Demand and lead time uncertainty in business logistics increase, but can be mitigated by risk pooling. Risk pooling can reduce costs for a given service level, which is especially valuable in the current economic downturn. The extensive, but fragmented and inconsistent risk pooling literature has grown particularly in the last years. It mostly deals with specific mathematical models, does not compare the various risk pooling methods in terms of their suitability for specific conditions, and has not produced a tool for choosing among these methods yet.

Therefore, for the first time, this treatise presents (1) a comprehensive and concise definition of risk pooling distinguishing between variability, uncertainty, and risk, (2) a classification, characterization, and juxtaposition of risk pooling methods in business logistics on the basis of value activities and their uncertainty reduction abilities, (3) a decision support tool to choose between risk pooling methods based on a contingency approach, (4) an application of risk pooling methods at a German paper wholesaler, and (5) a survey on the knowledge and utilization of risk pooling concepts and their associations in 102 German manufacturing and trading companies.
Methods of Risk Pooling in Business Logistics and Their Application

Inaugural dissertation

zur Erlangung des akademischen Grades „Doktor der Wirtschaftswissenschaften“
(Dr. rer. pol.)

eingereicht an der
Wirtschaftswissenschaftlichen Fakultät
der Europa-Universität Viadrina
in Frankfurt (Oder)
im September 2010

von

Gerald Oeser
Frankfurt (Oder)
“Uncertainty is the only certainty there is, and knowing how to live with insecurity is the only security.”

John Allen Paulos,
Professor of Mathematics at Temple University in Philadelphia
To my brother,
who never failed to support me
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Finally, I thank my father for constantly pushing and financially supporting me and proofreading my thesis.
Geleitwort


Es ließen sich viele weitere Vorzüge des hier veröffentlichten Werkes nennen. Es soll an dieser Stelle jedoch dem Leser überlassen bleiben sich ein Urteil zu bilden. Herr Oeser bietet dem Leser mit seiner Dissertation auf jeden Fall keine „leichte Kost“, denn der behandelte Gegenstand lässt eine oberflächliche Betrachtung nicht zu.


Prof. Dr. Dr. h.c. Knut Richter
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**List of Abbreviations, Signs, and Symbols**

Common general, business, logistics, supply chain management (SCM), operations research (OR), mathematical, and statistical abbreviations, signs, and symbols apply¹ and are not listed here.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>component commonality</td>
</tr>
<tr>
<td>CE</td>
<td>consolidation effect</td>
</tr>
<tr>
<td>CO</td>
<td>centralized ordering</td>
</tr>
<tr>
<td>COE</td>
<td>centralized ordering effect</td>
</tr>
<tr>
<td>COV</td>
<td>coefficient of variation of demand</td>
</tr>
<tr>
<td>CP</td>
<td>capacity pooling</td>
</tr>
<tr>
<td>CS</td>
<td>cycle stock</td>
</tr>
<tr>
<td>Dipl.-Kfm.</td>
<td>Diplomkaufmann (MBA equivalent)</td>
</tr>
<tr>
<td>DP</td>
<td>demand pooling</td>
</tr>
<tr>
<td>DUR</td>
<td>demand uncertainty reduction</td>
</tr>
<tr>
<td>EFR</td>
<td>effective fill rate for the customer</td>
</tr>
<tr>
<td>ELT</td>
<td>emergency lateral transshipment</td>
</tr>
<tr>
<td>EOS</td>
<td>economies of scale</td>
</tr>
<tr>
<td>FR</td>
<td>item fill rate</td>
</tr>
<tr>
<td>IC</td>
<td>inventory holding cost</td>
</tr>
<tr>
<td>i. i. d.</td>
<td>independent and identically distributed</td>
</tr>
<tr>
<td>IP</td>
<td>inventory pooling</td>
</tr>
<tr>
<td>ITO</td>
<td>in terms of</td>
</tr>
<tr>
<td>LP</td>
<td>lead time pooling</td>
</tr>
<tr>
<td>LT</td>
<td>lead time</td>
</tr>
<tr>
<td>LTUR</td>
<td>lead time or lead time uncertainty reduction</td>
</tr>
<tr>
<td>n. e. c.</td>
<td>not elsewhere classified</td>
</tr>
<tr>
<td>NLT</td>
<td>endogenous lead times</td>
</tr>
<tr>
<td>OP</td>
<td>order policy</td>
</tr>
<tr>
<td>OS</td>
<td>order splitting</td>
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</table>

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCE</td>
<td>portfolio cost effect</td>
</tr>
<tr>
<td>PE</td>
<td>portfolio effect</td>
</tr>
<tr>
<td>PM</td>
<td>postponement</td>
</tr>
<tr>
<td>PoD</td>
<td>point of (product) differentiation</td>
</tr>
<tr>
<td>PP</td>
<td>product pooling</td>
</tr>
<tr>
<td>PQE</td>
<td>portfolio quantity effect</td>
</tr>
<tr>
<td>PRE</td>
<td>proportional reduction of error</td>
</tr>
<tr>
<td>PS</td>
<td>product substitution</td>
</tr>
<tr>
<td>RMSE</td>
<td>root mean square error</td>
</tr>
<tr>
<td>RPDST</td>
<td>risk pooling decision support tool</td>
</tr>
<tr>
<td>RS</td>
<td>regular stock</td>
</tr>
<tr>
<td>SL</td>
<td>transshipment sending location</td>
</tr>
<tr>
<td>SLA</td>
<td>service level adjustment</td>
</tr>
<tr>
<td>sqrt</td>
<td>square root</td>
</tr>
<tr>
<td>SRL</td>
<td>square root law</td>
</tr>
<tr>
<td>SS</td>
<td>safety stock</td>
</tr>
<tr>
<td>TC</td>
<td>transportation cost</td>
</tr>
<tr>
<td>TS</td>
<td>transshipments</td>
</tr>
<tr>
<td>TSC</td>
<td>transshipment cost</td>
</tr>
<tr>
<td>VP</td>
<td>virtual pooling</td>
</tr>
<tr>
<td>vs.</td>
<td>versus, here: is traded off against</td>
</tr>
<tr>
<td>XLT</td>
<td>exogenous lead times</td>
</tr>
<tr>
<td>≈</td>
<td>is approximately equal to</td>
</tr>
<tr>
<td>&gt;</td>
<td>is preferred to</td>
</tr>
</tbody>
</table>
Abstract

**Purpose/topicality:** Demand and lead time uncertainty in business logistics increase, but can be mitigated by risk pooling. Risk pooling can reduce costs for a given service level, which is especially valuable in the current economic downturn. The extensive, but fragmented and inconsistent risk pooling literature has grown particularly in the last years. It mostly deals with specific mathematical models and does not compare the various risk pooling methods in terms of their suitability for specific conditions.

**Approach:** Therefore this treatise provides an integrated review of research on risk pooling, notably on inventory pooling and the square root law, according to a value-chain structure. It identifies ten major risk pooling methods and develops tools to compare and choose between them for different economic conditions following a contingency approach. These tools are applied to a German paper merchant wholesaler, which suffers from customer demand and supplier lead time uncertainty. Finally, a survey explores the knowledge and usage of the various risk pooling concepts and their associations in 102 German manufacturing and trading companies. Triangulation (combining literature, example, modeling, and survey research) enhances our investigation.

**Originality/value:** For the first time this research presents (1) a comprehensive and concise definition of risk pooling distinguishing between variability, uncertainty, and risk, (2) a classification, characterization, and juxtaposition of risk pooling methods in business logistics on the basis of value activities and their uncertainty reduction abilities, (3) a decision support tool to choose between risk pooling methods based on a contingency approach, (4) an application of risk pooling methods at a German paper wholesaler, and (5) a survey on the knowledge and utilization of risk pooling concepts and their associations in 102 German manufacturing and trading companies.
1 Introduction

1.1 Problem: Growing Uncertainty in Business Logistics and Need for a Tool to Choose Among Risk Pooling Countermeasures

Product variety has increased dramatically in almost every industry particularly due to increased customization. Product life cycles have become shorter, demand fluctuations more rapid, and products can be found and compared easily on the internet.

This causes difficulties in forecasting for an increased number of products, demand and lead time uncertainty, intensified pressure for product availability, and higher inventory levels to provide the same service. This trend is expected to continue and likely grow worse.

Supply chains are more susceptible to disturbances today because of their globalization, increased dependence on outsourcing and partnerships, single sourcing, little leeway in the supply chain, and increasing global competition. Disruptions, such as production or shipment delays, affect profitability (growth in operating income, sales, costs, assets, and inventory).

Risk pooling is “one of the most powerful tools used to address [demand and/or lead time] variability in the supply chain” particularly in a period of economic downturn, as it allows to reduce costs and to increase competitiveness.

---

5 Dubelaar et al. (2001: 96).
7 Cecere and Keltz (2008).
8 “A supply chain consists of all parties involved, directly or indirectly, in fulfilling a customer request. The supply chain includes not only the manufacturer and suppliers, but also transporters, warehouses, retailers, and even customers themselves” (Chopra and Meindl 2007: 3).
9 Dilts (2005: 21). These ideas of Professor David M. Dilts, Owen Graduate School of Management, Vanderbilt University, have not appeared in a formal publication yet. He granted us permission to cite them as personal correspondence on July 23, 2008.
11 Simchi-Levi et al. (2008: 48). We will differentiate between the often confused terms variability, uncertainty, and risk in section 2.3.
Although “risk pooling is often central to many recent operational innovations and strategies”\(^{13}\), an important concept in business logistics and supply chain management (SCM)\(^{14}\), and was already described in logistics in 1967\(^ {15}\), it is mentioned in few German text books\(^ {16}\) mostly limited to the square root law (SRL). Most other publications also only consider inventory pooling\(^ {17}\) or a single other type\(^ {18}\) of risk pooling\(^ {19}\). Exceptions are Neale et al. (2003: 44f., 50, 55), Fleischmann et al. (2004: 70, 93), Taylor (2004: 301ff.), Muckstadt (2005: 150ff.), Reiner (2005: 434), Anupindi et al. (2006), Heil (2006), Brandimarte and Zotteri (2007: 30, 36, 38, 39, 57, 58, 70), Sheffi (2007), Simchi-Levi et al. (2008), Sobel (2008: 172), Van Mieghem (2008), Cachon and Terwiesch (2009), and Bidgoli (2010).

Our survey of 102 German manufacturing and trading companies of various sizes and industries (see appendix A\(^ {20}\)) showed that the different risk pooling concepts are known fairly well, but not widely applied despite their potential benefits. Choosing risk pooling methods is difficult for companies, as the literature does not compare the various methods in terms of their suitability for certain conditions holistically.\(^ {21}\) Most of the work in risk

\(^{13}\) Cachon and Terwiesch (2009: 350).
\(^{15}\) Flaks (1967: 266).
\(^{18}\) A type is “a category of […] things having common characteristics” (Soanes and Hawker 2008). We distinguish ten main types of risk pooling that have in common that they may reduce total demand and/or lead time variability and thus uncertainty and risk by pooling individual demand and/or lead time variabilities. We call them methods (e.g. in the title of this treatise), whenever we focus on the ways of risk pooling, as a method is “a way of doing something” (Soanes and Hawker 2008). If the focus is on choosing and implementing one or several risk pooling methods for a specific company under specific conditions, we refer to this as risk pooling strategy. A strategy is “a plan designed to achieve a particular long-term aim” (Soanes and Hawker 2008). In the case of risk pooling this plan can comprise one or more risk pooling methods combined in order to reduce demand and/or lead time uncertainty. We use the term concept, if we aim at the “abstract idea” (Soanes and Hawker 2008) and would like to include the SRL, PE, and inventory turnover curve, which are rather tools to measure the risk pooling effect on inventories than risk pooling methods.
\(^{20}\) For the sake of readability and content unity we placed the survey in the appendix.
\(^{21}\) However, Evers (1999) compares inventory centralization, transshipments, and order splitting. Swaminathan (2001) designs a framework for deciding between part and procurement standardization (component commonality), process standardization ( postponement), and product standardization (substitution) according to product and process modularity, Wanke and Saliby (2009: 690) one for choosing between inventory centralization (demand pooling) and regular transshipments (“serving […] demands from all centralized facilities” and enabling demand and lead time pooling). Benjaafar et al. (2004a, 2005) find in systems with endogenous supply lead times, multisourcing (Benjaafar et al. 2004a: 1441f., 1446) and capacity pooling (Benjaafar et al. 2005: 550, 563) perform better than inventory pooling, if utilization (arrival rate divided by service rate) is high. Eynan and Fouque (2005) show that demand reshape is more efficient than component commonality.
pooling is rather focused on one aspect and holistic treatments are rare.\textsuperscript{22} There is little empirical and – to our knowledge – no survey research on the various methods of risk pooling combined. Most publications develop mathematical models for a specific risk pooling method under certain assumptions and (optimal inventory) policies that minimize inventory for a given service level or maximize service level for a given inventory. They do not explore whether this risk pooling method is the best for the given situation or whether it can be combined with other ones.

### 1.2 Objective

Thus the objective of this treatise is to advance research on and aid practice in selecting and applying risk pooling methods in business logistics. More specifically, the aims of this research can be formulated as follows:

1. Develop the first comprehensive and concise definition of risk pooling.
2. Critically review and structure the research on risk pooling within a value-chain framework according to this definition.
3. Develop tools to compare and choose appropriate risk pooling methods and models for different economic conditions with a contingency approach.
4. Apply these tools to a German paper merchant wholesaler, which faces customer demand and supplier lead time uncertainty.
5. Examine the knowledge and usage of the various risk pooling concepts and their associations in 102 German trading and manufacturing companies by means of a survey.

### 1.3 Object and Method

The research object (German: Erfahrungsgegenstand) is an empirical phenomenon (a part of reality) that is to be described. The scientific object or selection principle (German: Erkenntnisgegenstand) is the perspective and specific question used to examine the research object.\textsuperscript{23}

Our research object comprises business logistics in a company that experiences demand and/or lead time uncertainty. Our scientific object is risk pooling that can decrease this uncertainty of the company, which is perceived as a collection of value activities (val-

\textsuperscript{22} Personal correspondence with Professor Christian Terwiesch, The Wharton School, University of Pennsylvania on July 2, 2008.

ue chain approach). Business logistics plans, organizes, handles, and controls all material, product, and information flows across these value activities in an efficient, effective, and customer-oriented manner (logistics perspective). Our main specific research questions are: What risk pooling methods are available? What economic conditions make the individual methods worthwhile? How can a company choose adequate risk pooling methods? We derive the adequacy of the identified risk pooling methods from contingency factors (contingency approach).

In order to enhance the quality of our research we use triangulation to gather various types of information on risk pooling by literature, example, modeling, and survey research. This integrated approach also accounts for our holistic ambition and leads to results not attainable by the individual research methods separately. Weaknesses of some methods can be balanced by the strengths of others. Van Hoek (2001: 182f.) already proposed triangulation to improve research on postponement, one type of risk pooling. For problems of triangulation, such as coping with conflicting results, epistemological problems, and the debatable higher validity of findings, please refer to e.g. Bryman (1992: 63f.), Denzin and Lincoln (2005: 912), Blaikie (1991: 122f.), and Fielding and Fielding (1986: 33). A holistic approach may not be as profound as an atomistic one. However, as noted before such a holistic approach is novel to risk pooling research.

1.4 Structure and Contents

This treatise is divided into six chapters and an appendix. After this introduction (chapter 1), we outline previous risk pooling research in business logistics, identify ten main types of risk pooling, and place them in the supply chain, business logistics, and a value chain. This results in the five logistics value activities storage, transportation, procurement, production, and sales and distribution, where risk pooling is important. Completing outlining our research framework, we define, explain, and characterize risk pooling in business logistics (chapter 2).

Chapter 3 defines, classifies, and characterizes the ten identified risk pooling methods within the five logistics value activities and according to their uncertainty reduction abilities.

---

24 To Porter (2008: 75) inbound and outbound logistics are primary value activities themselves besides operations, marketing and sales, and service. We adopt a cross-functional view of logistics.
25 Denzin (1978: 291) defines triangulation as “the combination of methodologies in the study of the same phenomenon”.
Research on inventory pooling is reviewed in more detail\(^{29}\), as it is the earliest and most extensive and prominent one. In particular, we attempt to remedy inconsistencies regarding the SRL, a tool to estimate the inventory savings from risk pooling by inventory pooling: Under what assumptions can the SRL be applied to regular, safety, and total stock, as researchers do not agree on them? What causes the inventory savings measured by the SRL? Are its results confirmed in practice? Is the SRL questioned justifiedly? After examining the portfolio effect (PE), a generalization of the SRL, and the inventory turnover curve, we compare the various SRL and PE models in a synopsis (table D.2) based on their assumptions and assign them to groups. This facilitates choosing an appropriate model to determine stock savings from inventory pooling for specific conditions or adapt the existing models by adding or dropping assumptions.

Chapter 4 merges the results of our literature review in a synopsis about conditions making the various risk pooling methods favorable, their advantages, disadvantages, and basic trade-offs. Based on this synopsis and contingency theory, a Risk Pooling Decision Support Tool is developed for choosing an appropriate risk pooling strategy for a specific company and specific conditions.

This tool is applied to a German paper wholesaler in chapter 5 to choose suitable risk pooling methods to cope with demand and lead time uncertainty. In this context we also show that in contrast to Maister (1976: 132) and Evers (1995: 2, 14f.) centralization or centralized ordering can reduce cycle stocks, if the replacement principle or stock-to-demand replenishment policy is followed in case minimum order and saltus quantities have to be observed (section 5.3.3.2).

If risk pooling is shown to be beneficial in theory and in practice also for this German paper wholesaler, to what extent are its different methods known, applied, and associated in 102 German manufacturing and trading companies? To answer this question we present a survey in appendix A for the above reasons. Such a survey has not been conducted before and is demanded by some authors\(^{30}\).

The conclusion (chapter 6) summarizes our findings and identifies avenues for further research.

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\(^{29}\) Professor Walter Zinn, Fisher College of Business, The Ohio State University, believes this is sorely needed (personal correspondence on July 4, 2008).

\(^{30}\) For example by Thomas and Tyworth (2006: 254f.) for order splitting and by Huang and Li (2008b: 19) for postponement.
2 Risk Pooling in Business Logistics

This chapter outlines our research framework: It gives an overview of previous risk pooling research (section 2.1), identifies ten main types of risk pooling and embeds them in the supply chain, business logistics, and a value chain (section 2.2), which sets the structure for chapter 3, defines risk pooling in business logistics (section 2.3), explains its mathematical and statistical foundations (section 2.4) and examines five general features of risk pooling (section 2.5).

2.1 Business Logistics Risk Pooling Research

Risk pooling in business logistics is an active field of research with well over 600 publications so far. The number of publications in this area has steadily increased since its scarce beginnings in the 1960s, gained momentum especially in the 80s and 90s and reached its peak in 2003 as figure 2.1 shows. Perhaps driven by the economic downturn, research activity in 2009 was the highest after 2003. Most research focused on inventory pooling (centralization, the square root law, portfolio effect, and inventory turnover curve), postponement and delayed (product) differentiation, and transshipments and inventory sharing. Figure 2.1 is based on the literature databases Business Source Complete, Business Source Premier, EconLit, and Regional Business News accessed via EBSCOhost® January 11, 2010.

After the concept borrowed from modern portfolio and insurance theory has been mainly applied to inventory centralization, meanwhile research focuses on other forms of risk pooling, especially postponement and transshipments, and the coordination of risk pooling arrangements and cost and profit allocation through contracts and fair allocation rules, schemes, or methods with game theory.

