.*
Qualitätsorientierte Entwicklung von Montagesystemen
1998 · 84 Abb. · 164 Seiten · ISBN 3-540-64686-8

116 *Koehrer, J.*
Prozeßorientierte Teamstrukturen in Betrieben mit Großserienfertigung
1998 · 75 Abb. · 185 Seiten · ISBN 3-540-65037-7

117 *Schuller, R. W.*
Leitfaden zum automatisierten Auftrag von hochviskosen Dichtmassen
1999 · 76 Abb. · 162 Seiten · ISBN 3-540-65320-1

118 *Debuschewitz, M.*
Integrierte Methodik und Werkzeuge zur herstellungsorientierten Produktentwicklung
1999 · 104 Abb. · 169 Seiten · ISBN 3-540-65350-3

119 *Bauer, L.*
Strategien zur rechnergestützten Offline-Programmierung von 3D-Laseranlagen
1999 · 98 Abb. · 145 Seiten · ISBN 3-540-65382-1

120 *Pfob, E.*
Modellgestützte Arbeitsplanung bei Fertigungsmaschinen
1999 · 69 Abb. · 154 Seiten · ISBN 3-540-65525-5

121 *Spitznagel, J.*
Erfahrungsgeleitete Planung von Laseranlagen
1999 · 63 Abb. · 156 Seiten · ISBN 3-540-65896-3

Seminarberichte iwb

herausgegeben von Prof. Dr.-Ing. Gunther Reinhart und Prof. Dr.-Ing. Michael Zäh,
Institut für Werkzeugmaschinen und Betriebswissenschaften
der Technischen Universität München

Seminarberichte iwb sind erhältlich im Buchhandel oder beim
Herbert Utz Verlag, München, Fax 089-277791-01, info@utz.de

1 Innovative Montagesysteme - Anlagengestaltung, -bewertung und -überwachung
115 Seiten · ISBN 3-931327-01-9

2 Integriertes Produktmodell - Von der Idee zum fertigen Produkt
82 Seiten · ISBN 3-931327-02-7

3 Konstruktion von Werkzeugmaschinen - Berechnung, Simulation und Optimierung
110 Seiten · ISBN 3-931327-03-5

4 Simulation - Einsatzmöglichkeiten und Erfahrungsberichte
134 Seiten · ISBN 3-931327-04-3

5 Optimierung der Kooperation in der Produktentwicklung
95 Seiten · ISBN 3-931327-05-1

6 Materialbearbeitung mit Laser · von der Planung zur Anwendung
86 Seiten · ISBN 3-931327-76-0

7 Dynamisches Verhalten von Werkzeugmaschinen
80 Seiten · ISBN 3-931327-77-9

8 Qualitätsmanagement · der Weg ist das Ziel
130 Seiten · ISBN 3-931327-78-7

9 Installationstechnik an Werkzeugmaschinen · Analysen und Konzepte
120 Seiten · ISBN 3-931327-79-5

10 3D-Simulation - Schneller, sicherer und kostengünstiger zum Ziel
90 Seiten · ISBN 3-931327-10-8

11 Unternehmensorganisation - Schlüssel für eine effiziente Produktion
110 Seiten · ISBN 3-931327-11-6

12 Autonome Produktionssysteme
100 Seiten · ISBN 3-931327-12-4

13 Planung von Montageanlagen
130 Seiten · ISBN 3-931327-13-2

14 Nicht erschienen – wird nicht erscheinen

15 Flexible fluide Kleb/Dichtstoffe · Dosierung und Prozeßgestaltung
80 Seiten · ISBN 3-931327-15-9

16 Time to Market - Von der Idee zum Produktionsstart
80 Seiten · ISBN 3-931327-16-7

17 Industriekeramik in Forschung und Praxis - Probleme, Analysen und Lösungen
80 Seiten · ISBN 3-931327-17-5

18 Das Unternehmen im Internet - Chancen für produzierende Unternehmen
165 Seiten · ISBN 3-931327-18-3

19 Leittechnik und Informationslogistik - mehr Transparenz in der Fertigung
85 Seiten · ISBN 3-931327-19-1

20 Dezentrale Steuerungen in Produktionsanlagen - Plug & Play - Vereinfachung von Entwicklung und Inbetriebnahme
105 Seiten · ISBN 3-931327-20-5