The academics dealing with risk pooling in business logistics are of different backgrounds (mathematics, operations research (OR), operations management (OM), management science, decision sciences, statistics, computer sciences, engineering, business administration, management, economics, game theory, production, marketing, logistics/supply chain management, physical distribution, and transportation), orientation (quantitative, analytical, modeling, simulation, empirical, and qualitative research), and

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prominence. Therefore they use inconsistent terms\textsuperscript{33}, frameworks, and structures and made our thorough literature review and definitions necessary. One might argue that due to these differences this research must not be compared and only major research should be cited. However, in contrast to previous research we would like to pursue a more holistic approach to convey an integrated overview of business logistics risk pooling. Even less prominent research can draw attention to important details and show directions for further research. Some often cited risk pooling research has not been published in highly ranked journals.\textsuperscript{34} Nevertheless most of the cited references are from the latter.

Most risk pooling research is quantitative and designs mathematical models of problems, develops solution methods (exact methods, algorithms, simulation methods, and heuristics), and determines solutions (optimal inventory control and risk pooling, e. g. transshipment, policies).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{risk_pooling_publications.png}
\caption{Number of Publications on Risk Pooling in Business Logistics}
\end{figure}

\textsuperscript{33} Bender et al. (2004: 233) made similar observations for location theory.

\textsuperscript{34} For example Eppen and Schrage (1981).
2.2 Placing Risk Pooling in the Supply Chain, Business Logistics, and a Value Chain

Business logistics\cite{35} comprises the holistic, market-conform, and efficient planning, organization, handling, and control of all material, product, and information flows from the supplier to the company, within the company, and from the company to the customer\cite{36} and back (reverse logistics\cite{37}).

As figure 2.2 shows, the efficient and effective material, product, and information flow is impaired by inter alia demand and lead time uncertainty. Risk pooling methods can mitigate these uncertainties. They can be implemented at or between the various supply chain members (suppliers, manufacturers, wholesalers, distribution centers, central warehouses, delivery or regional warehouses, retailers, stores, and customers).

Thoroughly reviewing the literature referred to in section 2.1, we identified ten risk pooling methods: capacity pooling, central ordering, component commonality, inventory pooling, order splitting, postponement, product pooling, product substitution, transshipments, and virtual pooling. We will define and characterize them in detail in chapter 3.

They can be implemented everywhere along the supply chain. Component commonality rather concerns production. In general capacity and inventory pooling and postponement may pool inventories or capacities of or for different locations. Component commonality, postponement, product pooling, and product substitution may refer to products or their components. Transshipments and virtual pooling deal with product, material, and information flows between supply chain members within an echelon or across echelons, and central ordering and order splitting with procurement between supply chain members.

In our opinion, all mentioned risk pooling methods but order splitting can reduce demand uncertainty, order splitting only lead time uncertainty, component commonality, capacity pooling, inventory pooling, product pooling, and product substitution only de-

\footnote{Business logistics (management) is difficult to distinguish from supply chain management (SCM). The terms are often used synonymously, although logistics is majorly seen as a part of SCM and not vice versa as in earlier literature (Ballou 2004b: 4, 6f., Larson and Halldörsson 2004, CSCMP 2010). According to Kotzab (2000) the German business logistics conception already comprised a holistic management along the whole value creation chain before it adopted the English term SCM. Gabler's business encyclopedia defines SCM as building and administrating integrated logistics chains (material and information flows) from raw materials production via processing to end consumers (Alisch et al. 2004: 2870).}

\footnote{Wegner (1996: 8f.).}

mand uncertainty. Transshipments and virtual pooling, postponement, and central ordering may dampen both uncertainties. Concerning order splitting and component commonality there are dissenting individual opinions, which we will elaborate on in section 4.4.

Various **economic conditions** have been found to favor the different risk pooling methods. We will focus on these favorable conditions in chapter 4. They flow into a Risk Pooling Decision Support Tool that helps to determine suitable risk pooling methods for specific conditions (section 4.4). This tool is applied to determine adequate risk pooling methods for a German paper merchant wholesaler for coping with its demand and lead time uncertainty in chapter 5.

![Figure 2.2: Placing Risk Pooling in Business Logistics](image)

Logistics may be considered as a cross-organizational (figure 2.2) and at every member of the above supply chain a cross-departmental coordination function across all divisions, especially **storage, transportation, procurement, production** of goods and services (including R&D, recycling, and remanufacturing), and **sales and distribution** (including order processing, recovery, return, and disposal)\(^{38}\) in the **value chain** in figure 2.3.

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The value chain is a management concept that was developed by Porter (1985: 33ff.) and describes a company as a collection of activities. These activities create value, use resources, and are linked in processes. In our value chain, the main value activities are procurement, production, and sales and distribution, which are supported by the value activities transportation and storage. Value activities are “technologically and economically distinct activities […] a company] performs to do business”\textsuperscript{39}.

Inventory pooling (IP) mainly pertains to storage, virtual pooling (VP) via drop-shipping and cross-filling and transshipments (TS) to transportation, centralized ordering (CO) and order splitting (OS) to procurement, capacity pooling (CP), component commonality (CC), and (form) postponement (PM) to production, and product pooling (PP) and product substitution (PS) to sales. However, VP, extending a location's inventories to other locations' ones, is also related to storage and sales, transportation and sales or service capacities may be pooled, any logistics decision may be postponed, and PP and PS may be applied in production as well. This not mutually exclusive and exhaustive classification is reflected in figure 2.3 and the next chapter's structure. We structured our review according to the value chain approach, because we focus on the impact of risk pooling on the five mentioned logistics value activities.

Risk pooling helps a company to cope with demand and/or lead time uncertainty and thus to carry out these value activities at a lower cost for a given service level, a higher service level for a given cost, or a combination of both\textsuperscript{40}. Thus it may increase expected profit\textsuperscript{41} by reducing expected costs and/or increasing expected revenue.

It may allow a company to win a competitive advantage over its competitors by effectively combining Porter's (2008: 75) competition strategies of differentiation and cost leadership, e. g. in mass customization enabled by postponement\textsuperscript{42}.

\textsuperscript{39} Porter (2008: 75)
\textsuperscript{41} Porter's (1985: 38) value chain considers margin instead of profit. “Margin is the difference between total value and the collective cost of performing the value activities”.
\textsuperscript{42} For example Feitzinger and Lee (1997).
2.3 Defining Risk Pooling

The literature offers various definitions of and confusion about the terms variability, variance, or volatility\(^{43}\), uncertainty\(^{44}\), and risk\(^{45}\). Lead time and demand uncertainty may arise from lead time and demand variability or incomplete knowledge\(^{46}\). “Uncertainty is the inability to determine the true state of affairs of a system”\(^{47}\). “Uncertainty caused by variability is a result of inherent fluctuations or differences in the quantity of concern. More precisely, variability occurs when the quantity of concern is not a specific value but rather a population of values”\(^{48}\). Lead time and demand uncertainty may lead to economic risk\(^{49}\), the possibility\(^{50}\) of a negative deviation from expected values or desired targets\(^{51}\). The corporate target is expected profit (figure 2.3), the difference of expected revenue and expected cost\(^{52}\). The possibility of a positive deviation from an expected value constitutes a chance\(^{53}\).

Despite the costs risk pooling entails\(^{54}\), it may reduce variability and thus uncertainty and expected (ordering, inventory holding, stockout, and backorder) costs\(^{55}\) and/or increase expected revenue (product availability, fill rate, service level)\(^{56}\) and thus expected profit\(^{57}\).

---

\(^{43}\) Hubbard (2009: 84f.). “Outside of finance, volatility may not necessarily entail risk—this excludes considering volatility alone as synonymous with risk” (Hubbard 2009: 91).

\(^{44}\) Knight (2005: 19ff.), Haines (2009: 265ff.), Hubbard (2010: 49f.).


\(^{47}\) Haines (2009: 265).

\(^{48}\) Haines (2009: 266).


\(^{50}\) Wagner (1997: 51).

\(^{51}\) Cf. e. g. Wagner (1997: 51), Köhne (2007: 321).

\(^{52}\) Wagner (1997: 52).


We define risk pooling in business logistics as consolidating individual variabilities (measured with the standard deviation) of demand and/or lead time in order to reduce the total variability they form and thus uncertainty and risk (the possibility of not achieving business objectives). The individual variabilities are consolidated by aggregating demands (demand pooling) and/or lead times (lead time pooling). Consolidating and aggregating mean “combining several different elements [...] into a whole”.

As individual variabilities and not individual risks are pooled, the term risk pooling is misleading. Nonetheless, we use it, because it is conventional.

58 Sussams (1986: 8), Romano (2006: 320). “The standard deviation is the most commonly used and the most important measure of variability” (Gravetter and Wallnau 2008: 109). Zinn et al. (1989: 2) and Chopra and Meindl (2007: 307) consider the standard deviation a measure of uncertainty. Cachon and Terveisz (2009: 331f., 282f.) and Chopra and Meindl (2007: 307) use the derived coefficient of variation (standard deviation divided by mean) as a measure for demand variability or uncertainty. Pooling independent random variables does not change total variability measured with the variance. Of course, one could argue that the measuring unit of the variance is squared and therefore difficult to interpret and that the standard deviation and not the variance is used to calculate safety stock. Pooling variabilities measured with the range may even increase total variability.
59 Cf. e. g. Chopra and Meindl (2007: 336).
60 Cf. e. g. Pischchulov (2008: 18).
67 Soanes and Hawker (2008).
69 The business logistics risk pooling literature finds “the risk related to the uncertainty” of individual demands (Zinn 1990: 12), risk “over uncertainty in customer demand” (Anupindi and Bassok 1999: 187), standard deviations (Zinn 1990: 13) or variances of individual demands (Zinn 1990: 16), risk “over demand uncertainty” (Weng 1999: 75) or risk “over random supply lead time” (Weng 1999: 82), “inventory
Among others Hempel (1970: 654), Wacker (2004: 630), and the references they give make requirements for a “good” definition. To our knowledge previous attempts to define risk pooling do not satisfy them. They merely describe its causes, effects, or aim, only target demand pooling, and equate risk pooling with inventory pooling and the square root law. Moreover they do neither define nor differentiate between variability, uncertainty, and risk. The business logistics risk pooling literature states risk pooling reduces

- variability, “lead-time variability”, lead time demand variability, demand variability, demand variation, variation, “demand variance”, variance of delivery time, “the variance of the retailers' net inventory processes”, “the mean and variance of cycle stock”,
- uncertainty, demand uncertainty, “the uncertainty the firm faces”, “the effect of uncertainty”,


“A ‘good’ [formal conceptual] definition […] is a concise, clear verbal expression of a unique concept that can be used for strict empirical testing” (Wacker 2004: 631). Hempel (1970: 654) requires inclusivity, exclusivity, differentiability, clarity, communicability, consistency, and parsimony.


Anupindi et al. (2006: 168).

Wisner et al. (2009: 513).


Evers (1999: 133).


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- “the risk associated to the variability”\textsuperscript{92}, the “impact of individual risks”\textsuperscript{93}, “risks associated with forecasting errors and inventory mismanagement”\textsuperscript{94}, and “inventory risk”\textsuperscript{95}.

Risk pooling is described “to hedge uncertainty so that the firm is in a better position to mitigate the consequence of uncertainty”\textsuperscript{96}, “enables one to avoid […] uncertainty”\textsuperscript{97}, or “removes some of the uncertainty involved in planning stock levels”\textsuperscript{98}.

It is also referred to as “statistical economies of scale”\textsuperscript{99}, “portfolio efficiencies”\textsuperscript{100}, “Pooling Efficiency trough Aggregation” or “Principle of Aggregation”\textsuperscript{101}, and “IMPACT OF AGGREGATION ON SAFETY INVENTORY”\textsuperscript{102}.

Risk pooling is also considered a form of operational hedging. “Hedging is the action of a decision maker to mitigate a particular risk exposure. Operational hedging is risk mitigation using operational instruments”\textsuperscript{103}, e. g. pure diversification or demand pooling\textsuperscript{104}.


### 2.4 Explaining Risk Pooling

Risk pooling can be shown e. g. for inventory or location pooling: Let a single product be stocked at \(n\) separate locations. Demand for this product is a normal random variable\textsuperscript{105} \(x_i\) with known mean \(\mu_i\) and standard deviation\textsuperscript{106} \(\sigma_i\) for each location \(i = 1, \ldots, n\). The standard devia-

\textsuperscript{90} Cachon and Terwiesch (2009: 321).
\textsuperscript{91} Özer (2003: 269).
\textsuperscript{92} Risk pooling “is applied to portfolio theory in finance here [sic!] the risk associated to the variability in the return from individual stocks is diluted when an investor keeps a portfolio of stocks” (Zinn 1990: 12).
\textsuperscript{93} Dilts (2005: 23).
\textsuperscript{94} Yang and Schrage (2009: 837).
\textsuperscript{95} Chopra and Sodhi (2004: 59).
\textsuperscript{96} Cachon and Terwiesch (2009: 321).
\textsuperscript{97} Pishchulov (2008: 26) remarks this for risk pooling through delayed differentiation.
\textsuperscript{98} Jackson and Muckstadt (1989: 2).
\textsuperscript{100} Eppen and Schrage (1981: 52).
\textsuperscript{101} Anupindi et al. (2006: 187, 189).
\textsuperscript{102} Chopra and Meindl (2007: 318).
\textsuperscript{103} Van Mieghem (2007: 1270).
\textsuperscript{104} Van Mieghem (2007: 1270f.).
\textsuperscript{105} A random variable is a variable that takes its values (realizations) with certain probabilities respectively whose values are assigned to certain probability densities (Alisch et al. 2004: 3454).
\textsuperscript{106} If (the empirical distribution of) demand is forecast (Thonemann 2005: 255f.), \(\sigma_i\) is the standard deviation of the distribution of the forecast error in formula (2.1) for calculating safety stock (Caron and Marchet 1996: 239, Pfohl 2004a: 114, Thonemann 2005: 255f., Chopra and Meindl 2007: 306). An estimate of expected demand (forecast value) is ordered to satisfy the expected value of demand and safety stock is
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σ_i is a measure of dispersion of individual values of the random variable x_i around the mean μ_i for every entity i and therefore a measure of x_i's variability\(^{107}\).

If each location just satisfies its own demand, location i needs to hold an amount of safety stock that allows it to hedge against the demand uncertainty associated with x_i. Let the optimal safety stock at location i in accordance with the newsboy model\(^{108}\) be

\[
ss_i = z \sigma_i,
\]

where z is the safety factor that corresponds to a certain target service level. Therefore, the total safety stock across all locations is

\[
ss = z \sum_{i=1}^{n} \sigma_i.
\]

If all inventory holding is centralized at one location, this location needs to serve the total demand

\[
x = \sum_{i=1}^{n} x_i.
\]

The individual demands are aggregated across all locations. Safety stock in the centralized system is

\[
ss_c = z \sigma_a,
\]

where

\[
\sigma_a = \sqrt{\frac{\sum_{i=1}^{n} (\sigma_i)^2 + 2 \sum_{i=1}^{n} \sum_{j<i} \sigma_i \sigma_j \rho_{ij}}{n}} \quad \text{(2.5)}
\]

is the standard deviation of x and \(\rho_{ij}\) is the correlation coefficient of the value of the random variable for locations i and j. It can be formally shown that the aggregated variability (standard deviation of total demand \(\sigma_a\)) is less than or equal to the sum of the individual variabilities built up as protection against the forecast error, which is at least as high as the demand uncertainty or standard deviation of demand (personal correspondence with Professor Ulrich W. Thonemann, University of Cologne, in 2008), and not against uncertainty in demand (Thonemann 2005: 255f.). A high safety stock is needed, if the (standard deviation of the) forecast error is high. The size of demand fluctuations is irrelevant (Thonemann 2005: 257). If the distribution of demand is known, \(\sigma_i\) is the standard deviation of demand (Zinn et al. 1989: 4) and safety stock is held to hedge against uncertainty in demand. The higher the uncertainty in demand, the higher is the safety stock. The standard deviation of demand is zero and no safety stock is needed, if there is no demand uncertainty (Thonemann 2005: 238) and no lead time uncertainty either. Nonetheless, some companies forecast demand, but wrongly use the standard deviation of demand instead of the standard deviation of the forecast error in calculating safety stock (Korovessi and Linninger 2006: 489f.).


\(^{109}\) Cf. Mood et al. (1974: 178), Zinn et al. (1989: 5), Jorion (2009: 43). This expression is also written \(\sigma_a = \frac{\sum_{i=1}^{n} (\sigma_i)^2 + 2 \sum_{i=1}^{n} \sum_{j<i} \sigma_i \sigma_j \rho_{ij}}{n} \) (Eppen 1979: 500) or \(\sigma_a = \frac{\sum_{i=1}^{n} (\sigma_i)^2 + 2 \sum_{i=1}^{n} \sum_{j<i} \sigma_i \sigma_j \rho_{ij}}{n} \) (cf. Weisstein 2010). “The double summation sign (\(\sum \sum\)) indicates that all possible combinations of i and j should be included in calculating the total value” (Moyer et al. 1992: 222), where j is larger than i.
(sum of standard deviations of demand at the n locations $\sigma$) because of the subadditivity property of the square root of non-negative real numbers$^{110}$:

$$\sigma = \sqrt{\sum_{i=1}^{n} (\sigma_i)^2 + 2 \sum_{i=1}^{n} \sum_{i < j} \sigma_i \sigma_j \rho_{ij}}.$$  

Therefore the safety stock in the centralized system is less than or equal to the one in the decentralized one

$$ss = z \sum_{i=1}^{n} \sigma_i \geq ss_c = z \sqrt{\sum_{i=1}^{n} (\sigma_i)^2 + 2 \sum_{i=1}^{n} \sum_{i < j} \sigma_i \sigma_j \rho_{ij}}.$$  

Inequality (2.6) is a special case of the known Minkowski inequality for $p = 2$. It is always correct, if the variances exist, therefore also for the Poisson and Binomial distribution.$^{111}$

Hence, the standard deviation of the aggregate demand is lower than or equal to the sum of the standard deviations of the individual demands. Consequently, inventory pooling or centralization at a single location can reduce the amount of safety stock necessary to ensure a given service level. The reduction in safety stock depends on the correlations between $x_i$, $i = 1, \ldots, n$. Inventory pooling does not always reduce safety stock due to the less-than-or-equal sign.

Yet, the sum of the individual variabilities (standard deviations) only equals the total aggregated variability (the square root of the sum of the individual variances plus two times the covariance of the random variable's value for two entities i and j) in two cases:

(1) The random variables $x_i$ are perfectly positively correlated (the coefficient of correlation $\rho_{ij}$ equals 1, $\forall i, j$):

$$\sigma_a = \sqrt{\sum_{i=1}^{n} (\sigma_i)^2 + 2 \sum_{i=1}^{n} \sum_{i < j} \sigma_i \sigma_j \rho_{ij}} = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} \sigma_i \sigma_j \rho_{ij}}$$  

$$= \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} \sigma_i \sigma_j} \cdot 1 = \sqrt{(\sum_{i=1}^{n} \sigma_i)^2} = \sum_{i=1}^{n} \sigma_i = \sigma.$$  

(2) Random variables $x_i$ cannot mutually balance their fluctuations, if at least $n-1$ $\sigma_i$ equal zero: If $n-1$ $\sigma_i$ equal zero, (2.6) becomes

$$\sigma = \sigma_i = \sigma_a$$  

for this single non-zero $\sigma_i$. If all $\sigma_i$ are zero, (2.6) becomes

---

$^{110}$ Gaukler (2007).


$^{112}$ Cf. Moyer et al. (1992: 222). This expression is also written $\sigma_a = \sqrt{\sum_{i=1}^{n} (\sigma_i)^2 + \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} \sigma_i \sigma_j \rho_{ij}}$ (cf. Jorion 2009: 43).
Apart from this, for independent (the correlation coefficient $\rho_{ij}$ is equal to 0, $\forall \ i, j$) normally distributed random variables risk pooling leads to variability reduction:

$$\sigma = \sum_{i=1}^{n} \sigma_i > \sigma_n = \sqrt{\sum_{i=1}^{n} (\sigma_i)^2}.$$  \hspace{1cm} (2.11)

The **highest possible variability reduction** is achieved, if there are **negative correlations** which make the second term under the square root equal to minus the first term$^{113}$ in (2.6).

Some authors$^{114}$ give the impression that risk pooling always reduces total variability or enables to reduce inventory, although this **must not** be the case as shown above.

Likewise industry and academia often assume that inventory pooling, a type of risk pooling, always is beneficial, i.e. it either reduces costs or increases profits, and that the value of inventory pooling increases with increasing variability of demand.$^{115}$ Kemahlioğlu-Ziya (2004: 40) states this was only always correct for normally distributed demand such as in Eppen (1979) or Eppen and Schrage (1981). She neglects though that this is not correct for perfectly positively correlated demands and if at least $n-1$ $\sigma_i$ equal zero.

Furthermore, for uncertain demand and certain conditions more willingness to substitute may not lead to higher expected profits or “lower optimal total inventory”$^{116}$ for full$^{117}$ and partial substitution or risk pooling$^{118}$.

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$^{114}$ Tallon (1993: 186) imprecisely remarks, “Mathematically, the square root of the sum of the variances is less than the sum of the individual standard deviations”. Likewise, Anupindi et al. (2006: 191) inaccurately state “the inventory benefits” from physical centralization “result from the statistical principle called the **principle of aggregation**, which states that the standard deviation of the sum of random variables is less than the sum of the individual standard deviations”. Gaukler (2007) uses the less-than-or-equal sign, but inconsistently says the standard deviation of the aggregate demand was lower than (not lower than or equal to) the sum of the standard deviations of the individual demands. Although Gaukler (2007) states his remarks were not intended to be a rigorous derivation of this concept, they should be consistent. “It is well known that the pooled demand has a lower standard deviation than the sum of standard deviations of individual demands. Thus, the safety stock as well as inventory holding and shortage costs are lower when products are more substitutable” (Ganesh et al. 2008: 1134). “Inventory pooling represents a strategy of consolidating inventories and aggregating stochastic demands, enabling reductions in inventory holding and shortage costs” (Pischchulov 2008: 8). “Risk pooling suggests that demand variability is reduced if one aggregates demand across locations” (Romano 2006: 320, Simchi-Levi et al. 2008: 48). “The aggregation of demand stemming from risk pooling leads to reduction in demand variability, and thus a decrease in safety stock and average inventory” (Simchi-Levi et al. 2008: 50). “Centralizing inventory reduces both safety stock and average inventory in the system” (Simchi-Levi et al. 2008: 51). Finally, inventory pooling does not automatically reduce inventory, but it may allow to reduce the inventory necessary to provide a given service level.


Yang and Schrage (2009) show this “inventory anomaly” (after demand substitution or risk pooling the company ought to hold more stock rather than less) for full substitution with any right skewed demand distribution\(^{119}\) if the shortage is somewhat higher than the holding cost per unit, for partial substitution with exponential, Normal, Poisson, and uniform demands even if they are negatively correlated, as well as for more than one period, with backlogging, lost sales, more than two products, and with setup costs. The inventory anomaly is increasing as the underage is close to the overage cost per unit and as the correlation between demands decreases.\(^{120}\) The relative difference of the shortage to holding cost for which the anomaly arises increases with increasing right skewedness. A company will not face the inventory anomaly, if it uses a shortage penalty, but minimizes inventory carrying costs subject to a fixed target service level. However, it may not seize the chance to increase sales and profits, if it augments demand pooling without raising inventory. The likelihood of the inventory anomaly is higher with short lead times and lower with less frequent but larger orders, e. g. with high setup costs.\(^{121}\)

Inventory pooling may reduce costs and increase profits for the supply chain party holding inventory\(^{122}\), but may reduce the total supply chain profits. In a two-echelon supply chain, where the upper echelon (the supplier) carries inventory, the lower echelon (the retailers), whose revenues depend only on sales, may lose profits due to pooling.\(^{123}\) The supplier and the retailers are likely to benefit from risk pooling inventory, if the stockout penalty cost is high.\(^{124}\)

The normal random variable \(x\) in our derivation of risk pooling can also be the demands for \(i\) unique components, product versions, substitute products, customized products, or (replenishment) lead times to \(i\) locations. They are aggregated to the demand for a common component in component commonality\(^{125}\), universal product in product pooling, all substitutes in product substitution or demand reshape, the undifferentiated generic product in postponement or delayed product differentiation, or to an aggregated lead time across all locations, suppliers, or deliveries in lead time pooling (emergency transshipments and order splitting). The aggregated demand and/or lead time \(x\) may fluctuate less, as the stochas-

\(^{119}\) “Actual demand distributions tend to be right skewed” (Yang and Schrage 2009: 847).

\(^{120}\) Yang and Schrage (2003: 1).

\(^{121}\) Yang and Schrage (2009: 847).


\(^{123}\) Anupindi and Bassok (1999).

\(^{124}\) Dai et al. (2008: 411).

\(^{125}\) Dogramaci (1979: 130) shows that “the standard deviation of demand for the common component (\(\sigma_c\)) would be less than or equal to” the sum of “the standard deviation[s] of lead time demand” of the components it replaces.
tic fluctuations (σi) of the individual demands and/or lead times usually balance each other to a certain extent (equation 2.6).

Risk pooling by demand pooling in transshipments, virtual pooling, centralized ordering, and capacity pooling can be derived in the same manner as shown for inventory pooling: Demands are pooled across locations.

2.5 Characteristics of Risk Pooling

We now turn to describing five important characteristics common to most risk pooling methods: (1) increasing returns, but (2) diminishing marginal returns with increasing application as well as increasing benefit with (3) increasing demand variability, (4) decreasing demand correlation, and (5) decreasing concentration of uncertainty.

(1) The benefit of or return on risk pooling is variability reduction and thus enabled inventory reduction for a given service level or increase in service level for a given inventory. The risk pooling return generally (in the following cases) increases with increasing application or the number of participants:

It augments with the number of

- participating stock-keeping locations in inventory pooling126, time and logistics postponement127, transshipments128, and cross-filling129,
- (substitutable) products and degree of substitution in product substitution, demand reshape130, and resource flexibility131,
- products in the product line132 or products being postponed133 in manufacturing postponement,
- products sharing components (increasing commonality) in component commonality134, as well as

\[ \text{(127) Zinn and Bowersox (1988: 133), Heil (2006: 170).} \]
\[ \text{(129) Ballou and Burnetas (2000, 2003), Ballou (2004b: 385-389).} \]
\[ \text{(130) Eynan and Fouque (2003, 2005), Ganesh et al. (2008: 1124).} \]
\[ \text{(131) Tomlin and Wang (2005: 51).} \]
\[ \text{(132) Zinn (1990: 14), Swaminathan and Tayur (1998).} \]
\[ \text{(133) Graman and Magazine (2006: 1075).} \]
• retailers in pooling over the outside-supplier lead time or centralized ordering and risk pooling by drop-shipping or virtual pooling.

(2) However, the marginal benefit of risk pooling commonly decreases with each additional increase in risk pooling or participant. There appear to be diminishing marginal returns to risk pooling, e.g. to cross-filling and transshipments with increasing number of locations transshipping or increasingly even allocation of demand across locations, to virtual pooling by drop-shipping with increasing number of retailers, to component commonality, postponement, product substitution, capacity pooling, and location pooling.

The marginal benefit of location pooling decreases with increasing number of pooled locations, so that the main benefit is gained by consolidating a few locations and it might not be necessary to pool all locations. The same applies to transshipments.

Capacity pooling with a little bit of flexibility as long as it is designed with long chains almost has the same benefit as full flexibility. Companies can benefit from any

137 Similarly, in corporate finance we can observe diminishing marginal risk reduction with increasing number of securities: At first diversification reduces portfolio risk (standard deviation or volatility) rapidly, then more slowly with increasing number of randomly chosen stocks (Statman 1987: 353, 355). In recent years stocks have become individually more volatile but are increasingly less than perfectly correlated. Therefore an investor needs to hold more stocks to capture the majority of benefits from diversification than before (Campbell et al. 2001: 40).
138 Ballou and Burnetas (2000, 2003), Ballou (2004b: 385-389). Based on Ballou's numerical example, we devise the general formula for the effective fill rate EFR for the customer in dependence of the for all locations equal item fill rate FR (0 < FR < 1) and the number n of locations that cross-fill as EFR = 1 − (1 − FR)n. The first derivative of EFR with respect to n shows that the more locations cross-fill the higher is the EFR: dEFR/dn = −(1 − FR)n · ln(1 − FR) > 0. However, the incremental increase in EFR diminishes with increasing number of locations taking part in cross-filling: d²EFR/dn² = −(1 − FR)n · ln(1 − FR) · ln(1 − FR) < 0.
139 Evers (1997: 70).
142 Chopra and Meindl (2007: 327f.) find by a numerical example that “the marginal benefit […] marginal reduction in safety stock” decreases with increasing commonality for independent and normally distributed end-product demand, but formulate this result as if generally valid. Bagchi and Gutierrez (1992) show by two numerical examples (817) that “increasing component commonality results in increasing marginal returns when the criteria are aggregate service level and aggregate stock requirement” (815) for two end-products that face independent, identically exponentially, geometrically, or Poisson distributed demands and share up to three components (815, 817f., 824). They do not give an intuitive explanation (829).
147 Cachon and Terwiesch (2009: 323f.).
amount of risk pooling as long as they implement it appropriately and demand is not perfectly positively correlated. Graman and Magazine (2006: 1075) similarly observe pertaining to postponement “that it is only necessary to postpone a portion of a product to realize most of the benefits of such a strategy”. “The mathematical inventory model shows that almost all of the positive benefits of postponement (such as lower inventories) can be achieved with a partial (low-capacity) postponement scenario”.

Cachon and Terwiesch (2009: 324) show diminishing marginal returns of location pooling with increasing mean for independent Poisson demands. This must not necessarily hold for other distributions such as the normal one.

(3) The (demand) risk pooling effect decreases with increasing demand correlation and any Magnitude (relative sizes of the standard deviations of demand), and increases...

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150 Flexibility means that a plant is capable of producing more than one product. With no flexibility each plant can only produce one product; with total flexibility every plant can produce every product (as in manufacturing postponement). Graphically lines called links indicate which plant is capable of producing which product. Flexibility allows production shifts to high selling products to avoid lost sales (Cachon and Terwiesch 2009: 344f.).

151 “A chain is a group of plants and […] products that are connected via links” (Cachon and Terwiesch 2009: 346).


154 “[T]he standard deviation of a Poisson distribution equals the square root of its mean. Therefore, Coefficient of variation of a Poisson distribution...” (Cachon and Terwiesch 2006: 324). This can also be derived formally: The first derivative of the coefficient of variation $COV = \sigma / \mu = \sqrt{\lambda / \lambda}$ with respect to the mean $\lambda$ is smaller than zero, the second one larger than zero: $\frac{\partial COV}{\partial \lambda} = -\frac{1}{2\lambda^{3/2}} < 0$, $\frac{\partial^2 COV}{\partial \lambda^2} = -\frac{3}{4\lambda^{5/2}} > 0$.

155 For the normal distribution it depends on how the coefficient of variation changes with respect to the mean. With the Poisson distribution it decreases as the mean increases, but this is not necessarily the case with the normal distribution. However, we find that there are at least diminishing marginal returns to pooling of normally distributed independent demands with the same standard deviation and mean. For normally distributed independent demand the coefficient of variation of pooled demand is $COV = \sqrt{\frac{\sum_{i=1}^{n}(\sigma_i^2)}{\sum_{i=1}^{n} \mu_i}}$. If the standard deviation and mean is the same at each pooled location $i$, this expression simplifies to $COV = \sqrt{\frac{n\sigma^2}{n\mu}} = \frac{\sigma}{\mu}$. The first and second derivative of $COV$ with respect to the number $n$ of pooled locations shows that as $n$ increases $COV$ decreases at a decreasing rate: $\frac{\partial COV}{\partial n} = -\frac{\sigma}{2n\mu^{3/2}} < 0$, $\frac{\partial^2 COV}{\partial n^2} = -\frac{3\sigma}{4n\mu^{5/2}} > 0$.

with decreasing correlation and Magnitude\textsuperscript{156}. Likewise the value of lead time risk pooling (order splitting\textsuperscript{157} and transshipments) increases with decreasing correlation of replenishment lead times.

Therefore, many “companies attempt to reduce inventory and manufacturing costs by manipulating correlated demand sources, or inducing demand patterns that balance each other in an average sense”\textsuperscript{158}, i.e. by risk pooling, while maintaining sales.\textsuperscript{159}

The bullwhip effect\textsuperscript{160} can be reduced by risk pooling (effects)\textsuperscript{161}, production smoothing, and seasonality\textsuperscript{162}, so that it may be overestimated\textsuperscript{163}.

Evers and Beier (1993) and Evers (1995) debatably show that there are no further savings in safety stock after a first consolidation because of the arising perfectly positive correlation.

Tyagi and Das (1999: 211) show that if demands are correlated and one appropriately takes advantage of their characteristics, a partial may be more cost-efficient than complete pooling of customers.

On the other hand, Xu and Evers (2003) claim that partial can never outperform complete pooling only based on demand correlation. Examples suggesting that one should prefer partial to complete aggregation were based on inconsistent correlation matrices.

(4) The benefits of risk pooling generally increase with a structured (“a common linear transformation”\textsuperscript{164}) increase in demand variability\textsuperscript{165}, if lead times are exogenous (for inventory pooling, product consolidation, and delayed differentiation\textsuperscript{166}). Gerchak and He
(2003) provide a newsvendor counterexample with convex ordering where increased variability of two individual demands reduces the benefits of risk pooling.

If supply lead times are endogenous in multi-item finite capacity production-inventory systems, both higher demand variability and capacity utilization (arrival rate divided by service rate) or asymmetric backordering or holding costs make risk (inventory) pooling less valuable.

(5) Assuming a multivariate normal distribution and uncorrelated demands, the value of pooling is lower when uncertainty is more concentrated, i.e. the less uniform or more dispersed the values of the standard deviations of the demands are. Correspondingly, “the PE will be larger when variances are of similar rather than highly varying magnitude”.

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169 “While the relative benefit of inventory pooling tends to diminish with utilization, the relative benefit of capacity pooling tends to increase with utilization” (Benjaafar et al. 2005: 550).
3 Methods of Risk Pooling

After clarifying the prerequisites in the previous chapter, we will now enumerate the ten identified risk pooling methods and their synonyms, present a classification according to their ability to pool demands and/or lead times, and define, classify, and characterize them correspondingly within the structure of the aforementioned five logistics value activities.

First, under the heading storage we deal with inventory pooling and centralization, the SRL, PE, and inventory turnover curve, as this area shows the earliest and most extensive research in risk pooling (cf. figure 2.1) and requires a review. The various SRL and PE models are compared in a synopsis (table D.2) based on their assumptions. This facilitates choosing an appropriate model to determine stock savings from inventory pooling for specific conditions or adapt the existing models by adding or dropping assumptions and relates our centralized ordering considerations in section 5.3.3.2 to these models.

Afterwards, virtual pooling, which is related to inventory pooling, and transshipments are examined (transportation). Upon considering risk pooling in these two original (traditional) logistics duties that refer to the transfer of objects (above all of goods), we survey it in the derivative logistics areas procurement (centralized ordering and order splitting), production (component commonality, postponement, and capacity pooling), and sales and distribution (product pooling and substitution) downstream the value chain.

Perhaps since risk pooling and centralization of inventories (distribution or warehouse networks) are closely related, the terms inventory pooling or just pooling are often used interchangeably and ambiguously for risk pooling (methods), although inventory pooling literally merely refers to the consolidation or centralization of inventory, is a type or manifestation of risk pooling, and takes advantage of the possible benefits of risk pooling.

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173 Personal correspondence with Professor Walter Zinn, Fisher College of Business, The Ohio State University on July 4, 2008.
178 “A finite set of outlets with randomly fluctuating demands bands together to reduce costs by buying, storing and distributing their inventory jointly. This is termed inventory centralization and is a type of risk pooling” (Burer and Dror 2006: 1). Cachon and Terwiesch (2009: 321).
After a thorough literature review we conclude that apart from

(1) **inventory pooling**, location pooling, or (physical) inventory or warehouse centralization (SRL, PE, selective stock keeping, inventory turnover curve),

risk pooling in business logistics can also be achieved by

(2) **virtual pooling**, virtual inventory or inventories, “electronic inventory”, virtual centralization, virtual warehouse or warehousing, “virtually aggregating inventories”, or information centralization,

(3) **transshipments** (stock sharing between inventory locations) or “location substitution”,

(4) **centralized ordering**, “consolidated distribution”, “risk pooling over the outside-supplier lead time”, or “warehouse risk-pooling”,

(5) **order splitting** or multiple suppliers,

(6) **component commonality**, component sharing, part standardization, or procurement standardization.

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181 Cachon and Terwiesch (2009: 321ff.).


186 Anupindi et al. (2006: 194f., 314, 335).


188 Verkoeijen and deHaas (1998).


190 Chopra and Meindl (2007: 321ff.).


194 Cachon and Terwiesch (2009: 336ff.).


postponement, delayed (product) differentiation,\(^{202}\) process standardization\(^{203}\), or “modularization strategies”\(^{204}\),
capacity pooling and flexible manufacturing\(^{205}\),
product pooling\(^{206}\), stock keeping unit (SKU) rationalization\(^{207}\), universal or
generic design\(^{208}\), or product standardization\(^{209}\), as well as
product substitution\(^{210}\), “item substitution”\(^{211}\), interchangeability\(^{212}\), “de-
mand reshape”\(^{213}\), or “product commonalities”\(^{214}\).

<table>
<thead>
<tr>
<th>Building Blocks</th>
<th>IP</th>
<th>VP</th>
<th>TS</th>
<th>CO</th>
<th>OS</th>
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Table 3.1: Risk Pooling Methods’ Building Blocks

As highlighted in our definition in section 2.3, risk pooling (methods) may take advantage of
demand pooling (DP) and/or lead time pooling (LP). DP aggregates stochastic demands, so
that higher-than-average demands may balance lower-than-average ones.\(^{215}\) LP balances higher-than-average and lower-than-average lead times: A late-arriving order may be compensated by an early-arriving one\(^{216}\), so that safety stock can be reduced, inventory availability in-

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\(^{204}\) Reiner (2005: 434).


\(^{206}\) Cachon and Terwiesch (2009: 321, 330ff.).


\(^{213}\) Eynan and Fouque (2003, 2005).

\(^{214}\) Reiner (2005: 434).


\(^{216}\) Evers (1999: 122).
Methods of Risk Pooling

Increased, or both. Transshipments pool both lead times and demands, order splitting only the former.

Cachon and Terwiesch (2009: 336) consider consolidated distribution and delayed differentiation types of LP: Lead times between the supplier and the retail stores in the direct-delivery model are combined to a single lead time between the supplier and the distribution center (DC) in the consolidated-distribution model. Actually (forecast) demands are pooled over or during the outside-supplier lead time. Thus it is likely that higher-than-average and lower-than-average demands balance each other and inventory can be reduced for a given service level (DP).

All risk pooling building blocks can reduce variability and thus inventory for a given service level, increase the service level for a given inventory, or a combination of both.

Table 3.1 can result in a classification according to the notation DP/LP that indicates which risk pooling properties the risk pooling method of concern relies upon. A 1 indicates that the respective property applies, a 0 the contrary. IP would be classified as a 1/0 – risk pooling method.