21 Rapid Prototyping - Rapid Tooling - Schnell zu funktionalen Prototypen
95 Seiten · ISBN 3-931327-21-3

22 Mikrotechnik für die Produktion - Greifbare Produkte und Anwendungspotentiale
95 Seiten · ISBN 3-931327-22-1

24 EDM Engineering Data Management
195 Seiten · ISBN 3-931327-24-8

25 Rationelle Nutzung der Simulationstechnik - Entwicklungstrends und Praxisbeispiele
152 Seiten · ISBN 3-931327-25-6

26 Alternative Dichtungssysteme · Konzepte zur Dichtungsmontage und zum Dichtmittelauftrag
110 Seiten · ISBN 3-931327-26-4

27 Rapid Prototyping · Mit neuen Technologien schnell vom Entwurf zum Serienprodukt
111 Seiten · ISBN 3-931327-27-2

28 Rapid Tooling · Mit neuen Technologien schnell vom Entwurf zum Serienprodukt
154 Seiten · ISBN 3-931327-28-0

29 Installationstechnik an Werkzeugmaschinen · Abschlußseminar
156 Seiten · ISBN 3-931327-29-9

30 Nicht erschienen – wird nicht erscheinen

31 Engineering Data Management (EDM) · Erfahrungsberichte und Trends
183 Seiten · ISBN 3-931327-31-0

32 Nicht erschienen – wird nicht erscheinen

33 3D-CAD · Mehr als nur eine dritte Dimension
181 Seiten · ISBN 3-931327-33-7

34 Laser in der Produktion · Technologische Randbedingungen für den wirtschaftlichen Einsatz
102 Seiten · ISBN 3-931327-34-5

35 Ablaufsimulation · Anlagen effizient und sicher planen und betreiben
129 Seiten · ISBN 3-931327-35-3

36 Moderne Methoden zur Montageplanung · Schlüssel für eine effiziente Produktion
124 Seiten · ISBN 3-931327-36-1

37 Wettbewerbsfaktor Verfügbarkeit · Produktivitätsteigerung durch technische und organisatorische Ansätze
95 Seiten · ISBN 3-931327-37-X

38 Rapid Prototyping · Effizienter Einsatz von Modellen in der Produktentwicklung
128 Seiten · ISBN 3-931327-38-8

39 Rapid Tooling · Neue Strategien für den Werkzeug- und Formenbau
130 Seiten · ISBN 3-931327-39-6

40 Erfolgreich kooperieren in der produzierenden Industrie · Flexibler und schneller mit modernen Kooperationen
160 Seiten · ISBN 3-931327-40-X