3.1 Storage: Inventory Pooling

Inventory pooling is the combination of inventories and satisfying various demands from it in order to reduce inventory holding and shortage costs through risk pooling. It is also called vendor pooling, product consolidation, demand pooling, pooling, distributor integration, location pooling, or inventory centralization. It can e.g. be achieved by inventory or warehouse (system) centralization or selective stock keeping respectively specialization.

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231 Benjaafar et al. (2004a: 1438).
tion. The latter strives to reduce inventory carrying cost treating products differently without reducing the service level substantially. For example, products with a low turnover might be stocked only at few locations due to cost considerations.

Inventory pooling is e. g. considered in location and allocation decisions, satisfying both on-line and store demand, speculative online exchanges, airline revenue management, for spare parts of airlines and of U.S. manufacturing companies, and for Saturn, General Motors, Intel, and Airbus.

Inventory pooling is a 1/0 – risk pooling method: Inventories are consolidated and stochastic demands aggregated, as they are satisfied from the consolidated inventory. Thus demand variabilities may balance each other (demand pooling). The lead times to the separate inventories are pooled to the lead time to the consolidated stock according to Cachon and Terwiesch's (2009: 336, 339) notion of lead time pooling, but this actually is demand pooling during the replenishment lead time. Inventory pooling does not pool lead times, so that their variabilities may balance each other according to Evers (1997: 69ff., 1999: 121) and Wanke and Saliby (2009: 678ff.).

**Inventory centralization** can reduce expected costs in a cost minimization model or increase profits and service level in a profit maximization model or in incentive-compatible laboratory experiments in behavioral operations management (OM), even if...

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234 Pföhl (2004a: 122f.).
238 “Airline revenue management involves dynamically controlling the availability and prices of many different classes of tickets to maximize revenues” (Zhang and Cooper 2005: 415).
239 Hearn (2007), Burchell (2009), Cattrysse et al. (2009).
243 Johnson (2005).
244 Aviation Week & Space Technology (2006).
245 Pishchulov (2008: 8, 17).
246 For example Eppen (1979), Chen and Lin (1989).
248 For example Cherikh (2000), Lin et al. (2001a).
249 Ho et al. (2009).
locations differ in profitability (selling price and stockout costs)\textsuperscript{250}, because “of risk pooling over uncertainty in customer demand”\textsuperscript{251} and economies of scale\textsuperscript{252} and scope\textsuperscript{253}.

Centralization (decreasing the number of warehouses) generally reduces inbound transportation costs from the supplier to the warehouses because of a higher utilization of transportation means (economies of density\textsuperscript{254}), possibly the distances between the production facility and the central warehouse(s)\textsuperscript{255}, and the unit costs\textsuperscript{256} in the warehouse system due to higher utilization (economies of scale). The systemwide total throughput is distributed over a smaller number of warehouses and thus the average throughput per warehouse increases.\textsuperscript{257} The warehouse costs per item (unit costs for space, product handling, and personnel) decrease through economies of scale.\textsuperscript{258} The fixed costs per order and per unit holding costs usually diminish with centralization.\textsuperscript{259} Fixed warehouse costs, especially personnel costs, are distributed over a larger warehouse throughput so that the unit costs decrease with increasing utilization\textsuperscript{260} and the return on rationalization investments in more productive low-cost methods increases (economies of scale).\textsuperscript{261} Variable warehouse costs, particularly handling costs, diminish by mechanization or automation.\textsuperscript{262} However, increasing mechanization or automation reduces flexibility.\textsuperscript{263}

\textsuperscript{250} Eynan (1999: 38ff.) considers a central warehouse for a single product that supplies retailers from different markets, which differ in product prices and stockout costs, according to the first come, first served principle. Surprisingly the centralized system usually performs better than the decentralized one: Considering the whole system, possible cannibalization effects of low-price-market demands at the expense of high-price-market ones are overcompensated.


\textsuperscript{253} Rabinovich and Evers (2003a). Economies of scope arise as cost synergy effects, if the combined production of goods is cheaper than the separate one (Alisch et al. 2004: 771). In the literature among others the portfolio effect is given as an economic reasoning for them: Diversification in different projects reduces the total investment risk. Fritsch et al. (2001: 96) observe this effect with research and development in a multi-product company, Bohr (1996: 382f.) with the general use of financial means.

\textsuperscript{254} Economies of density are cost advantages due to increasing utilization in a transportation system (Harris 1977, Caves et al. 1984: 472).


\textsuperscript{256} Unit costs are the costs that are defined by the distribution of total costs to the output to be produced (Kistner and Steven 2002: 88).

\textsuperscript{257} Vahrenkamp (2000: 32).

\textsuperscript{258} Williams (1975), McKinnon (1989: 104).


\textsuperscript{262} Beuthe and Kreutzberger (2001: 249).

Centralization can lead to economies of massed reserves, if it is used to lower system-wide safety stock through risk pooling and thus unit holding costs.\textsuperscript{264} The latter are further reduced by less inventory loss and thus lower risk costs in the centralized system.\textsuperscript{265} Economies of massed reserves are cost savings due to centralized reserve holding with increasing firm size.\textsuperscript{266} Among others Bowersox et al. (1986: 283ff.), Fawcett et al. (1992: 5), Pföhl (1994: 141), and Delfmann (1999: 193) argue that in spite of constant basic inventory and increasing in transit inventory total inventory is lowered by reducing safety stock in the centralized system. Higher utilization of inbound transportation means with centralization decreases the number of stock placements and removals.\textsuperscript{267} Therefore setups are reduced and larger loading and unloading equipment can be used saving time in the transportation system. Reducing idle time leads to a higher utilization in time and therefore to economies of density using larger means of transportation.\textsuperscript{268}

On the other hand, in a centralized logistics system outbound transportation costs may be higher because of lower utilization\textsuperscript{269} and longer distances from the central warehouse(s) to customers\textsuperscript{270} and thus perhaps the service level might be lower\textsuperscript{271}. Centralization may entail diseconomies of scale mostly in organization.\textsuperscript{272} With increasing size there are no gains from rationalization anymore, but increasing transaction and coordination costs and thus increasing warehouse unit costs in big warehouse systems.\textsuperscript{273}

Das and Tyagi (1997) develop an optimization model for determining the optimal degree of centralization as a tradeoff between inventory and transportation costs.

**Inventory centralization games** optimize and allocate the savings from a centralized inventory, so that the participants' cooperation is maintained.\textsuperscript{274}

\textsuperscript{265} Vahrenkamp (2000: 32).
\textsuperscript{266} Scherer and Ross (1990: 100).
\textsuperscript{267} Schulte (1999: 377).
\textsuperscript{269} In the medium term smaller transportation vehicles might be used to increase utilization (Fawcett et al. 1992: 5, Delfmann 1999: 193, Vahrenkamp 2000: 31).
\textsuperscript{270} Delfmann (1999: 193), Ballou (2004b: 573ff.).
The risk pooling effect on (safety) stock levels evoked by inventory pooling or centralization can be quantified with the **square root law (SRL)**, portfolio effect (PE), and inventory turnover curve.

Maister's (1976) SRL states that the total system wide stock of \( n \) decentralized warehouses is equal to that of a single centralized one multiplied with the square root of the number of warehouses \( n \). There is some confusion about which part of inventory\(^{275} \) it can be applied to and about its underlying assumptions\(^{276} \).

Nevertheless, it **applies to** regular stock\(^{277} \), if an economic order quantity (EOQ) order policy is followed, the fixed cost per order and the per unit stock holding cost, demand at every location, and total system demand is the same both before and after centralization.\(^{278} \) It holds for safety stock, if demands at the decentralized locations are uncorrelated\(^{279} \), the variability (standard deviation) of demand at each decentralized location\(^{280} \), the safety factor (safety stock multiple)\(^{281} \) and average lead time are the same at all locations both before and after consolidation, average total system demand remains the same after consolidation\(^{282} \), no transshipments occur\(^{283} \), lead times and demands are independent and identically distributed random variables and independent of each other\(^{284} \), the variances of lead time are zero\(^{285} \), and the safety-factor (\( k\sigma \)) approach is used to set safety stock for all facilities both before and after consolidation\(^{286} \). It applies to total inventory, the sum of regular and safety stock\(^{287} \), if the aforementioned assumptions of the SRL as applied to regular and safety stock hold collectively. A formal proof is given in appendix B.

The **savings** in regular stock measured by the SRL **stem from** the assumption of constant


\(^{277} \) Regular or cycle stock is the inventory “necessary to meet the average demand during the time between successive replenishments. The amount of cycle stock is highly dependent on production lot sizes, economical shipment quantities, storage space limitations, replenishment lead times, price quantity discount schedules, and inventory carrying costs” (Ballou 2004b: 331), and “affected by inventory policy” (Ballou 2004b: 379).

\(^{278} \) Maister (1976: 125, 127, 131).

\(^{279} \) Maister (1976: 132).

\(^{280} \) Maister (1976: 130).

\(^{281} \) Maister (1976: 132).


\(^{286} \) Maister (1976: 129).

\(^{287} \) Ballou (2004b: 380). Total inventory might also include pipeline, speculative, and obsolete stock (Ballou 2004b: 330f.), which is neglected here.
fixed costs per order, holding costs, and total demand for all locations before and after centralization. Thus, if an EOQ policy is followed, the total order fixed cost usually is lower because of less orders and the inventory holding cost is lower due to a smaller total EOQ in the centralized than in the decentralized system. For the proof please refer to appendix C. This is called “EOQ cost effect” by Schwarz (1981: 147) and “order quantity effect” by Evers (1995: 5).

Savings in safety stock stem from the subadditivity of the square root (the square root of the sum of the individual demand variances of the decentralized locations is usually less than the sum of the standard deviations of demand of the decentralized locations), i.e. from balancing demand variabilities (demand risk pooling). Schwarz (1981: 147), Zinn et al. (1989: 3), and Evers (1995: 5) identify this as the portfolio effect.

Total cost savings from centralizing safety stock are probably larger than the ones from cycle stock centralization, because centralized cycle stocks have to be transported to the customer eventually, so that extra transportation costs are probably high. Centralized safety stocks only have to be transported to the customer in the less frequent case of a stockout, so that additional expenses for premium transportation are relatively small. If both cycle and safety stocks are centralized some warehouses might be closed and fixed costs saved.

Although some researchers claim the SRL estimated real savings well, in 13 of 14 practical cases we reviewed it overestimated actual inventory savings often sig-

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290 Pfohl (1994: 141). Sussams (1986: 10) gives an example where a company's savings in safety stock (calculated with the standard deviation of demand of the decentralized and centralized depots) from reducing the number of depots from five to one would only be 2.76% higher than the ones predicted by the SRL, although the variability (standard deviation) of demand at the decentralized depots is not the same, demands are not uncorrelated as the correlation coefficients we calculated show, but all locations use the same safety stock multiple (two times the standard deviation of demand). The SRL assuming uncorrelated demands coincidentally predicts similar savings to the ones calculated on the basis of the actual standard deviations in this case. Here the correlations of sales between the different depots balance each other when demands are consolidated, so that Zinn et al.'s (1989: 3) portfolio effect (percent reduction of safety stock due to centralization of correlated demands) of 57.25% resembles the savings of the SRL of 55.27%. However, as Zinn et al. (1989: 6, 10) show this need not be the case at all. Note that Sussams (1986: 10) compares two theoretical savings calculated with the SRL and on the basis of calculated standard deviations and not the theoretical savings estimated by the SRL with the actual savings realized by the company and his table contains mistakes. He concludes that the SRL “has been tested against 24 different situations, and in all cases there was close agreement between the theoretical and the practical results. It was concluded that, subject to the reservations concerning the normality of the demand pattern, the square root law may be used with confidence to estimate differences in buffer stock requirements for different configurations of depots”. However, it is not clear whether the savings theoretically predicted with the SRL were compared to actually realized or calculated savings and whether the assumptions of the SRL as applied to safety stock were fulfilled in the practical cases. Therefore Sussams' (1986: 10) conclusion is not intersubjectively verifiable.
290 Newson (1978), Voorhees and Sharp (1978: 75f.). Ballou (1981: 148ff.) shows for several real companies from different industries that the inventory savings predicted by the SRL are higher than the actual savings. This might be caused by joint ordering (to benefit from volume buying and shipping, which increases inventory levels), forward buying, diversion from the EOQ pull policy for some products, use of
significantly. This means its assumptions are not fulfilled\textsuperscript{293} in these cases or there were other inventory-\textsuperscript{294} or service-related changes. It is difficult to isolate the effect of inventory centralization.\textsuperscript{295} The SRL shows the inventory necessary for a given service level in dependence of the number of stocking locations, if its underlying assumptions are fulfilled. This does not mean that reducing the number of warehouses automatically reduces inventory.

None of the aforementioned sources states whether the assumptions to the SRL were fulfilled. Therefore actually no statements can be made about the accuracy of the SRL's results. However, it seems that the SRL “tends to over-predict”\textsuperscript{296} actual inventory savings, as its assumptions are not fulfilled: In a survey that we conducted in the winter of 2008 none of the eleven participating companies from different countries and industries fulfilled all assumptions of the SRL when applied to safety stock (table D.1). They fulfilled at least two (respondents 1, 4, and 5) and at the most seven (respondent 10) of these eleven assumptions. Only one company (respondent 3) fulfilled all five assumptions necessary for applying the SRL to regular stock. Two companies (respondents 4 and 11) did not fulfill any of the assumptions of the SRL when applied to regular stock. Evers (1995: 17) already remarked that the SRL is “based on numerous limiting assumptions which collectively are not likely to be found in practice”, although Coyle et al. (2003: 259) call them “reasonable”.

push distribution (where production considerations are more important than inventory replenishment ones) or a stock-to-demand order policy (relates inventory levels directly to demand), multiple product types with different service policies in the aggregated product group, no equal product service levels and costs, and poor inventory management. According to Ashford (1997: 20), Nike Europe intended to reduce its footwear storage locations from 20 to 2 and was predicted by the consultancy Touche Ross to save 11 % of inventory costs (calculated by us with the given data) instead of 68 % as predicted by the SRL. Nike planned to reduce its apparel storage locations from 20 to 1 with predicted savings of 12 % (calculated by us) as opposed to 78 %. Close-outs were estimated to decrease by 33 % for footwear and 50 % for apparel. It is not stated how the inventory savings were predicted and whether they were actually realized. McKinnon (1997: 81), Watson and Morton (2000), Hammel et al. (2002). McKinnon (2003: 24) considers two companies. Lovell et al. (2005), Progress Software Corporation (2007), clearpepper supply chain consulting & education (2009). We interviewed the Supply Chain Manager of a U.S. wireless telecommunication device production company with 6,000 employees. This manufacturer reduced the number of warehouses from 80 to 15 and thus reduced regular stock by 50, safety stock by 75, and total average inventory by 50 %. The SRL predicts inventory savings of 56.70 % and thus estimates the savings in regular and total stock fairly well in this case. Table D.1 shows which assumptions of the SRL this respondent 10 fulfilled.

\textsuperscript{292} A U.S. chemical company went from 100 to 89 warehouses. Inventory costs (including order processing and warehousing costs) were reduced (projected by DISPLAN and later verified from accounting records) by 76 % (compared to 6 % predicted by the SRL). These savings resulted not only from closing 11 warehouses, but also from reallocating demand among the remaining warehouses while maintaining the company's high level of customer service (Ballou 1979: 68).

\textsuperscript{293} Cf. Ballou (1981: 148ff.).

\textsuperscript{294} Ballou (1979: 68), McKinnon (1997: 81).

\textsuperscript{295} McKinnon (1997: 81).

\textsuperscript{296} McKinnon (1997: 81).
Researchers questioning Maister's (1976) SRL challenge its assumptions illogically\(^\text{297}\), do make other assumptions and therefore arrive at different results\(^\text{298}\), or give no clear reason\(^\text{299}\).

Nonetheless, the other SRL- and PE-models compared in table D.2 might be applied as their assumptions are fulfilled.

Eppen (1979) showed for the assumptions listed in table D.2 that the expected total system inventory holding and penalty costs increase with the square root of the number of warehouses.\(^\text{300}\) His research was extended to Poisson demand\(^\text{301}\), any (non-negative) demand distributions with concave holding and penalty cost functions\(^\text{302}\), and to include costs for the transportation of goods between locations with overage and underage in the centralized system\(^\text{303}\).

Zinn et al.'s (1989) portfolio effect (PE) is a generalization of the SRL and shows the reduction in aggregate safety stock by centralizing several warehouses' inventories in one warehouse in percent for the assumptions listed in table D.2. The PE was used to estimate the effect of postponement on safety stock\(^\text{304}\) and extended to include holding, transportation, facility investment, and procurement costs\(^\text{305}\), multiple consolidation points\(^\text{306}\), variable lead times\(^\text{307}\), both safety and cycle stocks (“consolidation effect”) as well as various assumptions\(^\text{308}\), the effect of non-emergency\(^\text{309}\) and emergency transshipments\(^\text{310}\), and unequal demand variances and possibly unequal capacities of centralized locations\(^\text{311}\).

\(^{297}\) Durand (2007).
\(^{299}\) Durand and Paché (2006).
\(^{300}\) Kemahlıoğlu-Ziya (2004: 9) wrongly states that Eppen (1979) “is the first to model and analyze the benefits of inventory centralization”.
\(^{301}\) Stulman (1987).
\(^{302}\) Chen and Lin (1989). They are extended by Chang et al. (1996), who consider delay supply product cost.
\(^{303}\) Zinn (1990).
\(^{304}\) Mahmoud (1992: 203ff.).
\(^{305}\) Evers and Beier (1993).
\(^{306}\) Tallon (1993).
\(^{307}\) Evers (1995).
\(^{308}\) Evers (1996). In nonemergency transshipments a certain proportion of demand is always filled from other locations' inventory (Evers 1996: 129). The PE model of Evers and Beier (1993) can be utilized to determine the percentage reduction in safety stocks from nonemergency transshipments without considering the effect on cycle stocks and transportation costs (Evers 1996: 111).
\(^{309}\) Evers (1997). The PE model of Evers (1996) underestimates the benefits of an emergency transshipment policy, as it does not adequately consider the number of locations, lead times, and desired fill rates (Evers 1997: 68ff.).
\(^{310}\) Tyagi and Das (1998: 197). Savings in aggregate safety stocks are maximal, if every centralized location delivers the same portion of each decentralized location's demand. Centralization can be beneficial, even if customers have unequal demand variances and more centralized locations are established than there are customer ones (Tyagi and Das 1998: 201f.).
The inventory turnover curve shows average inventory in dependence of the inventory throughput for a specific company. It can be constructed from a company's stock status reports and be used to estimate the average inventory (not only safety stock as with the PE) for any (planned) warehouse throughput (shipments from the warehouse or sales) without the limitations of the SRL. Thus one can assess the effect of centralization, decentralization (changing the number and/or size of warehouses), or combining warehouses on average inventory as well as the performance of inventory management and control policies for a specific company.312

3.2 Transportation

3.2.1 Virtual Pooling

Virtual pooling extends a company's warehouse or warehouses beyond its or their physical inventory to the inventory of other own or other companies' locations313 by means of information and communication technologies (ICT)314, drop-shipping315, and cross-filling316. “[D]emand across [these locations] is pooled, which smooths demand fluctuations”317. Therefore inventory availability is improved for a given “inventory investment” or maintained with less inventory.318 If virtual pooling entails cross-filling, it may pool lead times. However, this corresponds to transshipments and is considered in the next section. Therefore virtual pooling is a 1/0 – risk pooling method.

3.2.2 Transshipments

Lateral transshipments are monitored company internal or external product shipments on the same level or echelon of the value or supply chain, e. g. among retailers.319 They are also called intra-echelon transshipments320, stock transfer321, lateral (re)supply322, inventory sharing323, stock redistribution324, virtual pooling325, or information pooling326.

317 Randall et al. (2002: 56).
321 Archiballd et al. (1997).
Emergency or reactive lateral transshipments (ELT) transfer products from a location with a surplus to a location that faces a stockout. Yang and Schrage (2009: 838) regard ELT as “location substitution”.

Preventive or proactive lateral transshipments are conducted, if a retailer anticipates a stockout before demands are realized. Lee et al. (2007) combine emergency and preventive lateral transshipments in their transshipment policy “service level adjustment” (SLA).

In virtual lateral transshipments a capacitated manufacturing plant designates arriving demands to be served by another, more remote one. This can help capacitated plants to work together to better deal with random demands and save costs. In contrast to the source plant of real lateral transshipments the one of the virtual lateral transshipment may have negative inventory levels throughout the transshipment process.

All of the above lateral transshipments must not be confused with cross-docking (reloading of goods at transfer points or hubs) or shipping goods from a warehouse to a demand-satisfying location, which is also called transshipments sometimes.

If locations from the same echelon cannot transship inventory to prevent a stockout, an upper-level supplier can fill the demand via a cross-level, inter-echelon, or vertical transshipment. This might resemble virtual pooling carried out by drop-shipping.

Emergency transshipments pool both demands across locations or retailers (by permitting alternative locations to satisfy customer demands) and lead times (by providing the whole system with the possibility of partial stock replenishments) and allow a company

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325 Çömez et al. (2006).
327 Herer et al. (2006: 185f.).
329 Herer et al. (2006: 185f.).
330 Tagaras (1999), Lee et al. (2007). Preventive lateral transshipments are not useful in two-location periodic review inventory systems with nonzero replenishment lead times and uncertain future material requirements and availability (Tagaras and Cohen 1992).
331 Yang and Qin (2007).
335 Netessine and Rudi (2006).
to remain close to customers. They enable a company to exploit risk pooling or statistical economies of scale, i.e., “advantages that result from the pooling of uncertainty”.

As a result (safety) stock and (inventory holding, shortage, backorder, or total system) costs can be reduced for a given service level, which leads to leanness, customer service level (fill rates, product availability, or delivery time) can be improved without raising inventory levels, which enables agility or flexibility, or a combination of both (increasing service while decreasing inventory levels), which is called “leagility.” Transshipments may decrease lost sales, the rejection rate of returns, and replenishment lead times and improve revenues and performance.

In a static stochastic demand system, transshipments balance stock levels at different locations through emergency stock transfers from one location with overage to another one with underage. In a dynamic deterministic demand system, transshipments may save fixed and variable replenishment costs, if e.g. one location makes a larger replenishment order to transship some of it to other locations (cf. section 3.3.1 on centralized ordering).

Inventory consolidations do not pool lead times, may close stock keeping installations near markets, restructure the logistics network fundamentally, which is difficult to change or undo at least in the short term, and increase order cycle times and/or transpor-
tation costs to customers.\(^{356}\) The stockout probability for a given system inventory level is lower in a decentralized system with emergency transshipments than in a centralized one.\(^{357}\) Therefore these two systems are not generally equal as in Chang and Lin (1991) with no replenishment times and no transshipment transportation costs.\(^{358}\)

Transshipments are similar to order splitting\(^{359}\), but orders from facilities employing transshipments are not necessarily placed at the same time, while split orders are\(^{360}\) and order splitting only pools lead times\(^{361}\).

Transshipments may decrease customer service (increase the number of receipts per order and/or order cycle times) and increase transportation or rebalancing\(^{362}\), transaction (shipment documentation, receiving, handling and administration) costs\(^{363}\), the sending location's cost of reordering the transshipped product from the supplier and its probability of a stockout\(^{364}\), and daily average inventories\(^{365}\), and require willingness to share stock\(^{366}\).

**Not all supply chain members may benefit from transshipments:** they can increase overall or retailer inventories and harm the distributor or individual retailers in a supply chain, in which a manufacturer supplies integrated or autonomous retailers with a one-for-one inventory policy via a central depot.\(^{367}\)

Dong and Rudi (2002, 2004) find that if the wholesale price is endogenous, a single manufacturer benefits from its retailers' transshipments, the more, the larger the risk pooling effect. The identical (except in their normal demands) retailers in many situations are worse off under transshipment due to a higher wholesale price, especially if the risk pooling effect is large. Zhang (2005) extends Dong and Rudi's (2004) results under normal demand to general demand distributions.

Shao et al. (2009) also conclude that a manufacturer and the decentralized retailers via which he sells may be hurt by transshipments. If the manufacturer controls the transshipment price, he prefers selling through decentralized retailers. If the latter control the trans-

\(^{356}\) Evers (1999: 122).
\(^{358}\) Evers (1997: 69ff.).
\(^{360}\) Evers (1997: 75).
\(^{361}\) Evers (1999: 122, 132).
\(^{363}\) Evers (1999: 122, 2001: 312f.).
\(^{364}\) Evers (2001: 312f.).
\(^{365}\) Reyes and Meade (2006).
\(^{366}\) Evers (1999: 122).
\(^{367}\) Grahovac and Chakravarty (2001).
shipment price, they realize higher profits than a chain store and the manufacturer may prefer selling via a chain store.

Most research deals with transshipments of goods or commodities between warehouses, retailers, or production locations. Cohen et al. (1980) consider transfers of patients between hospitals and capacity decisions. Lue (2006) introduces transshipments to chemical manufacturing systems with continuous material flows to maintain non-stop operations, since it is costly to shut down and restart the production process.

Transshipments affect the ordering policy and should be considered in it. The majority of publications model transshipments and determine (optimal) replenishment order and transshipment, ordering, stocking, or inventory control, stocking or inventory control and transshipment, production and transshipment, and transshipment policies, rules, heuristics, or algorithms under different assumptions.

Similarly to the inventory centralization games in section 3.1, Anupindi et al. (2001), Granot and Sošić (2003), Sošić (2006), and Zhao et al. (2005) study the conditions (profit allocations) that make retailers jointly share their residual supply/demand with the other retailers in a manner that maximizes the additional profit in inventory sharing games. Small incentives for transshipments can achieve the benefits of a full-inventory sharing policy.

Köchel (1998a) provides a survey on multi-location inventory models with lateral transshipments, foremost on research conducted at the Technical University Chemnitz, Germany concerning the coordination of ordering decisions of all locations. Chiou (2008) and Paterson et al. (2009) present more general reviews of transshipment problems in supply chain systems and inventory models with lateral transshipments.

In summary, transshipments are a 1/1 – risk pooling method.

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Robinson (1990), Hu et al. (2005), Kukreja and Schmidt (2005).


For example Robinson (1990), Tagaras and Vlachos (2002), Hu et al. (2005), Herer et al. (2006), Olsson (2009).


Diks and de Kok (1996), Archibald et al. (1997), Hu et al. (2008).

Zhao et al. (2008).


Zhao et al. (2005).
3 Methods of Risk Pooling

3.3 Procurement

3.3.1 Centralized Ordering

Centralized ordering\(^{376}\) places joint orders for several locations and later allocates the orders (perhaps by a depot) to the requisitioners or distribution points in consolidated distribution according to current demand information.\(^{377}\) This is also called pooling risk over (the) outside-supplier lead time(s)\(^{378}\), "lead time pooling […] achieved by consolidated distribution"\(^{379}\), "coordinated replenishment"\(^{380}\), "central ordering"\(^{381}\), or "centralized purchasing"\(^{382}\).

The allocation decision is postponed and stochastic demands can be treated in an aggregate form until it is made. This reduces uncertainty and system stock “because of a portfolio effect over the lead time from the supplier”\(^{383}\), “portfolio efficiencies”\(^{384}\), or “statistical economies of scale”\(^{385}\). As explained at the beginning of this chapter, centralized ordering does not entail lead time pooling, so that lower-than-average supplier lead times may not balance higher-than-average ones. Consequently, centralized ordering is a 1/0 – risk pooling method.

Compared to independent and individual or local\(^{386}\) ordering centralized ordering can lead to economies of scale, i.e. it can take advantage of quantity discounts (“joint ordering effect”\(^{387}\)) and save ordering\(^{388}\) and shipping costs\(^{389}\). It can make more frequent shipments economical in comparison to direct delivery from the suppliers and thus reduce inventory even further or increase the service level\(^{390}\).

If a warehouse, depot, or distribution center (DC) is introduced to allocate the stock\(^{391}\), DC operating and extra transportation costs from the DC to the requisitioners or retailers are incurred.\(^{392}\) A unit must travel a longer distance from the supplier to the retailer. However,

\(^{380}\) Gürbüz et al. (2007: 293).
\(^{381}\) Ganeshan et al. (2007: 341).
\(^{382}\) Anupindi et al. (2006: 149f.).
\(^{384}\) Eppen and Schrage (1981: 52).
\(^{386}\) Ganeshan et al. (2007: 341).
\(^{388}\) Eppen and Schrage (1981: 52).
\(^{392}\) Cachon and Terwiesch (2009: 341).
the holding cost for each unit of inventory at the DC is probably lower than at the retail stores.393

The value of risk pooling through holding inventory at the warehouse, depot, or DC (“depot effect”394) and using this inventory “between system replenishments to ‘rebalance’ retailer inventories which have become ‘unbalanced’ due to variations in individual retailer demands” (between replenishment risk pooling)395 can be substantial396 (cf. inventory pooling). Schwarz et al. (1985) and Badinelli and Schwarz (1988) find it is not significant, perhaps because the model of Deuermeyer and Schwarz (1981) that they use does not allow the warehouse to balance retailer inventory levels, if system stocks are low397.

3.3.2 Order Splitting

Order splitting is simultaneously partitioning a replenishment order into multiple orders with multiple suppliers398 or into multiple deliveries (scheduled-release)399. The single order and thus its lead time are split into multiple orders or deliveries and their lead times, so that the variabilities of these lead times may balance each other400. Thus safety stock needed for a given service level (inventory availability, expected number of backorders or shortage cost) can be reduced, service level increased for a given safety stock level, or both.401 It can also reduce cycle stock due to successive deliveries of smaller split orders.402 Consequently, order splitting only pools lead times, not demands403 and constitutes a 0/1 – risk pooling method.

Disadvantages of order splitting might include no “quantity and transportation discounts” because of smaller orders, a higher “administrative effort”, which electronic data interchange might mitigate, and no “long-term partnership with a single supplier”, but multiple “suppliers may ensure competitive pricing and other favorable terms”.404

Thomas and Tyworth (2006: 246f., 2007: 170f.) critically review the literature on order splitting: On the one hand, the literature assesses the effect of order splitting on the distri-
bution of effective lead times and safety stock carrying and shortage costs with statistics. On the other hand, it compares the average total cost (inventory holding, ordering, shortage, and purchase cost) of order splitting with the one of not order splitting and finds that it reduces cycle stock. Order splitting and the just-in-time inventory strategy are analyzed by Pan and Liao (1989), Ramasesh (1990), Hong and Hayya (1992), Hong et al. (1992), Kelle and Miller (2001), and Ryu and Lee (2003). Simultaneously splitting an order among suppliers does not decrease the sum of in-transit and cycle stock, but only total safety stock in the system and increases ordering and shipping costs. Most researchers neglect transportation economies of scale, the size of transportation costs compared to inventory costs, in-transit inventory, the probability of lead time correlation, order dependent supply lead times and unit purchasing prices, and the derived disadvantages and advantages of order splitting.

Options other than simultaneously splitting replenishment orders among several suppliers might be more promising. Delivering an order in sequential shipments can reduce demand and production variability because of advance demand and delivery information. Orders can also be split between a fast, reliable and a cheaper, less reliable mode or supplier in order to take advantage of cost-performance differences in transportation modes or between capacitated suppliers. Lead time variability and freight rates could be
reduced by stable, periodic, long-term transportation commitments.\textsuperscript{419} Using emergency transshipments instead of order splitting to reduce variation is attractive in many situations, not only because order splitting is contrary to current theory and practice of vendor relations and lean production.\textsuperscript{420}

3.4 Production

3.4.1 Component Commonality

Component commonality or part standardization\textsuperscript{421} designs products that share parts or components\textsuperscript{422}. These common components can be used for several products.\textsuperscript{423}

Component commonality is a 1/0 – risk pooling method: Demand for the individual components is aggregated (pooled\textsuperscript{424}) to the demand for the (fewer) generic common component(s).\textsuperscript{425}

This may\textsuperscript{426} reduce the variability of demand (quantity and timing uncertainty) and the required (safety) stock for any constant service level\textsuperscript{427}, increase the service level for a given inventory, or lead to a combination of both, inventory reduction and service increase\textsuperscript{428} due to risk pooling\textsuperscript{429}. Furthermore, component commonality can lower setup, ordering, inventory holding\textsuperscript{430}, manufacturing\textsuperscript{431}, logistics\textsuperscript{432}, and part costs\textsuperscript{433} due to econ-

\textsuperscript{419} Thomas and Hackman (2003), Henig et al. (1997).
\textsuperscript{420} Evers (1999: 133).
\textsuperscript{422} Srinivasan et al. (1992), Jönsson et al. (1993), Meyer and Lehnard (1997), Ma et al. (2002), Mirchandani and Mishra (2002), Kim and Chhajed (2001), Labro (2004), Van Mieghem (2004), Ashayeri and Selen (2005), Chew et al. (2006), Humair and Willems (2006). Swaminathan (2001: 131) and Simchi-Levi et al. (2008: 348) also consider commonality in procurement standardization, which exploits commonality in part and equipment purchasing. Demand can be pooled across a large variety of end products, if they are produced on similar machines and/or use common components. Procurement standardization is most effective, if the product is nonmodular and the process modular.
\textsuperscript{423} Grotzinger et al. (1993: 524).
\textsuperscript{424} Yang and Schrage (2009: 837).
\textsuperscript{426} Component commonality does not always reduce inventory in a dynamic inventory system with lead times under some common allocation rules (Song and Zhao 2009: 493).
omies of scale\textsuperscript{434} or order pooling\textsuperscript{435}, as well as product design costs\textsuperscript{436} and design and manufacturing time\textsuperscript{437}. The order-pooling benefit may be more important than the risk-pooling one.\textsuperscript{438} Component commonality increases the survival probability of start-up companies\textsuperscript{439} and possibly revenue\textsuperscript{440}.

Total stock of product-specific components may increase though\textsuperscript{441} depending on the used service-level measure\textsuperscript{442}. Although component commonality may reduce the average work load, it may increase workload variability and work-in-process inventory variability.\textsuperscript{443}

Excessive part commonality can reduce product differentiation, so that less expensive customization options might cannibalize sales of more expensive parts.\textsuperscript{444} While customer valuation for the high-value product and the chargeable price may be reduced, the ones for the low-value one may be increased by using commonality in vertical product line extensions.\textsuperscript{445}

Sometimes, it is necessary to redesign products and/or processes to achieve commonality.\textsuperscript{446} This may result in a smaller and more economical set of components though.\textsuperscript{447} The

\textsuperscript{432} Kim and Chhajed (2001: 219).
\textsuperscript{433} Collier (1982: 1303).
\textsuperscript{435} Hillier (2002b: 570).
\textsuperscript{436} Desai et al. (2001).
\textsuperscript{438} Hillier (2002b: 570).
\textsuperscript{439} Thomas et al. (2003).
\textsuperscript{440} Component commonality allows to produce more of a higher-margin product instead of a low-margin one, if demand exceeds capacity. Therefore it may be optimal even for perfectly positively correlated demands (no risk-pooling benefit), if products have sufficiently different margins (“revenue-maximization option”) (Van Mieghem 2004: 422).
\textsuperscript{442} Gerchak et al. (1988).
\textsuperscript{443} Guerrero (1985: 409), Vakharia et al. (1996: 3), Ma et al. (2002).
\textsuperscript{445} Kim and Chhajed (2001: 219).
\textsuperscript{447} Whybark (1989).
common component may be more expensive than the unique components it replaces. Still component commonality may reduce total cost.449

Using commonality as backup safety stock, if unique parts are not available, is better than no commonality or pure commonality, where only common parts are used.450 Pure commonality is not optimal unless it is free or there are high fixed product and process redesign or complexity costs for procuring and handling two inputs.451

A component-mismatch problem due to demand uncertainty for end products may arise.452 The equal-fractile allocation policy453 that allocates the components so that all products have an equal probability of being out of stock at the end of the period can help to reduce the required safety stock for a given target service level. However, it may keep amply available components at the component level for the product with the highest demand variability (“worst-case product”), although they may be employed to manufacture other end products. This can be avoided by modifying the policy accordingly.454

Although some publications assert that cost decreases with commonality in general, there are contradictory claims on the effect of commonality on various cost elements and commonality's impact on total cost cannot be determined in general yet.455

Wazed et al. (2008) review the literature on component commonality. For a review of advantages and disadvantages of component commonality in manufacturing and degree of commonality indices in designing new or assessing existing product families please refer to Wazed et al. (2009). Boysen and Scholl (2009) develop a general solution framework for component-commonality problems.

3.4.2 Postponement

Postponement in general means delaying a decision in production, logistics, or distribution in order to be able to use more accurate information because of a shorter forecast period and an aggregate forecast456, especially in industries with high demand uncertainty,457 and commit-

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450 Hillier (2002a).
ting resources rather than to demand rather to forecast. The opposite strategy of holding finished goods at locations close to customers in anticipation of sales is called speculation.

Postponement strategies can be applied to form, time, and place. This can include product development, purchasing, order(ing), fulfillment assignment, production, manufacturing, assembly, packaging, labeling, delivery, and pricing postponement. Form postponement delays product finalization or differentiation until after customer orders have been received. Time postponement delays the forward movement of stock. Rabinovich and Evers (2003b: 36, 41f.) consider emergency transshipments and inventory centralization forms of time postponement. Place postponement keeps inventories in centralized locations until customer orders are received. Logistics or geographic postponement combines time and place postponement. It delays the transportation to individual market areas. Pull postponement moves the decoupling point up-balancing effects, statistical economies of scale, or risk pooling (Bretzke 2010: 77f.). For further explanations please refer to e.g. Neumann (1996: 9f.), Sheffi (2004: 93), Nahmias (2005: 55), Donnellan et al. (2006: x), Simchi-Levi et al. (2008: 60), and Schnuckel (2010: 152).

References:


Bucklin (1965).

Van Hoek et al. (1998: 33).


Yang et al. (2004: 1052).

Granot and Yin (2008), Chen and Lee (2009), Li et al. (2009).

Allowing online sales to accumulate and postponing assigning them to fulfillment sites can reduce holding, backorder, and transportation costs (Mahar et al. 2009: 561).


Zinn and Bowersox (1988).


Anupindi and Jiang (2008: 1876).


Up to the decoupling point, order-penetration-point, variant determination point, freeze point (Piontek 2007: 86f.), or point of (product) differentiation (PoD) (Lee 1996, Lee and Tang 1997, Meyr 2003) standardized products are made to stock customer-anonymously based on sales forecasts (push strategy). After an order has been received, the standardized products are transformed into various variants customer-individually (make-to-order pull strategy) (Piontek 2007: 86f., Harrison and Skipworth 2008).
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Waller et al. (2000: 138) consider upstream postponement, e. g. delaying ordering of raw materials, and downstream postponement, e. g. distribution or place postponement. Postponement allows to ship a single common generic product longer down the supply chain and change it to individual products (differentiate it) more responsively according to more recent demand information later. On the preceding levels of the supply chain the demands for the individual products are aggregated to the demand for the generic product (demand pooling), which fluctuates less, since the stochastic fluctuations of the individual demands balance each other to a certain extent because of the risk pooling effect. Postponement constitutes a 1/0 – risk pooling method.