41 Innovative Entwicklung von Produktionsmaschinen
146 Seiten · ISBN 3-89675-041-0

42 Stückzahlflexible Montagesysteme
139 Seiten · ISBN 3-89675-042-9

43 Produktivität und Verfügbarkeit · ...durch Kooperation steigern
120 Seiten · ISBN 3-89675-043-7

44 Automatisierte Mikromontage · Handhaben und Positionieren von Mikrobauteilen
125 Seiten · ISBN 3-89675-044-5

45 Produzieren in Netzwerken · Lösungsansätze, Methoden, Praxisbeispiele
173 Seiten · ISBN 3-89675-045-3

46 Virtuelle Produktion · Ablaufsimulation
108 Seiten · ISBN 3-89675-046-1

47 Virtuelle Produktion · Prozeß- und Produktsimulation
131 Seiten · ISBN 3-89675-047-X
48 Sicherheitstechnik an Werkzeugmaschinen
106 Seiten · ISBN 3-89675-048-8
49 Rapid Prototyping · Methoden für die reaktionsfähige Produktentwicklung
150 Seiten · ISBN 3-89675-049-6
50 Rapid Manufacturing · Methoden für die reaktionsfähige Produktion
121 Seiten · ISBN 3-89675-050-X
51 Flexibles Kleben und Dichten · Produkt-& Prozeßgestaltung, Mischverbindungen, Qualitätskontrolle
137 Seiten · ISBN 3-89675-051-8
52 Rapid Manufacturing · Schnelle Herstellung von Klein- und Prototypenserien
124 Seiten · ISBN 3-89675-052-6
53 Mischverbindungen · Werkstoffauswahl, Verfahrensauswahl, Umsetzung
107 Seiten · ISBN 3-89675-054-2
54 Virtuelle Produktion · Integrierte Prozess- und Produktsimulation
133 Seiten · ISBN 3-89675-054-2
55 e-Business in der Produktion · Organisationskonzepte, IT-Lösungen, Praxisbeispiele
150 Seiten · ISBN 3-89675-055-0
56 Virtuelle Produktion – Ablaufsimulation als planungsbegleitendes Werkzeug
150 Seiten · ISBN 3-89675-056-9
57 Virtuelle Produktion – Datenintegration und Benutzerschnittstellen
150 Seiten · ISBN 3-89675-057-7
58 Rapid Manufacturing · Schnelle Herstellung qualitativ hochwertiger Bauteile oder Kleinserien
169 Seiten · ISBN 3-89675-058-7
59 Automatisierte Mikromontage · Werkzeuge und Fügetechnologien für die Mikrosystemtechnik
114 Seiten · ISBN 3-89675-059-3
60 Mechatronische Produktionssysteme · Genauigkeit gezielt entwickeln
131 Seiten · ISBN 3-89675-060-7
61 Nicht erschienen – wird nicht erscheinen
62 Rapid Technologien · Anspruch – Realität – Technologien
100 Seiten · ISBN 3-89675-062-3
63 Fabrikplanung 2002 · Visionen – Umsetzung – Werkzeuge
124 Seiten · ISBN 3-89675-063-1
64 Mischverbindungen · Einsatz und Innovationspotenzial
143 Seiten · ISBN 3-89675-064-X
65 Fabrikplanung 2003 – Basis für Wachstum · Erfahrungen Werkzeuge Visionen
136 Seiten · ISBN 3-89675-065-8
66 Mit Rapid Technologien zum Aufschwung · Neue Rapid Technologien und Verfahren, Neue Qualitäten, Neue Möglichkeiten, Neue Anwendungsfelder
185 Seiten · ISBN 3-89675-066-6
67 Mechatronische Produktionssysteme · Die Virtuelle Werkzeugmaschine: Mechatronisches Entwicklungsvorgehen, Integrierte Modellbildung, Applikationsfelder
148 Seiten · ISBN 3-89675-067-4
68 Virtuelle Produktion · Nutzenpotenziale im Lebenszyklus der Fabrik
139 Seiten · ISBN 3-89675-068-2
69 Kooperationsmanagement in der Produktion · Visionen und Methoden zur Kooperation – Geschäftsmodelle und Rechtsformen für die Kooperation – Kooperation entlang der Wertschöpfungskette
134 Seiten · ISBN 3-98675-069-0
70 Mechatronik · Strukturdynamik von Werkzeugmaschinen
161 Seiten · ISBN 3-89675-070-4
71 Klebtechnik · Zerstörungsfreie Qualitätssicherung beim flexibel automatisierten Kleben und Dichten
ISBN 3-89675-071-2 · vergriffen
72 Fabrikplanung 2004 Ergfolgsfaktor im Wettbewerb · Erfahrungen – Werkzeuge – Visionen
ISBN 3-89675-072-0 · vergriffen
73 Rapid Manufacturing Vom Prototyp zur Produktion · Erwartungen – Erfahrungen – Entwicklungen
179 Seiten · ISBN 3-89675-073-9
74 Virtuelle Produktionssystemplanung · Virtuelle Inbetriebnahme und Digitale Fabrik
133 Seiten · ISBN 3-89675-074-7
75 Nicht erschienen – wird nicht erscheinen
76 Berührungslose Handhabung · Vom Wafer zur Glaslinse, von der Kapsel zur aseptischen Ampulle
95 Seiten · ISBN 3-89675-076-3
77 ERP-Systeme - Einführung in die betriebliche Praxis · Erfahrungen, Best Practices, Visionen
153 Seiten · ISBN 3-89675-077-7
78 Mechatronik · Trends in der interdisziplinären Entwicklung von Werkzeugmaschinen
155 Seiten · ISBN 3-89675-078-X
79 Produktionsmanagement
267 Seiten · ISBN 3-89675-079-8
80 Rapid Manufacturing · Fertigungsverfahren für alle Ansprüche
154 Seiten · ISBN 3-89675-080-1
81 Rapid Manufacturing · Heutige Trends – Zukünftige Anwendungsfelder
172 Seiten · ISBN 3-89675-081-X
82 Produktionsmanagement · Herausforderung Variantenmanagement
100 Seiten · ISBN 3-89675-082-8
83 Mechatronik · Optimierungspotenzial der Werkzeugmaschine nutzen
160 Seiten · ISBN 3-89675-083-6
84 Virtuelle Inbetriebnahme · Von der Kür zur Pflicht?
104 Seiten · ISBN 978-3-89675-084-6
85 3D-Erfahrungsforum · Innovation im Werkzeug- und Formenbau
375 Seiten · ISBN 978-3-89675-085-3
86 Rapid Manufacturing · Erfolgreich produzieren durch innovative Fertigung
162 Seiten · ISBN 978-3-89675-086-0
87 Produktionsmanagement · Schlank im Mittelstand
102 Seiten · ISBN 978-3-89675-087-7
88 Mechatronik · Vorsprung durch Simulation
134 Seiten · ISBN 978-3-89675-088-4
89 RFID in der Produktion · Wertschöpfung effizient gestalten
122 Seiten · ISBN 978-3-89675-089-1