Furthermore, inventories of the common intermediate product can function as a common buffer. A learning effect may arise, if forecasts can be improved on the basis of observed sales data. Thus the total inventory holding costs and stockouts can be reduced and customer service level and profits increased by better matching supply and demand.

Besides this risk and cost reduction, postponement can lead to economies of scale, synergistic effects, delayed increase in costs in the value chain and thus decreased capital commitment, and higher flexibility or leagility. However, it is usually necessary to redesign the product specifically for delayed differentiation and to modify the order of manufacturing steps (resequence or operations reversal). This may decrease production volume variability though. Time-based postponement at the company level can increase

supply chain inventory, as other members of the supply chain may be forced to use more speculation, i.e. hold more inventories.\textsuperscript{491}

Postponement reduces risk associated with order mix and order quantity, but may increase stockouts or lost sales due to longer lead, delivery, or order cycle times.\textsuperscript{492} Speculation provides a high availability and flexibility because of short lead times and few stockouts.\textsuperscript{493} Decreasing (increasing) speculation and increasing (decreasing) postponement increases (decreases) transportation costs and decreases (increases) inventory holding costs.\textsuperscript{494}

Postponement and speculation can be combined installing an intermediary stage between the suppliers and the buyers close to the buyers and holding uncommitted, anticipatory inventory of the suppliers ready to be shipped on request\textsuperscript{495} or “postponing only the uncertain part of the demand and producing the predictable part at a lower cost without postponement” in “tailored postponement”\textsuperscript{496}. “The combined principle of postponement-speculation”\textsuperscript{497} may lower both inventory risk by centralization and order fulfillment times and lost sales.\textsuperscript{498} Internet retailers, for instance, depend more on both inventory location speculation (in-stock inventory) and postponement (drop-shipping) to fulfill their orders as their market share and product popularity increase.\textsuperscript{499}

As products are only delivered after a customer order is received, in general postponement leads to a \textit{centralized logistics system}.\textsuperscript{500} Speculation rather has a decentralizing effect on the logistics system\textsuperscript{501} and finished products inventory is stored as close as possible to customers. At the same time speculative processes lead to consolidated flows of goods because of higher order quantities.\textsuperscript{502} Consolidated flows of goods support the tendency towards centralized logistics systems.\textsuperscript{503} These opposite movements are no contra-

\textsuperscript{491} García-Dastugue and Lambert (2007).
\textsuperscript{495} Bucklin (1965: 31).
\textsuperscript{496} Chopra and Meindl (2007: 366).
\textsuperscript{497} Bucklin (1965: 28).
\textsuperscript{499} Bailey and Rabinovich (2005).
\textsuperscript{501} Bailey and Rabinovich (2005).
\textsuperscript{504} Pfohl et al. (1992: 95), Kloster (2002: 122).
diction, but rather proof of the complex interdependencies between process and structure variables in logistics systems.\textsuperscript{504}

In practice there is a trend towards customer order oriented logistics systems\textsuperscript{505} or postponement as a logical consequence to centralization\textsuperscript{506}, increasing uncertainty in buyer markets, increasing product variety, individualization of demands, and regional expansion of supply in a globalized economy\textsuperscript{507}.


Van Hoek (2001) reviews the literature on postponement dating back to 1965 and puts it in a systematic framework. Boone et al. (2007) review postponement literature published from 1999 to 2006 and conclude research should be extended to non-manufacturing postponement, investigate the slow rate of postponement adoption among practitioners, and continue assessing the relationship between postponement and uncertainty.

### 3.4.3 Capacity Pooling

Capacity pooling is the consolidation of production\textsuperscript{508}, service\textsuperscript{509}, transportation\textsuperscript{510}, or inventory capacities of several facilities.\textsuperscript{511} Without pooling every facility fulfills demand just with its

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\textsuperscript{504} Klaas (2002: 157f.).
\textsuperscript{505} Van Hoek et al. (1999b: 506).
\textsuperscript{506} Van Hoek (1998a: 95).
\textsuperscript{507} Ihde (2001: 36).
\textsuperscript{509} Cachon and Terwiesch (2009: 149ff., 325, 349, 467).
own capacity. With pooling demand is aggregated and fulfilled by a single (perhaps virtually) joint facility. If demand is stochastic, a higher service level can be attained with the same capacity or the same service level can be offered with less capacity. It is also advantageous, if there are economies of scale in obtaining capacity or satisfying demand. Capacity pooling may pool supplier lead times, if the capacities receive separate deliveries from the suppliers and provide the whole system with the possibility of partial stock replenishments. However, this is considered under stock sharing (transshipments). Consequently, capacity pooling is regarded as a 1/0 – risk pooling method.

It is predominantly associated with combining manufacturing capacity and thus creating manufacturing flexibility. We adopt this view in the following and subsume pooling of inventory capacity under inventory pooling. Manufacturing flexibility means that a plant is capable of producing more than one product. With no flexibility each plant can only produce one product, with total flexibility every plant can produce every product (as in manufacturing postponement). Flexibility allows production shifts to high selling products to avoid lost sales.

Capacity pooling can increase effective capacity to serve more demand, which leads to higher expected sales, profits, and capacity utilization or lower manufacturing flow time. Aggregating demands which were served by individual capacities before and are now served with pooled capacity can reduce demand variability and thus the demand-capacity mismatch cost. However, installing flexibility is expensive. If demands are of different variability, pooling production capacities may increase inventory costs for the low-demand-variability facility or total cost.

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512 Yu et al. (2008: 1).
513 Anupindi et al. (2006: 224), Yu et al. (2008: 1).
514 Yu et al. (2008: 1).
518 Cachon and Terwiesch (2009: 344f.).
519 Pooling server capacity in a queuing system does not affect utilization, as demand is never lost, but might have to wait longer than desired. The amount of demand fulfilled is independent of the capacity structure (Cachon and Terwiesch 2009: 346).
523 Jain (2007).
3 Methods of Risk Pooling

3.5 Sales and Distribution

3.5.1 Product Pooling

Product pooling is the unification of several product designs to a single generic or "universal design" or reducing the number of products or stock-keeping units ("SKU rationalization") thereby serving demands that were served by their own product variant before with fewer products.

The demands for the different products are aggregated to the demand for the universal design or the reduced number of SKUs, which fluctuates less thanks to risk pooling. Thus product pooling can reduce demand variability, improve matching of supply and demand, reduce the demand-supply mismatch cost, and increase sales and profit or lower inventory for a given target service level. Thus, product pooling constitutes a 1/0 – risk pooling method.

However, a universal design might not provide the desired functionality to consumers and therefore might not achieve the same total demand as a set of focused designs. It does not permit price discrimination and may be more expensive than focused designs, because the components or quality of components of the universal design targeted to many different uses might not be necessary to some consumers. There might be economies of scale in production and procurement of a single universal component relative to small quantities of several components and lower labor costs though. The risk pooling benefits of selling a universal product may compensate its higher cost.

Product pooling is closely related to postponement, where the differentiation of a universal product to individual ones is delayed, standardization, and component commonality. It may prohibit risk pooling benefits from product substitution.

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527 The demand-supply mismatch cost is the cost of left over inventory (overage cost) and the opportunity cost of lost sales (underage cost) (Cachon and Terwiesch 2009: 257-263, 433f.).
530 Cattani (2000).
3.5.2 Product Substitution

In product substitution one tries to make customers buy another alternative product, because the original customer wish is out of stock\(^{532}\) or although it is available ("demand reshape"\(^{533}\)).

In manufacturer-driven substitution the manufacturer or supplier makes the decision to substitute. Typically the manufacturer or supplier substitutes a higher-value or functionality product, component, or service for a lower-value or functionality one that is not available (downward substitution)\(^{534}\). Axsäter (2003b: 438) compares this to unidirectional transshipments, where transshipments are only allowed in one direction, perhaps because warehouses differ in their shortage costs. Swaminathan (2001: 130) and Simchi-Levi et al. (2008: 348) relate substitution to product standardization: With risk pooling through product standardization a large variety of products may be offered, but only a few kept in inventory. If a product not kept in stock is ordered, either the product is made or procured or the order filled by downward substitution.

In customer-driven substitution, a customer makes the decision to substitute, because his original wish is not available.\(^{535}\)

If only one of two products is a substitute for the other one, this is called one-way substitution. In two-way substitution either product substitutes for the other one.\(^{536}\)

Substitution allows the manufacturer or retailer to aggregate demand across substitutable components or products\(^{537}\) (demand pooling\(^{538}\)). Demand reshape increases the demand mean and variability of one product while reducing them for the other product. Substitution and demand reshape reduce total demand variance\(^{539}\) ("demand-pooling effect of substitution"\(^{540}\)) and thus allow to reduce the safety stock for a given customer service level (product availability, fill rate, or average backlogged demand)\(^{541}\), increase service level without increasing inventory, or a combination of both\(^{542}\) or increase total profit and raise the customer service level simultaneously by risk pooling\(^{543}\). Product substitution is a 1/0 – risk pooling method.

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\(^{533}\) Eynan and Fouque (2003, 2005).


\(^{536}\) Chopra and Meindl (2007: 325).

\(^{537}\) Chopra and Meindl (2007: 324ff.).


\(^{539}\) Eynan and Fouque (2003, 2005).

\(^{540}\) Ganesh et al. (2008: 1124).


\(^{542}\) Liu and Lee (2007).

4 Choosing Suitable Risk Pooling Methods

Findings from our thorough literature review are now merged in a synoptic comparison about conditions favoring the ten identified risk pooling methods, their advantages, disadvantages, and basic trade-offs. Based on this synopsis a decision support tool is developed for choosing appropriate risk pooling methods for a specific situation. Therefore a situational approach is used.

4.1 Contingency Theory

We adopt a situational approach similar to contingency theory. It claims that there is no “one best way” as e. g. in Weberian bureaucracy\(^{544}\) to manage a company or make decisions.\(^{545}\) It depends (is contingent) on internal and external conditions (contingency factors).\(^{546}\) “The best way to organize depends on the nature of the environment to which the organization must relate”\(^{547}\).

Contingency theory is mainly criticized for its positivist\(^{548}\), deterministic, unidirectional, linear relationships and reduction of complex situations to a limited number of contingency factors.\(^{549}\)

Different from the usual contingency approach we not only use quantitative, empirical\(^{550}\), but mainly qualitative analysis based on reviewed quantitative analyses, which Donaldson (1999) rejects. Kieser and Kubicek (1992: 220ff.), on the other hand, propose to use empirical correlations not as causalities, but for further interpretations, hypotheses, and empirical analyses. Höhne (2009: 89) and the references she gives support that contingency factors are based on both empirical analyses and plausibility assumptions.

We cannot confirm that there is “[o]ne best way for each given situation”\(^{551}\) as our contingency factors are not exhaustive and mutually exclusive and thus several risk pooling methods may be adequate. However, Donaldson (1996: 118ff.) remarks there are as many

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\(^{544}\) Weber (1980: 124ff., 551ff.).

\(^{545}\) Scherer and Beyer (1998: 333ff.).


\(^{547}\) Scott (1981: 114).

\(^{548}\) Positivism is “a system recognizing only that which can be scientifically verified or logically proved” (Soanes and Hawker 2008).


combinations of environment, strategy, and structure (“fits”) as there are different envi-
ronmental situations. Thus, for every situation (combination of contingency factors) there
may be one best risk pooling strategy, i. e. combination and implementation of risk pooling
methods.

contingency approach obsolete. Others, however, deem it important\textsuperscript{552}, popular, often used,
and useful\textsuperscript{553}, as it is open and flexible\textsuperscript{554}, allows to be combined with other approaches to
advance research\textsuperscript{555}, to make action and design recommendations\textsuperscript{556}, to systematize contingency factors\textsuperscript{557}, and to conduct a practice-oriented analysis\textsuperscript{558}. Therefore it seems ade-
quate for our research.

4.2 Conditions Favoring the Individual Risk Pooling Methods

Table D.3 is based on our thorough literature review and shows which conditions render which
risk pooling methods favorable. The favorable conditions are demand-, lead-time-, transpor-
tation-, service-level-, order-policy-, storage-, product-, process-, company-, and competition-
related. The risk pooling methods (columns) are arranged according to the previous chapter's
structure.

Further research is needed to complete this table and confirm the favorable conditions
for the different risk pooling methods, especially for product pooling, central ordering,
(particularly non-manufacturing) capacity pooling, virtual pooling, and product substitu-
tion/demand reshape. We could only speculate and hypothesize about which risk pooling
methods the stated favorable conditions also apply to. Therefore, we only check marked
them for methods where there is confirmation in the literature and the table is not exhaus-
tive. References and explanations are given in footnotes.

\textsuperscript{553} For example in management (Hiddemann 2007: 16, Schröder 2008: 68, Müller-Nedebock 2009: 22,
2010: 253), information systems (Andres and Zmud 2001, Sugumaran and Arogyaswamy 2003, Khazanchi
2005), supply management (Staudinger 2007), business logistics and SCM (Hult et al. 2007, Huang et
al. 2008, Doch 2009: 39ff.), and supply chain risk management (Wagner and Bode 2008) research. The li-
terature database Business Source Complete accessed via EBSCOhost\textsuperscript{8} showed 1,139 results for the
search term “contingency theory” on June 18, 2010.
\textsuperscript{554} Staudinger (2007: 41), Güttler (2009: 73f.).
\textsuperscript{555} Sommerrock (2009: 144), Güttler (2009: 73f.).
\textsuperscript{557} Doch (2009: 41).
4.3 The Risk Pooling Methods' Advantages, Disadvantages, Performance, and Trade-Offs

Table D.4 presents the considered risk pooling methods' possible advantages, disadvantages, and basic trade-offs in choosing or rejecting them and compares their performance vis-à-vis other ones.

In summary, the risk pooling methods may, on the one hand, reduce demand and/or lead time variability, (safety) stock, lead time, as well as procurement, production, transportation, personnel, and warehouse cost and increase service level (product availability and fill-rate), utilization, sales, profit, and competitiveness.

On the other hand, they may increase R&D, redesign, component, product, procurement, production, transportation, transaction, and warehousing cost, as well as cycle stock and cycle time, and decrease customer service, sales, profit, and product functionality. We only check marked the respective risk pooling method's most important effects that are confirmed in the studied literature. References are given in footnotes. Explanations are only given where essential, as we already dealt with the individual risk pooling methods in detail earlier. These three choices maintain the readability of the table.

Tables D.3 and D.4 can be used to choose suitable risk pooling methods for a specific company under specific conditions. Scoring methods could be applied or the risk pooling method with the highest net present value or profit (advantages minus disadvantages expressed in monetary units) could be chosen. However, the following decision support tool condenses the most definite distinguishing factors and helps to make a first decision on possible risk pooling methods elegantly, before carrying out a more thorough cost-benefit analysis.
4.4 A Risk Pooling Decision Support Tool

Figure 4.1: Risk Pooling Decision Support Tool
The Risk Pooling Decision Support Tool (RPDST) depicted by a flow chart in figure 4.1 helps in choosing a risk pooling strategy to cope with demand and/or lead time uncertainty (1), if it cannot be reduced more efficiently by other means.\(^{559}\)

To facilitate the reader's orientation we introduced numbers in round brackets in this explanation and the flow chart. We will guide you through the flow chart step by step and critically revisit it at the end.

(2) If product variety is important, inventory pooling (IP),\(^{560}\) capacity pooling (CP),\(^{561}\) component commonality (CC),\(^{562}\) postponement (PM),\(^{563}\) product substitution (PS),\(^{564}\) transshipments (TS),\(^{565}\) virtual pooling (VP),\(^{566}\) centralized ordering (CO), and order splitting (OS) are a possibility. IP, CP, TS, VP, CO, and OS may also be applied, if product variety is not important. The first four methods might make more sense, if product variety is important. CC, PM, and PS are not expedient without product variety.

If product variety is not important, product pooling (PP), IP, CP, TS, VP, CO, and OS are considered. PP is only meaningful, if product variety is not important. The other methods may also be applied, if product variety is important.

(3) If product variety is important and the stockout penalty cost high compared to inventory carrying cost (savings), PS,\(^{567}\) TS,\(^{568}\) VP, CP, CC, PM,\(^{569}\) CO,\(^{570}\) and OS\(^{571}\) may be

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\(^{559}\) In addition to risk pooling it may be reduced by e.g. adding inventory or capacity, having redundant suppliers, which resembles order splitting, increasing responsiveness (Chopra and Sodhi 2004: 55, 60) (quick response (Heil 2006)), flexibility, and capability (Chopra and Sodhi 2004: 55, 60), and improving forecasting (Heil 2006). In LeBlanc et al.’s (2009: 29) model, for instance, PM is favorable unless the forecast is completely accurate.


\(^{567}\) Liu and Lee (2007: 1, 41). Only the risk pooling effect is considered, the financial aspect of different product margins neglected.

\(^{568}\) TS reduce demand and lead time variability by pooling demand and lead times, decrease stockouts, and thus are sensible, if stockout costs are high (Evers 1997, Needham and Evers 1998, Evers 1999: 133, 2001: 313, Jung et al. 2003, Hu et al. 2005, Wee and Dada 2005: 1519, 1529, Zhao et al. 2005: 545, Lue 2006, Chiou 2008: 428). However, in Jung et al. (2003) the savings from lateral TS decrease with increasing shortage cost from a certain value upwards.
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58 applied. PS (costs of persuading a customer to buy a substitute in case of a stockout and possible customer dissatisfaction because he did not obtain the desired product\(^{572}\)), TS (transshipping costs), VP (drop-shipping or cross-filling costs), CP (large costs to have flexibility), and CC (common component costs) may only be worthwhile, if stockout costs are high. PS\(^{573}\), PM\(^{574}\), CO\(^{575}\), and OS\(^{576}\) may also be considered, if the stockout penalty cost is low. IP is suitable, if the stockout cost is low compared to the inventory (carrying cost) savings from combining inventories, as it increases the distance between the inventory and the buyer and thus delivery time and therefore might increase stockouts\(^{577}\). As noted earlier in section 2.4 and table D.3, Dai et al. (2008: 407, 410f.) show when IP by a supplier for two retailers may increase the supplier's and retailers' total profits. We consider IP for low stockout costs only, as the decision for or against inventory pooling vis-à-vis the other risk pooling methods is considered.

(4) If (2) is answered in the affirmative, (3) with “High”, and the supplier lead time is highly variable/uncertain or long, TS\(^{578}\), VP, PM\(^{579}\), CO, and OS\(^{580}\) are considered. TS

568 PM may increase flexibility and responsiveness to customer demand (Zinn and Bowersox 1988: 133, Herer et al. 2002, Davila and Wouters 2007), increase customer service, decrease stockout costs, and thus may be sensible, if stockout costs are high.

570 Eppen and Schrage (1981: 51), Schoenmeyr (2005: 5). CO may increase responsiveness to customer demand, if the allocation of the central order to the delivery warehouses, retailers, or stores can be postponed and made more responsively according to more recent demand information (Cachon and Terwiesch 2009: 341), decrease stockout costs, and thus may be sensible, if stockout costs are high.

571 OS can reduce lead time (variability) through lead time pooling and increase inventory availability. Therefore it can be reasonable, if stockout costs are high (Evers 1999: 122, 132).


573 PS may be worthwhile in case of low stockout costs, if the sold substitute's profit margin is higher than that of the original product wish. Besides, even if the original customer wish is available, PS or demand reshape lowers the total variability of demand and thus inventory costs (Eynan and Fouque 2003, 2005).

574 Besides the risk and stockout cost reduction, PM can lead to economies of scale, synergistic effects, delayed increase in costs in the value chain and thus decreased capital commitment, and higher flexibility (Lee and Tang 1997: 52, Van Hoek 2001: 162, Aviv and Federgruen 2001b: 579, Herer et al. 2002, Kim and Benjaafar 2002: 16, Ma et al. 2002: 534, Graman and Magazine 2006: 1078, Piontek 2007: 86f.). Therefore it may be worthwhile, even if stockout costs are not particularly high.

575 PM (Zinn and Bowersox 1988: 125f., Van Hoek 2001: 161, Rabinovich and Evers 2003b: 35, Yang et al. 2005b: 994, Graman and Magazine 2006: 1078, Pishchulov 2008: 13, Mahar and Wright 2009: 3061) and CO (McGavin et al. 1993: 1094, Cachon and Terwiesch 2009: 341) may lead to a longer delivery time (from the supplier to the retailer) and more stockouts, and therefore stockout costs should be low. Bucklin (1965: 27) remarks that speculation, the opposite strategy to postponement, “limits the loss of consumer goodwill due to stockouts”. CO may also increase stockouts, if it decreases local knowledge (Ganesan et al. 2007: 341).

576 Although OS may reduce lead time variability, the split orders are delivered sequentially and thus may lead to more stockouts than a single order or delivery and stockout costs should be low (Chiang 2001: 73, cf. Chiang and Chiang 1996).


578 Evers (1999: 132), Herer et al. (2002), Hu et al. (2005), Wanke and Saliby (2009). However, Evers (1996) finds the percentage reduction in safety stocks obtained by using non-emergency transshipments decreases with increasing coefficient of variation of lead time (lead time variability) and average lead
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and VP by cross-filling may pool demands and lead times, i.e., reduce demand and lead time variability. Long order cycles and inflexible production processes favor TS. Long supplier/production lead times support CO. For CO the lead time before the distribution center (DC) should be longer than the one after it. PM and CO may also reduce lead time (variability/uncertainty): “Postponement permits firms to be more responsive and other advantages that are often mentioned are risk-pooling and lead-time uncertainty reduction.” If, for instance, in CO or consolidated distribution product differentiation is delayed (PM) in the DC, total lead time may be reduced. Since larger common orders for multiple locations make more frequent shipments economically possible between the suppliers and the DC and the DC and the retailers, consolidated distribution might decrease lead time (uncertainty) despite the additional lead time from the DC to the various retailers. If there is no DC and the retailers merely place joint orders with the suppliers which are then allocated according to more recent demand information to the retailers just before the delivery means leave the suppliers, there is no additional lead time between the DC and the retailers. The retailers’ higher demand power through CO and closer collaboration between the retailers and the suppliers might further reduce average lead times and lead time fluctuations. OS only pools lead times and is only worthwhile, if lead time.

Transhipments may be seen as a type of time postponement (Rabinovich and Evers 2003b). Kelle and Silver (1990a, 1990b), Pan et al. (1991: 4), Evers (1997, 1999: 122, 132), Kelle and Miller (2001), Thomas and Tyworth (2006, 2007: 178, 188). According to Thomas and Tyworth (2007: 188), sequentially releasing a split order according to more recent demand information may reduce demand variability. Chiang and Chiang (1996) and Chiang (2001: 67, 73), however, recommend “splitting an order into multiple deliveries” for low demand variability or service level only. The number of stockout possibilities is proportional to the number of deliveries. Thus OS increases stockouts, the more, the more variable demand is. Kelle and Miller (2001: 407) find dual sourcing may decrease stockouts, if there is no “single, reliable supplier […] and the variability of the lead-time demand is considerable”, but is only suitable, if lead time uncertainty cannot be reduced. According to Evers (1999: 123) and Wanke and Saliby (2009: 679) splitting a replenishment order into multiple orders only pools lead times, not demand. Consequently, we recommend OS only for high lead time variability and its lead time pooling, but not its debatable demand variability reduction effect.

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variability\textsuperscript{590} and unit values are (unusually) high (in relation to industry standards)\textsuperscript{591}. For high stockout costs per unit (3), high lead time variability (4), low order quantity and/or safety stock levels emergency TS perform particularly well compared to OS.\textsuperscript{592}

In case (4) lead times are neither highly variable/uncertain nor long, but rather demand is variable/uncertain and thus demand pooling important, PS\textsuperscript{593}, CP\textsuperscript{594}, CC\textsuperscript{595}, PM\textsuperscript{596} and CO\textsuperscript{597} may be appropriate.

\textsuperscript{591} Thomas and Tyworth (2007: 178, 188).
\textsuperscript{592} Evers (1999: 132).
\textsuperscript{594} Yu et al. (2008: 1).
\textsuperscript{595} We will now examine whether CC reduces (the effects of) lead time variability/uncertainty and therefore should be considered, if it is high:

Benton and Krajewski (1990: 407) show in a computer simulation experiment with 320 observations that manufacturing “environments with intermediate stocking points and commonality significantly dampen the effects of lead time uncertainty” (410), “tend[...] to reduce the level of backlogs as well as dampen their sensitivity to lead time uncertainty” (412), because “commonality causes intermediate inventories to increase” (413, cf. 410). However, they are more sensitive to vendor quality (“the ability to supply the requested quantity of nondefective parts or raw materials” (404)) and therefore might increase backlogs (413). Yet, the ambition of risk pooling is to decrease inventory for a given service level or vice versa or a combination of both. If there are no intermediate stocking points, they are more sensitive to lead time uncertainty (410). Hence, **CC by itself does not reduce** “the effects of lead time uncertainty”. Benton and Krajewski (1990) give no intuitive explanation for the increasing total inventory. Usually common components reduce safety and thus total stock, because they are used in several products (Labro 2004: 362).


Although Ma et al. (2002) assume “deterministic replenishment leadtimes” (Ma et al. 2002: 526), they find “the major benefits of commonality are risk-pooling and lead time uncertainty reduction. These lead to a safety stock reduction and have been studied extensively by many researchers, including, but not limited to, Baker et al. (1986), Collier (1982), Guerrero (1985), Gerchak et al. (1988), Eynan and Rosenblatt (1996), and Grotzinger et al. (1993)” (Ma et al. 2002: 524).


Under restrictive assumptions, Mohabbi and Choobineh (2005: 476, 481) conclude CC tends to be more beneficial with both random component procurement order delays and demand uncertainty than with only one of these uncertainties. They assume, for instance, that the **component procurement lead time can only be longer not shorter than the planned one**. Actual uniformly distributed demand for finished products, however, can be higher or lower than the forecast (476). Costs (481), safety stock and safety lead times are neglected. Backorders are filled after current demand (475). These researchers do not explain the causes for their observations. Lead time delays mostly reduce average total inventory per component per period (477f.), as they perhaps reduce the time a component remains in storage. This effect increases with increasing demand uncertainty (477), perhaps because a longer-than-planned delivery time may be offset by lower-than-forecast actual demand. This may be amplified by CC and lead to a higher service level than without commonality. However, the product with the lowest number of (three) components and without commonality shows the lowest inventory per component and the highest service levels (478f.).

Song and Zhao (2009: 22) even find that in dynamic assemble-to-order systems commonality may not decrease inventories under the first-in-first-out (FIFO) with identical and under the FIFO and modified FIFO (MFIFO) rule for dynamically allocating common components to demand with non-identical com-
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(5) If (2) is “Yes”, (3) “High”, (4) “Yes”, and the fixed cost per order high, TS, VP, PM, and CO are favorable. If the replenishment order cost is high, one rather resorts to other cheaper and/or faster possibilities (TS, VP, and PM) than placing a replenishment order or tries to combine orders by CO to reduce the number of orders and exploit economies of scale (EOS) and thus lower ordering costs. If it is low and there are no transportation EOS, OS may be considered. Due to smaller orders OS cannot take advantage of quantity and transportation discounts and a long-term partnership with a single supplier, but several suppliers may guarantee competitive pricing and other advantageous terms. TS, VP, and PM may also be applied, if the fixed order cost is low.

(6) In case (2) is “Yes”, (3) “High”, (4) “Yes”, (5) “High”, and the transshipment or transportation cost is high and there are EOS in ordering, CO or PM can be worthwhile. If the transshipment or transportation cost is low and there are no EOS in ordering, TS, VP or likewise PM can be applied. PM may forego EOS.

Component replenishment lead times. “The value of commonality tends to decrease as […] the common component replenishment lead time] increases under either FIFO or MFIFO”. If the common component replenishment lead time fluctuates strongly and the common component is not available, all the products using this component cannot be built. Thus lead time variability/uncertainty of the common component supplier might be more severe than of a specific component supplier (cf. Benton and Krajewski 1990: 413, Labro 2004: 363).

All these findings led us to not recommend CC by itself for coping with high lead time variability/uncertainty and to only consider it for the low lead time variability/uncertainty case.

If we follow Cachon and Terwiesch (2009: 336, 339, 341f., 349), CO may only pool demands and may also be applied if lead time (variability) is low. PM or delayed differentiation and CO may increase lead time and only pool demands during lead time.


Evers (1999: 122f.).

For TS the fixed order cost is irrelevant (Evers 1999: 132).


Allowing online sales to accumulate and postponing assigning them to a fulfillment site can lead to lower inventory costs (Mahar and Wright 2009), higher utilization of transportation means, and EOS in ordering. PM does not necessarily increase transportation distance, so that transportation costs may be irrelevant. Customers may be willing to wait, so that no premium transportation cost is incurred. The product and process are usually designed, so that the delayed differentiation can be conducted fast (Lee and Tang 1997), the delivery delay is insignificant, and no premium transportation cost is incurred. PM can exploit EOS (Piontek 2007: 87).


Anupindi et al. (2006: 191). In VP small-orders may be drop-shipped more expensively than full truck loads (Randall et al. 2002, Cachon and Terwiesch 2009: 328f.).
Bowersox (1988: 124f.) find that labeling, packaging, and manufacturing PM can lead to lost EOS. In case of large EOS in the manufacturing and/or logistics processes some speculation should be applied instead of manufacturing and full PM. Speculation, the opposite strategy to PM, rather leads to EOS: “Speculation permits goods to be ordered in large quantities rather than in small frequent orders. This reduces the costs of sorting and transportation”\(^6\).

(7) If (2) is “Yes”, (3) “High”, (4) “Yes”, (5) “High”, and (6) “Yes”, do you prefer redesigning your products and/or processes\(^6\) to achieve leagility, both agility (responsiveness) and leanness (cost minimization), (PM)\(^6\) to a less expensive, fast implementable and changeable solution that keeps inventory closer to customers (CO)\(^6\)? If yes, you may implement PM (8), otherwise CO (9). Time and form PM are appropriate, if well-timed product delivery to and differentiation for the customer are more important than company-internal cost issues.\(^6\) On the one hand, CO may decrease responsiveness because of a lack of local knowledge about sales\(^6\) when ordering. On the other hand, it may increase responsiveness because of allocating the joint order to the delivery warehouses, retailers, or stores according to more recent demand information and because aggregate forecasts usually are more accurate than disaggregate ones.\(^6\) It is more likely that CO leads to EOS in ordering than PM. While CO and speculation lead to consolidation of goods in jointly used transfer and transformation processes and EOS\(^6\), PM tends to singularize batches of goods in separate transfer and transformation processes.\(^6\) To determine which PM strategy might be most appropriate, you may turn to Zinn and Bowersox (1988), Cooper (1993), Pagh and Cooper (1998), Yang et al. (2004), and Yeung et al. (2007).

(10) In case (6) is answered in the negative, and the less expensive, fast implementable and changeable, less cross-functional solution is preferred to redesigning products


\(^{610}\) Bucklin (1965: 27).


\(^{614}\) Alderson (1957), Rabinovich and Evers (2003b: 34).

\(^{615}\) Ganeshan et al. (2007).

\(^{616}\) Cf. footnote 456.


and/or processes and there is no or no significant lead time (uncertainty) reduction benefit in PM after all, TS and VP are considered. If in addition your supplier, wholesaler, or warehouse locations have small-order drop-shipping or cross-filling capabilities (11), VP (12) may be appropriate. If not, TS (13) may do, especially if the TS cost is lower than the VP cost. VP may reduce investment in inventory and fulfillment capabilities as well as overall handling and warehousing costs more than TS. However, VP is only recommendable, if your company possesses the necessary IS capabilities and is powerful within the supply chain, because it might lose product margin and control to the drop-shipping party, which could negatively affect service quality. The drop-shipping party might bypass the company and directly sell to customers as it possesses all the information transparency it needs. “Virtual inventories provide little benefit in product categories, such as grocery, where consolidation of orders is necessary but impossible to accomplish from a few consolidated wholesalers”.

TS and PM might be used in combination, as emergency TS, an important type of time PM, support implementing form PM.

If you do not mind redesigning products and/or processes and a more expensive mid-to long-term cross-functional implementation and your PM strategy may reduce lead time uncertainty (10), PM (14) might be the right method to reduce both demand and lead time uncertainty. TS can increase leagility like PM, but perhaps more inexpensively and faster.

Returning to (5), if the fixed order cost is low, and both demand uncertainty reduction and lead time (uncertainty) reduction and fewer order placements are preferred to only lead time uncertainty reduction, but avoiding premium transportation and in-transit inventory costs, TS, VP and PM come into question and the al-

620 Randall et al. (2002: 56), Cachon and Terwiesch (2009: 328f.).
621 Randall et al. (2002: 55).
622 Randall et al. (2002: 56).
623 Randall et al. (2002: 57).
624 Rabinovich and Evers (2003b: 41f.).
625 Herer et al. (2002: 201), Zhao et al. (2008).
627 Randall et al. (2002: 56).
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ready explained decision process (10) through (14) starts. If (15) is negated, OS\textsuperscript{629} (16) may be implemented.

Moving upwards again, in case (3) is low and (17) inventory reduction is more important than agility (customer responsiveness), IP\textsuperscript{630} and PS\textsuperscript{631} are considered. If (17) is negated, PM, PS, CO, and OS come into consideration. PM improves agility\textsuperscript{632} and flexibility\textsuperscript{633} and enables product variety\textsuperscript{634}, but may not decrease inventory as much as IP or PS. PS performs better than IP in terms of location accessibility and lost sales (customer responsiveness)\textsuperscript{635}, but may not decrease inventory as much as IP. With PS the customer may get a product right away, but not the originally desired one. CO performs worse than IP in terms of inventory reduction, but keeps inventory near customers\textsuperscript{636}. The allocation of the central order to the delivery warehouses, retailers, or stores can be postponed and made more responsively according to more recent demand information. Reducing lead time uncertainty OS may lower (safety) stock for a given service level\textsuperscript{637}, but not as much as IP, as the former only pools lead times, not demands\textsuperscript{638}. Simultaneously splitting an order among suppliers can reduce cycle stock due to successive deliveries of smaller split orders\textsuperscript{639}, but not the sum of in-transit and cycle stock in the system\textsuperscript{640}. OS may be more responsive than IP, because it reduces lead time variability and keeps inventory close to customers. However, OS may increase stockouts, if demand variability is high due to successive deliveries.\textsuperscript{641}

In case (17) is confirmed, and (18) the fast implementable, changeable, less expensive (especially in terms of transportation cost) solution with higher location accessibility and


\textsuperscript{631} PS might be seen as not as responsive as PM because the customer does not receive his original wish and is persuaded to buy a substitute, which may cause some customer dissatisfaction, but might reduce inventory more than PM.

\textsuperscript{632} Zinn and Bowersox (1988), Herer et al. (2002), Davila and Wouters (2007).


\textsuperscript{634} Cachon and Terwiesch (2009: 341).

\textsuperscript{635} Eynan and Fouque (2003, 2005).


\textsuperscript{638} Evers (1999: 122, 132).


\textsuperscript{640} Thomas and Tyworth (2006: 254).

fewer lost sales is preferred to product functionality and inventory reduction. PS (19) may be suitable. If (18) is negated, IP (20) might be the right method. In contrast to PS, IP entails aggregate and thus more accurate forecasts. Individual demand forecasts for controlling the previously separate inventories are replaced by a more accurate aggregate forecast for managing the consolidated inventory. Of course, PS can only be applied, if products or parts are substitutable, which the preceding affirmation of question (2) suggested.

If (17) is negated and (21) lead times are highly variable/uncertain or long, PM, CO, and OS are considered (cf. (4)). If then (22) the fixed order cost is high (CO and PM may be appropriate (cf. (5))) and (23) a perhaps cheaper solution, that keeps inventory closer to customers, is preferred to redesigning products and/or processes to offer customized products more responsively and there are EOS in ordering, CO (24) may be chosen. If (23) is negated, PM (25) might be appropriate.

If (22) is low (OS and PM may be appropriate (cf. (5))) and product and/or process redesign to reduce demand uncertainty and perhaps lead time (uncertainty) (cf. (4)) is preferred to only lead time pooling and keeping inventory close to customers, but incurring higher ordering costs (26), then PM (25) might be suitable. Otherwise, OS (27) may be worthwhile.

If (21) is negated and rather demand pooling is important, PM, PS, and CO are scrutinized (cf. (4)). If then (28) the less expensive, fast implementable, and changeable solution is preferred to giving the customer always the desired product (not a substitute), but in a longer delivery time and with product and/or process redesign, PS (19) may be appropriate, otherwise PM and CO are considered. If in this latter case (29) the cheaper solution that keeps inventory closer to customers is preferred to product and/or process redesign and leagility and there are EOS in ordering, then CO (24) may be appropriate, otherwise PM (14) (cf. (23) to (25)).

If the importance of product variety is denied in (2) and lead times are highly variable/uncertain or long (30), TS, VP, OS, and CO are considered (cf. (4)). In case (30) is negated and rather demand uncertainty reduction is important, PP, IP, CP, and CO (cf. (4)) are considered as they only pool demands and thus reduce demand variability, but not lead time variability. According to Dilts (2005) CO may also reduce lead times (cf. (4)).

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642 Cf. footnote 456.
644 Cachon and Terwiesch (2009: 331f.).
If (30) is affirmed, (31) the fixed order cost is high (CO, TS, and VP are considered (cf. (5))), (32) the transshipment or transportation cost is high and there are EOS in ordering. CO (33) may be reasonable (cf. (6)). If (32) is negated and (34) your supplier, wholesaler, or warehouse locations have small-order drop-shipping or cross-filling capabilities (cf. (11)), VP (35) may be appropriate, especially if it is less expensive than TS. If not, TS (36) may do (cf. (11) to (13)).

If (31) is low (OS, TS, and VP are considered (cf. (5))) and (37) both demand uncertainty and lead time (uncertainty) reduction, fewer stockouts, and order placements are preferred to only lead time pooling, but avoiding premium transportation and in-transit inventory costs of stock transfers, then TS and VP are considered further and the already explained decision process (34) to (36) is triggered again. If (37) is answered in the negative, OS (38) may be economically sensible.

If (30) is negated and (39) accommodating demand uncertainty is preferred to reducing inventory and system utilization (arrival divided by service rate) is high, CP and CO are considered. “While the relative benefit of inventory pooling tends to diminish with utilization, the relative benefit of capacity pooling tends to increase with utilization” in a production-inventory system with endogenous supply lead times. CP or manufacturing flexibility is more valuable with approximately equal total capacity and expected demand. CO does not reduce inventory as much as IP, but keeps it near customers. The postponed more responsive allocation of the central order to the delivery warehouses, retailers, or stores according to more recent demand information enables better matching of supply and demand (also cf. (17)). If afterwards EOS in ordering and a preference for a possibly less expensive, fast implementable and changeable solution are affirmed in (40), CO (33) may be appropriate. If (40) is negated and (41) CP/(manufacturing) flexibility is cheaper than capacity, CP (42) might be applied. Goyal and Netessine (2005) may help to choose a type of manufacturing flexibility (volume and/or product flexibility). If capacity is cheap-

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647 Randall et al. (2002: 56).
650 Benjaafar et al. (2005: 565).
655 Volume flexibility is “[t]he ability to adjust the output volume of a product without incurring large costs”, product flexibility “the ability to manufacture different products and to efficiently shift production from products with low demand to products with high demand” (Goyal and Netessine 2005: 2). For a monopolist, product flexibility reduces uncertainty in demand for individual products more and in aggregate de-
er than CP/flexibility, adding capacity (43) might be a better choice.\textsuperscript{656} CP may be more appropriate for manufacturing, CO for trading companies (cf. (48)).