Forschungsberichte iwb

herausgegeben von Prof. Dr.-Ing. Gunther Reinhart und Prof. Dr.-Ing. Michael Zäh,
Institut für Werkzeugmaschinen und Betriebswissenschaften
der Technischen Universität München

Forschungsberichte iwb ab Band 122 sind erhältlich im Buchhandel oder beim
Herbert Utz Verlag, München, Fax 089-277791-01, info@utz.de

122 Schneider, Burghard
Prozesskettenorientierte Bereitstellung nicht formstabiler Bauteile
1999 · 183 Seiten · 98 Abb. · 14 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-559-5

123 Goldstein, Bernd
Modellgestützte Geschäftsprozeßgestaltung in der Produktentwicklung
1999 · 170 Seiten · 65 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-546-3

124 Mößmer, Helmut E.
Methode zur simulationsbasierten Regelung zeitvarianter Produktionssysteme
1999 · 164 Seiten · 67 Abb. · 5 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-585-4

125 Gräser, Ralf-Gunter
Ein Verfahren zur Kompensation temperaturinduzierter Verformungen an Industrierobotern
1999 · 167 Seiten · 63 Abb. · 5 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-603-6

126 Trossin, Hans-Jürgen
Nutzung der Ähnlichkeitstheorie zur Modellbildung in der Produktionstechnik
1999 · 162 Seiten · 75 Abb. · 11 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-614-1

127 Kugelmann, Doris
Aufgabenorientierte Offline-Programmierung von Industrierobotern
1999 · 168 Seiten · 68 Abb. · 2 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-615-X

128 Diesch, Rolf
Steigerung der organisatorischen Verfügbarkeit von Fertigungszellen
1999 · 160 Seiten · 69 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-618-4

129 Lulay, Werner E.
Hybrid-hierarchische Simulationsmodelle zur Koordination teilautonomer Produktionsstrukturen
1999 · 182 Seiten · 51 Abb. · 14 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-620-6

130 Murr, Otto
Adaptive Planung und Steuerung von integrierten Entwicklungs- und Planungsprozessen
1999 · 178 Seiten · 85 Abb. · 3 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-636-2

131 Macht, Michael
Ein Vorgehensmodell für den Einsatz von Rapid Prototyping
1999 · 170 Seiten · 87 Abb. · 5 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-638-9

132 Mehler, Bruno H.
Aufbau virtueller Fabriken aus dezentralen Partnerverbünden
1999 · 152 Seiten · 44 Abb. · 27 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-645-1

133 Heitmann, Knut
Sichere Prognosen für die Produktionsptimierung mittels stochastischer Modelle
1999 · 146 Seiten · 60 Abb. · 13 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-675-3

134 Blessing, Stefan
Gestaltung der Materialflußsteuerung in dynamischen Produktionsstrukturen
1999 · 160 Seiten · 67 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-690-7

135 Abay, Can
Numerische Optimierung multivariater mehrstufiger Prozesse am Beispiel der Hartbearbeitung von Industriekeramik
2000 · 159 Seiten · 46 Abb. · 5 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-697-4

136 Brandner, Stefan
Integriertes Produktdaten- und Prozeßmanagement in virtuellen Fabriken
2000 · 172 Seiten · 61 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-715-6

137 Hirschberg, Arnd G.
Verbindung der Produkt- und Funktionsorientierung in der Fertigung
2000 · 165 Seiten · 49 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-729-6

138 Reek, Alexandra
Strategien zur Fokuspositionierung beim Laserstrahlschweißen
2000 · 193 Seiten · 103 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-730-X

139 Sabbah, Khalid-Alexander
Methodische Entwicklung störungstoleranter Steuerungen
2000 · 148 Seiten · 75 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-739-3

140 Schliffenbacher, Klaus U.
Konfiguration virtueller Wertschöpfungsketten in dynamischen, heterarchischen Kompetenznetzwerken
2000 · 187 Seiten · 70 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-754-7

141 Sprenzel, Andreas
Integrierte Kostenkalkulationsverfahren für die Werkzeugmaschinenentwicklung
2000 · 144 Seiten · 55 Abb. · 6 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-757-1

142 Gallasch, Andreas
Informationstechnische Architektur zur Unterstützung des Wandels in der Produktion
2000 · 150 Seiten · 69 Abb. · 6 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-781-4

143 Cuiper, Ralf
Durchgängige rechnergestützte Planung und Steuerung von automatisierten Montagevorgängen
2000 · 168 Seiten · 75 Abb. · 3 Tab. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-783-0

144 Schneider, Christian
Strukturmechanische Berechnungen in der Werkzeugmaschinenkonstruktion
2000 · 180 Seiten · 66 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-789-X

145 Jonas, Christian
Konzept einer durchgängigen, rechnergestützten Planung von Montageanlagen
2000 · 183 Seiten · 82 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-870-5

146 Willnecker, Ulrich
Gestaltung und Planung leistungsorientierter manueller Fließmontagen
2001 · 175 Seiten · 67 Abb. · broschiert · 20,5 x 14,5 cm · ISBN 3-89675-891-8

147 Lehner, Christof
Beschreibung des Nd:Yag-Laserstrahlschweißprozesses von Magnesiumdruckguss
2001 · 205 Seiten · 94 Abb. · 24 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0004-X

148 Rick, Frank
Simulationsgestützte Gestaltung von Produkt und Prozess am Beispiel Laserstrahlschweißen
2001 · 145 Seiten · 57 Abb. · 2 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0008-2

149 Höhn, Michael
Sensorgeführte Montage hybrider Mikrosysteme
2001 · 171 Seiten · 74 Abb. · 7 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0012-0

150 Böhl, Jörn
Wissensmanagement im Klein- und mittelständischen Unternehmen der Einzel- und Kleinserienfertigung
2001 · 179 Seiten · 88 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0020-1

151 Bürgel, Robert
Prozessanalyse an spanenden Werkzeugmaschinen mit digital geregelten Antrieben
2001 · 185 Seiten · 60 Abb. · 10 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0021-X

152 Stephan Dürrschmidt
Planung und Betrieb wandlungsfähiger Logistiksysteme in der variantenreichen Serienproduktion
2001 · 914 Seiten · 61 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0023-6

153 Bernhard Eich
Methode zur prozesskettenorientierten Planung der Teilebereitstellung
2001 · 132 Seiten · 48 Abb. · 6 Tabellen · 20,5 x 14,5 cm · ISBN 3-8316-0028-7

154 Wolfgang Rudorfer
Eine Methode zur Qualifizierung von produzierenden Unternehmen für Kompetenznetzwerke
2001 · 207 Seiten · 89 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0037-6

155 Hans Meier
Verteilte kooperative Steuerung maschinennaher Abläufe
2001 · 162 Seiten · 85 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0044-9

156 Gerhard Nowak
Informationstechnische Integration des industriellen Service in das Unternehmen
2001 · 203 Seiten · 95 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0055-4

157 Martin Werner
Simulationsgestützte Reorganisation von Produktions- und Logistikprozessen
2001 · 191 Seiten · 20,5 x 14,5 cm · ISBN 3-8316-0058-9

158 Bernhard Lenz
Finite Elemente-Modellierung des Laserstrahlschweißens für den Einsatz in der Fertigungsplanung
2001 · 150 Seiten · 47 Abb. · 5 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0094-5

159 Stefan Grunwald
Methode zur Anwendung der flexiblen integrierten Produktentwicklung und Montageplanung
2002 · 206 Seiten · 80 Abb. · 25 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0095-3

160 Josef Gartner
Qualitätssicherung bei der automatisierten Applikation hochviskoser Dichtungen
2002 · 165 Seiten · 74 Abb. · 21 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0096-1

161 Wolfgang Zeller
Gesamtheitliches Sicherheitskonzept für die Antriebs- und Steuerungstechnik bei Werkzeugmaschinen
2002 · 192 Seiten · 54 Abb. · 15 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0100-3

162 Michael Loferer
Rechnergestützte Gestaltung von Montagesystemen
2002 · 178 Seiten · 80 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0118-6

163 Jörg Fährer
Ganzheitliche Optimierung des indirekten Metall-Lasersinterprozesses
2002 · 176 Seiten · 69 Abb. · 13 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0124-0

164 Jürgen Höppner
Verfahren zur berührungslosen Handhabung mittels leistungsstarker Schallwandler
2002 · 132 Seiten · 24 Abb. · 3 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0125-9

165 Hubert Götte
Entwicklung eines Assistenzrobotersystems für die Knieendoprothetik
2002 · 258 Seiten · 123 Abb. · 5 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0126-7

166 Martin Weißenberger
Optimierung der Bewegungsdynamik von Werkzeugmaschinen im rechnergestützten Entwicklungsprozess
2002 · 210 Seiten · 86 Abb. · 2 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0138-0

167 Dirk Jacob
Verfahren zur Positionierung unterseitenstrukturierter Bauelemente in der Mikrosystemtechnik
2002 · 200 Seiten · 82 Abb. · 24 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0142-9

168 Ulrich Roßgoderer
System zur effizienten Layout- und Prozessplanung von hybriden Montageanlagen
2002 · 175 Seiten · 20,5 x 14,5 cm · ISBN 3-8316-0154-2

169 Robert Klingel
Anziehverfahren für hochfeste Schraubenverbindungen auf Basis akustischer Emissionen
2002 · 164 Seiten · 89 Abb. · 27 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0174-7

170 Paul Jens Peter Ross
Bestimmung des wirtschaftlichen Automatisierungsgrades von Montageprozessen in der frühen Phase der Montageplanung
2002 · 144 Seiten · 38 Abb. · 38 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0191-7

171 Stefan von Praun
Toleranzanalyse nachgiebiger Baugruppen im Produktentstehungsprozess
2002 · 250 Seiten · 62 Abb. · 7 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0202-6

172 Florian von der Hagen
Gestaltung kurzfristiger und unternehmensübergreifender Engineering-Kooperationen
2002 · 220 Seiten · 104 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0208-5
173 Oliver Kramer
Methode zur Optimierung der Wertschöpfungskette mittelständischer Betriebe
2002 · 212 Seiten · 84 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0211-5
174 Winfried Dohmen
Interdisziplinäre Methoden für die integrierte Entwicklung komplexer mechatronischer Systeme
2002 · 200 Seiten · 67 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0214-X
175 Oliver Anton
Ein Beitrag zur Entwicklung telepräsenter Montagesysteme
2002 · 158 Seiten · 85 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0215-8
176 Welf Broser
Methode zur Definition und Bewertung von Anwendungsfeldern für Kompetenznetzwerke
2002 · 224 Seiten · 122 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0217-4
177 Frank Breitinger
Ein ganzheitliches Konzept zum Einsatz des indirekten Metall-Lasersinterns für das Druckgießen
2003 · 156 Seiten · 20,5 x 14,5 cm · ISBN 3-8316-0227-1
178 Johann von Pieverling
Ein Vorgehensmodell zur Auswahl von Konturfertigungsverfahren für das Rapid Tooling
2003 · 163 Seiten · 88 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0230-1
179 Thomas Baudisch
Simulationsumgebung zur Auslegung der Bewegungsdynamik des mechatronischen Systems Werkzeugmaschine
2003 · 190 Seiten · 67 Abb. · 8 Tab. · 20,5 x 14,5 cm · ISBN 3-8316-0249-2
180 Heinrich Schieferstein
Experimentelle Analyse des menschlichen Kausystems
2003 · 132 Seiten · 20,5 x 14,5 cm · ISBN 3-8316-0251-4
181 Joachim Berlak
Methodik zur strukturierten Auswahl von Auftragsabwicklungssystemen
2003 · 244 Seiten · 20,5 x 14,5 cm · ISBN 3-8316-0258-1
182 Christian Meierlohr
Konzept zur rechnergestützten Integration von Produktions- und Gebäudeplanung in der Fabrikgestaltung
2003 · 181 Seiten · 84 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0292-1
183 Volker Weber
Dynamisches Kostenmanagement in kompetenzzentrierten Unternehmensnetzwerken
2004 · 210 Seiten · 64 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0330-8
184 Thomas Bongardt
Methode zur Kompensation betriebsabhängiger Einflüsse auf die Absolutgenauigkeit von Industrierobotern
2004 · 170 Seiten · 40 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0332-4
185 Tim Angerer
Effizienzsteigerung in der automatisierten Montage durch aktive Nutzung mechatronischer Produktkomponenten
2004 · 180 Seiten · 67 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0336-7
186 Alexander Krüger
Planung und Kapazitätsabstimmung stückzahlflexibler Montagesysteme
2004 · 197 Seiten · 83 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0371-5
187 Matthias Meindl
Beitrag zur Entwicklung generativer Fertigungsverfahren für das Rapid Manufacturing
2005 · 222 Seiten · 97 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0465-7
188 Thomas Fusch
Betriebsbegleitende Prozessplanung in der Montage mit Hilfe der Virtuellen Produktion am Beispiel der Automobilindustrie
2005 · 190 Seiten · 99 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0467-3

189 Thomas Mosandl
Qualitätssteigerung bei automatisiertem Klebstoffauftrag durch den Einsatz optischer Konturfolgesysteme
2005 · 182 Seiten · 58 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0471-1
190 Christian Patron
Konzept für den Einsatz von Augmented Reality in der Montageplanung
2005 · 150 Seiten · 61 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0474-6
191 Robert Cisek
Planung und Bewertung von Rekonfigurationsprozessen in Produktionssystemen
2005 · 200 Seiten · 64 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0475-4
192 Florian Auer
Methode zur Simulation des Laserstrahlschweißens unter Berücksichtigung der Ergebnisse vorangegangener Umformsimulationen
2005 · 160 Seiten · 65 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0485-1
193 Carsten Selke
Entwicklung von Methoden zur automatischen Simulationsmodellgenerierung
2005 · 137 Seiten · 53 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0495-9
194 Markus Seefried
Simulation des Prozessschrittes der Wärmebehandlung beim Indirekten-Metall-Lasersintern
2005 · 216 Seiten · 82 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0503-3
195 Wolfgang Wagner
Fabrikplanung für die standortübergreifende Kostensenkung bei marktnaher Produktion
2006 · 208 Seiten · 43 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0586-6
196 Christopher Ulrich
Erhöhung des Nutzungsgrades von Laserstrahlquellen durch Mehrfach-Anwendungen
2006 · 178 Seiten · 74 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0590-4
197 Johann Härtl
Prozessgaseinfluss beim Schweißen mit Hochleistungsdiodenlasern
2006 · 140 Seiten · 55 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0611-0
198 Bernd Hartmann
Die Bestimmung des Personalbedarfs für den Materialfluss in Abhängigkeit von Produktionsfläche und -menge
2006 · 208 Seiten · 105 Abb. · 20,5 x 14,5 cm · ISBN 3-8316-0615-3
199 Michael Schilp
Auslegung und Gestaltung von Werkzeugen zum berührungslosen Greifen kleiner Bauteile in der Mikromontage
2006 · 130 Seiten · 20,5 x 14,5 cm · ISBN 3-8316-0631-5
200 Florian Manfred Grätz
Teilautomatische Generierung von Stromlauf- und Fluidplänen für mechatronische Systeme
2006 · 192 Seiten · 20,5 x 14,5 cm · ISBN 3-8316-0643-9
201 Dieter Eireiner
Prozessmodelle zur statischen Auslegung von Anlagen für das Friction Stir Welding
2006 · 214 Seiten · 20,5 x 14,5 cm · ISBN 3-8316-0650-1
202 Gerhard Volkwein
Konzept zur effizienten Bereitstellung von Steuerungsfunktionalität für die NC-Simulation
2007 · 192 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0668-9
203 Sven Roeren
Komplexitätsvariable Einflussgrößen für die bauteilbezogene Struktursimulation thermischer Fertigungsprozesse
2007 · 224 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0680-1
204 Henning Rudolf
Wissensbasierte Montageplanung in der Digitalen Fabrik am Beispiel der Automobilindustrie
2007 · 200 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0697-9
205 Stella Clarke-Griebsch
Overcoming the Network Problem in Telepresence Systems with Prediction and Inertia
2007 · 150 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0701-3
206 Michael Ehrenstraßer
Sensoreinsatz in der telepräsenten Mikromontage
2008 · 160 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0743-3

207 Rainer Schack
Methodik zur bewertungsorientierten Skalierung der Digitalen Fabrik
2008 · 248 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0748-8

208 Wolfgang Sudhoff
Methodik zur Bewertung standortübergreifender Mobilität in der Produktion
2008 · 276 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0749-5

209 Stefan Müller
Methodik für die entwicklungs- und planungsbegleitende Generierung und Bewertung von Produktionsalternativen
2008 · 240 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0750-1

210 Ulrich Kohler
Methodik zur kontinuierlichen und kostenorientierten Planung produktionstechnischer Systeme
2008 · 232 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0753-2

211 Klaus Schlickenrieder
Methodik zur Prozessoptimierung beim automatisierten elastischen Kleben großflächiger Bauteile
2008 · 204 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0776-1

212 Niklas Möller
Bestimmung der Wirtschaftlichkeit wandlungsfähiger Produktionssysteme
2008 · 260 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0778-5

213 Daniel Siedl
Simulation des dynamischen Verhaltens von Werkzeugmaschinen während Verfahrbewegungen
2008 · 200 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0779-2

214 Dirk Ansorge
Auftragsabwicklung in heterogenen Produktionsstrukturen mit spezifischen Planungsfreiräumen
2008 · 146 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0785-3

215 Georg Wünsch
Methoden für die virtuelle Inbetriebnahme automatisierter Produktionssysteme
2008 · 224 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0795-2

216 Thomas Oertli
Strukturmechanische Berechnung und Regelungssimulation von Werkzeugmaschinen mit elektromechanischen Vorschubantrieben
2008 · 194 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0798-3

217 Bernd Petzold
Entwicklung eines Operatorarbeitsplatzes für die telepräsente Mikromontage
2008 · 234 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0805-8

218 Loucas Papadakis
Simulation of the Structural Effects of Welded Frame Assemblies in Manufacturing Process Chains
2008 · 260 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0813-3

219 Mathias Mörtl
Ressourcenplanung in der variantenreichen Fertigung
2008 · 210 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0820-1

220 Sebastian Weig
Konzept eines integrierten Risikomanagements für die Ablauf- und Strukturgestaltung in Fabrikplanungsprojekten
2008 · 232 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0823-2

221 Tobias Hornfeck
Laserstrahlbiegen komplexer Aluminiumstrukturen für Anwendungen in der Luftfahrtindustrie
2008 · 150 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0826-3

222 Hans Egermeier
Entwicklung eines Virtual-Reality-Systems für die Montagesimulation mit kraftrückkoppelnden Handschuhen
2008 · 210 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0833-1

223 Matthäus Sigl
Ein Beitrag zur Entwicklung des Elektronenstrahlsinterns
2008 · 185 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0841-6

224 Mark Harfensteller
Eine Methodik zur Entwicklung und Herstellung von Radiumtargets
2009 · 196 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0849-8
225 Jochen Werner
Methode zur roboterbasierten förderbandsynchronen Fließmontage am Beispiel der Automobilindustrie
2009 · 210 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0857-7
226 Florian Hagemann
Ein formflexibles Werkzeug für das Rapid Tooling beim Spritzgießen
2009 · 226 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0861-4
227 Haitham Rashidy
Knowledge-based quality control in manufacturing processes with application to the automotive industry
2009 · 212 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0862-1
228 Wolfgang Vogl
Eine interaktive räumliche Benutzerschnittstelle für die Programmierung von Industrierobotern
2009 · 200 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0869-0
229 Sonja Schedl
Integration von Anforderungsmanagement in den mechatronischen Entwicklungsprozess
2009 · 160 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0874-4
230 Andreas Trautmann
Bifocal Hybrid Laser Welding – A Technology for Welding of Aluminium and Zinc-Coated Steels
2009 · 268 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0876-8
231 Patrick Neise
Managing Quality and Delivery Reliability of Suppliers by Using Incentives and Simulation Models
2009 · 226 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0878-2
232 Christian Habicht
Einsatz und Auslegung zeitfensterbasierter Planungssysteme in überbetrieblichen Wertschöpfungsketten
2009 · 200 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0891-1
233 Michael Spitzweg
Methode und Konzept für den Einsatz eines physikalischen Modells in der Entwicklung von Produktionsanlagen
2009 · 180 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0931-4
234 Ulrich Munzert
Bahnplanungsalgorithmen für das robotergestützte Remote-Laserstrahlschweißen
2010 · 160 Seiten · 20,5 x 14,5 cm · ISBN 978-3-8316-0948-2