If (39) is negated, PP and IP (cf. (17)) are considered, as inventory reduction is given priority. If then (44) product availability is preferred to product functionality, PP (45) may lead to a higher product availability than IP (46): It does not increase the distance between products and customers and may enable EOS in production and procurement of a single universal component or product, but might degrade product functionality, not achieve the same total demand as a set of focused designs, and eliminate some brand/price segmentation opportunities.\textsuperscript{657}

Returning to (4), if lead times are not highly variable/uncertain or long, rather demand pooling is important (PS, CP, CC, PM, and CO are considered), and (47) your products share components or qualities to satisfy the same or similar needs or you are willing to create these commonalities, then PS, CP, CC, PM, and CO may be applied.

Substitute goods satisfy the same or similar needs and therefore are seen as an alternative or replacement by consumers. The reason for this replacement relationship is the functional replaceability between two goods, if they correspond in price, quality, and utility or performance so that they are able to meet the consumer's need. This thus enables substitution structurally.\textsuperscript{658}

CP is also based on commonalities: Common design, assembly processing, training in common methods, suppliers capable of coping with common design and processing and reacting to volume and complexity are needed.\textsuperscript{659} CC designs products that share components.\textsuperscript{660}

PM advantages partly arise from CC.\textsuperscript{661} CO does not require (component) commonality. However, the centrally ordered products usually are needed by several requisitioners (delivery warehouses, stores, or departments). Therefore one could say the products are common to two or more locations.

\textsuperscript{656} Cachon and Terwiesch (2009: 348).
\textsuperscript{657} Cachon and Terwiesch (2009: 335).
\textsuperscript{658} Wildemann (2008: 72).
\textsuperscript{659} Mayne et al. (2008).
\textsuperscript{660} Chopra and Meindl (2007: 326ff.).
PM and CP perform better with similar demand. For PM that means that demand is of comparable size\(^{662}\) or that the standard deviations of demand for items in the product line are similar\(^{663}\), for CP approximately equal total capacity and expected demand\(^{664}\) and similar demand variability\(^{665}\). Capacity sharing among independent companies is more beneficial, if they are similar in their characteristics (work content, demand rates, or delay costs).\(^{666}\) PM may reduce EOS\(^{667}\) or increase the cycle/delivery lead time\(^{668}\).

If then (48) a less expensive, fast implementable and changeable solution is preferred to product and/or process redesign and leagility and you run a trading or retail company rather than a pure manufacturing company, then PS and CO may be applied, otherwise CP, CC, and PM.

PS can be implemented faster than CP, CC, and PM. It may only incur the costs of persuading a customer to buy a substitute\(^{669}\) and maybe cause customer dissatisfaction with the substitute purchase\(^{670}\).

CO may be less responsive, but also less expensive, implemented within a shorter time frame, and involve less departments (mainly purchasing and sales) than CP, CC, and PM. It does not require a product redesign either. CP\(^{671}\), CC\(^{672}\), and PM\(^{673}\) may necessitate a costly product and/or process redesign and therefore also involve at least manufacturing and R&D in addition.

As products are only delivered after a customer order is received, in general PM leads to a centralized logistics system\(^{674}\) and may increase the distance between inventory and customers relative to CO\(^{675}\) and even more so compared to PS. With CP a product is produced,

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662 Chopra and Meindl (2007: 363ff.).
666 Yu et al. (2008: 26).
stored, or transported, or a customer served where there is capacity, so that the distance between inventory and customers may increase.


Our survey results in appendix A support that CC\(^{679}\), PM, and CP\(^{680}\) are predominantly applied in manufacturing, CO or consolidated distribution\(^{681}\) and PS\(^{682}\) rather in trade, so that their implementation might be more promising here. PS is more efficient than CC\(^{683}\).

In case (48) is answered in the affirmative (PS and CO are considered) and (49) matching supply and demand and product functionality are preferred to a less costly, fast implementable and changeable solution with higher (substitute) product availability, but possible customer dissatisfaction because of substitution and there are EOS in ordering, then CO (33) may be appropriate, otherwise PS (50). PS offers the customer a product right away, however, not the originally desired one but a substitute, which may lead to customer dissatisfaction. CO gives the customer the desired product maybe in a longer lead time or the sale is lost. PS can be implemented and changed faster and less expensively than CO. The latter may benefit from EOS in procurement though (cf. (23)).

\(^{676}\) Yang et al. (2005b: 994).

\(^{677}\) Boone et al. (2007: 594).

\(^{678}\) Van Hoek and Van Dierdonck (2000: 205).


\(^{681}\) Eynan and Fouque (2003, 2005), Zhao and Atkins (2009).

\(^{682}\) Eynan and Fouque (2005).
If (48) is negated (CP, CC, and PM are considered), (51) the costs to have CP or (manufacturing) flexibility are lower than the costs for CC (common components, product redesign, and possible cannibalization) and PM (product and/or process redesign or resequencing), then the already explained decision process (41) through (43) has to be completed.

If (51) is answered in the negative (CC and PM are considered) and the product\(^{684}\) (cf. (47)) and (52) (manufacturing) process is modular\(^{685}\), “the firm maximizes its performance by adopting”\(^{686}\) PM (53): It “will help to maximize effective forecast accuracy and minimize inventory costs”\(^{687}\). In case the product is modular\(^{688}\) (cf. (47)) but the process is not\(^{689}\), then differentiation cannot be delayed, but CC (54) “is the most effective approach”\(^{690}\). Simchi-Levi et al. (2008: 348) express this more cautiously: CC “is likely to be effective”. However, we follow the primary source Swaminathan (2001: 132). To determine the optimal level of CC you may refer to Boysen and Scholl (2009).

Nevertheless, if the process (and the product) is modular, CC and PM may both be applied. To choose between them the CC\(^{691}\) cost (product redesign\(^{692}\) and possible cannibalization of higher priced components\(^{693}\) ) has to be traded off against the PM cost (higher production, transportation, and process and/or product redesign cost (cf. (7))). This be-


\(^{685}\) Feitzinger and Lee (1997), Van Hoek et al. (1998), Swaminathan (2001: 131), Van Hoek (2001: 173), Simchi-Levi et al. (2008: 348). A modular product, e. g. a personal computer as opposed to a shirt, is assembled from a variety of modules such that there is a number of options the customer is interested in for each module. This is important for concurrent and parallel processing (Swaminathan 2001: 128, Simchi-Levi et al. 2008: 345).

A modular (manufacturing) process, e. g. semiconductor wafer fabrication as opposed to oil refining, consists of discrete operations, so that inventory can be stored in semi-finished form between operations. Products are differentiated by undergoing a different subset of operations during the manufacturing process. Modular products are not necessarily made in modular processes (Swaminathan 2001: 128, Simchi-Levi et al. 2008: 345).


\(^{690}\) Swaminathan (2001: 132).


\(^{692}\) Sometimes, it is necessary to redesign products and/or processes to achieve commonality (Bagchi and Gutierrez 1992: 817, Swaminathan 2001: 129, 131, Ma et al. 2002: 536, Simchi-Levi et al. 2008: 345, 348), which may result in a smaller and more economical set of components though (Whybark 1989).

comes important if not form, but place and time PM are considered. CC and PM often are connected and can be applied together. Maybe applying both of them may be more economical than applying only one. PM implementation may require CC\textsuperscript{694} (“postponement through standardization”\textsuperscript{695}). According to Caux et al. (2006: 3244), PM in the form of delayed differentiation can be implemented by “process restructuring, component commonality and product design”.

If (47) is negated, then CO and CP are considered, because they do not require CC, especially if transportation or storage capacity is pooled. Yet, we consider CP related to inventories under IP. If then (55) the costs of CO are lower than both the ones of CP and adding capacity and there are EOS in ordering, then CO (33) may be effective. Otherwise CP and adding capacity are considered and the already explained decision process (41) to (43) still has to be followed.

Frequently the risk pooling methods cannot be separated mutually exclusively, because they are favorable under similar conditions as tables D.3 and D.4 already showed. If the decisions in the RPDST are not selective and disjunctive, the respective risk pooling methods are considered for both choices. The RPDST only shows tendencies and enables general statements about the advantageousness of risk pooling design options, since the specific size of the costs and benefits are unknown and the complex interdependencies are simplified. The advantageousness of specific risk pooling methods in a specific situation for a specific company depends on specific cost parameters and their interaction or ratios.\textsuperscript{696}

In a particular company case risk pooling design recommendations might differ from this RPDST. The identified conditions and recommendations for risk pooling methods depend on the selected reference framework. Therefore a study with the same topic might attain a different classification and thus different results. The framework gives general recommendations about the advantageousness of risk pooling methods. Afterwards a company should weigh the costs and benefits of the different suitable options expressed in monetary units to reach a decision about which risk pooling strategy to implement. Expenses for implementing the risk pooling strategy might exceed the achievable savings.\textsuperscript{697}

Some benefits besides decreased (inventory) cost such as increased flexibility, responsiveness, and customer service level are hard to quantify. Resequencing due to PM might lower inventory levels, but increase the inventory value per unit. However, if customiza-

\textsuperscript{695} Ma et al. (2002: 534).
\textsuperscript{696} Cf. e. g. Wanke (2009) on IP.
tion is postponed, the generic products may have a lower value than the customized ones. Tariffs and duties for undifferentiated products might be lower. Still, products and processes might be more expensive under some risk pooling methods.  

Implementing risk pooling might lead to positive or negative effects not studied in detail in this RPDST, such as human resistance or negative impacts on the whole supply chain. It might be appropriate to apply risk pooling methods just to certain products (e.g., the ones with uncertain demand).  

Combining several risk pooling methods might improve performance. Using, for instance, time PM (e.g., emergency TS and inventory centralization), form PM (product customization), and enterprise-wide information systems together improved “enterprise-wide inventory management performance” more than using each of these methods separately in an empirical model based on 216 large and established U.S. manufacturing firms. (Logistics) PM might go hand in hand with IP (inventory centralization) or CO (centralized distribution).  

A hybrid strategy of pooling demand by centralizing inventories (IP) but splitting supply by multisourcing (OS) can be worthwhile. Substitutable products support the implementation of variety PM. Demand substitution furthermore facilitates flexible manufacturing without competition and may facilitate its adoption with competition. CP may exploit CC.  

Kutanoglu (2008) considers both emergency lateral shipments from other local facilities and direct shipments (VP in the sense of Netessine and Rudi 2006) from one central warehouse of service parts to repair high-technology hardware systems such as computers and telecommunication devices in case of a stockout at a local facility within the time window necessary for the target service level. Alfredsson and Verrijdt (1999: 1430) find conjoint use of lateral TS and direct deliveries can reduce costs significantly, particularly for slow moving parts. Investing only in direct delivery flexibility may increase costs dramatically, unless pipeline flexibility is applied. Pipeline flexibility means that a customer backorder is satisfied by the part that arrives first either via normal replenishment or via direct delivery. Similarly, Wong et al. (2007b: 1056) remark emergency direct deliveries from the central

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700 Cf. e.g. Hong-Minh et al. (2000).
701 Rabinovich and Evers (2003b: 38, 42f.).
703 Benjaafar et al. (2004a: 1442).
705 Goyal and Netessine (2006: 1).
706 Mayne et al. (2008).
warehouse and the plant in case of stockouts in a two-echelon system are only worthwhile, if lateral TS between local warehouses are not possible.

The RPDST neglects the degree to which the different favorable risk pooling methods should be applied and their opposite methods. Often two opposing methods are applied in combination to a certain degree (e.g. centralization and decentralization, consolidation and singularization, postponement and speculation). Speculative inventories, for instance, should be held in the logistics channel wherever their costs do not exceed the savings achievable by postponement.\textsuperscript{707} Furthermore, the certain part of the product line or the generic product can be made less expensively to stock, the uncertain products or product variants to order.

An empirical verification of the derived results pertaining to the design recommendations appears worthwhile. The theoretical analysis revealed fundamental interdependencies of risk pooling methods and facilitates the practical risk pooling design. Possible deviations from business practice can be disclosed by empiricism. The analytic process can be adapted accordingly. Therefore, we will apply the RPDST to a German paper wholesaler to determine risk pooling methods that may reduce the demand and lead time uncertainty it faces.

\textsuperscript{707} Bucklin (1965: 28).
5 Applying Risk Pooling at Papierco

In this chapter we will first introduce Papierco to you and some problems it faces. Afterwards we will determine risk pooling methods with the help of the RPDST developed in the previous chapter to solve these problems and consider their application at Papierco in more detail. Finally we will summarize our results.

5.1 Papierco

A German paper wholesale company (to protect confidentiality we call it Papierco in the following) pursues the business strategy of a decentralized, differentiated full-line distributor and system provider of paper, printing accessories, as well as screen printing and advertising systems, which precludes central warehouses and minimal storage. This corporate strategy seems to be Papierco's competitive advantage, as its competitors cannot offer such a ubiquitous and fast delivery service as well as broad assortment. The decentralized warehouse network also constitutes a competitive advantage in the light of increasing fuel costs, autobahn toll, climate change, environmental legislation, and increased traffic volume. Papierco delivers its products from its warehouses with its own truck fleet or has them drop-shipped from paper plants to its customers.

According to its management, Papierco is a full-line wholesaler, as its 32,739 customers (mainly printing offices) need all kinds of different product specifications mostly within 24 hours. If a product with a low turnover was eliminated from the assortment, some customers might not buy some other products either anymore due to product interdependencies. The alliance Papierco of several legally independent paper wholesalers and exchange of items between 21 regional warehouses in case of a stockout (emergency transshipments) allow the individual companies and locations to offer a larger product assortment than they could store on their own. Not every of the 7,000 product specifications Papierco offers is stored at every location. Products with a low turnover share are only stocked at few locations due to cost considerations.\textsuperscript{708} This is called “selective stocking”\textsuperscript{709}, \textbf{selective stock keeping}\textsuperscript{710}, or “specialization”\textsuperscript{711}. The idea behind selective stock keeping is lowering inventory holding costs by treating products differently without impairing the service level.

\textsuperscript{709} Ross (1996: 310f.).
\textsuperscript{710} Pfohl (2004a: 118ff.).
\textsuperscript{711} Anupindi et al. (2006: 191f.).
considerably.712 **Transshipments** between Papierco's locations are necessary, so that every location can offer the complete assortment. The shipping decision is postponed until a customer order is received. Every warehouse thus functions as both a regional and central warehouse and can access products in every other warehouse as if all warehouses were one single warehouse (**virtual inventory** or warehouse). Hence Papierco takes advantage of **inventory pooling**, but mitigates some of the disadvantages of a central warehouse through the use of transshipments and information technology.713

### 5.2 Problems Papierco Faces

#### 5.2.1 Fierce Competition in German Paper Wholesale

Paper wholesale in Germany is characterized by strong competition especially in office, illustration printing, and offset paper: Sales stagnate, sales prices decrease, raw material, energy, and logistics costs increase. A lot of customers go bankrupt and there is an ongoing concentration process in the printing industry.714 Paper manufacturers, the paper wholesale's suppliers, suffer from bad profitability due to increasing costs, overcapacities, and price pressure715, as well as competition pressure from Asia and Eastern Europe716, which they seek to improve by mergers and markups. The current international economic downturn intensifies the cost and competition pressure in all industrial sectors. Insufficient capacity utilization is a strain on the paper wholesale, its customers, and suppliers. Increasing profit margin pressure is believed to promote the consolidation tendency on all levels of the value chain.717 Thus paper wholesale faces strong competition and economically stricken customers and suppliers, whose negotiation power increases because of mergers. Competitiveness and economic success can be secured on this market by efficient supply, storage, and distribution planning enabled by risk pooling, particularly since logistics incurs the highest costs at Papierco.

#### 5.2.2 Supplier Lead Time Uncertainty

The lead time of paper manufacturers fluctuates strongly, ranges from 14 to 154 days, and is on average 28.49 days. It fluctuates subject to price increases, drop-shipping sales, (international) demand, and production setup times. Supplier lead times are entered into the enterprise

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714 BVdDP (2009).
717 BVdDP (2009).
resource planning (ERP) system by a central master data maintenance in three German Papierco locations. The actual lead time of each supplier should rather be recorded for every delivery to improve the purchasing policy.

Because of long and uncertain lead times for certain products paper merchants sometimes place so called “phantom orders” for product quantities they do not actually need as a precaution, which intensifies the bullwhip effect\textsuperscript{718} and leads to even longer and more variable lead times. This once resulted in all orders having to be cancelled and only entering real orders (with a corresponding real demand) again afterwards. Thus lead times normalized again.

\subsection{5.2.3 Customer Demand Uncertainty}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{sales_data.png}
\caption{Total Fine Paper Sales in Tons per Month in Germany (BVdDP 2010a: 8)}
\end{figure}

\textsuperscript{718} Lee et al. (1997a: 98).
Total demand for fine paper in Germany is seasonal: It is higher in January, February, and March, lower from April till July, and increases up to November in order to decrease again in December as figures 5.1 and 5.2 show. Total customer demand depends on the overall economic development, i. e. on the available financial means for e. g. new products and advertising budgets.

Warehouse sales made up 42 %, drop-shipping sales 58 % of all sales in 2007 and 2008,\textsuperscript{719} respectively 43 % and 57 % in 2009\textsuperscript{720}. Warehouse sales of individual products per week per warehouse are sporadic without a trend or seasonal pattern as figure 5.3 shows exemplarily.

\textsuperscript{719} BVdDP (2009).
\textsuperscript{720} BVdDP (2010b).
Figure 5.3: Papierco's 2007 Warehouse Sales to Customers per Week of Seven Standard Paper Products from the Hemmingen Warehouse
“When demand for items is intermittent, because of low volume overall and a high degree of uncertainty as to when and at what level demand will occur, the time series is said to be lumpy, or irregular.”

Among others many products and stocking locations might explain the lumpiness of demand for individual Papierco products. The lumpy demand condition occurs when two or three times the standard deviation of the historical data exceed the forecast of the best model that can be fit to the time series. Ballou (2003a: 9) states in the PowerPoint presentation to Ballou (2004b) a time series is lumpy, if the mean of the series is less than or equal to three times the standard deviation of the series.

Although the items in figure 5.3 are considered standard, on average they did not sell 8.29 weeks or around 16% of the year 2007 and their standard deviation of sales per week per warehouse was on average 0.94 times their mean. Fast moving copy papers selling nearly every week were the least lumpy with the standard deviation being only 0.37 times the mean on average. Uncoated Cut-Size White Wood-Pulp Paper was the lushest with no sale in 34 weeks or almost two thirds of the year 2007 and a lumpiness factor (standard deviation of demand divided by mean demand) of 2.11, followed by the Folding Box Board with no sale in 15 weeks and a lumpiness factor of 1.32.

On average the standard deviation of an item's sale per month per warehouse is 2.24 times the mean sale per month per warehouse in 2007. Nearly one third (31.45%) of the products show a standard deviation that is more than three times the arithmetic mean of sales per month per warehouse. In these cases the standard deviation is on average 3.78 times the mean. Of a lot of articles no unit is sold for several months and then suddenly some month a lot of units are sold. On average 7.83 months or nearly two thirds of the year 2007 a specific product is not sold. We conclude that demand per product per month is very random and lumpy or sporadic and therefore “difficult to predict accurately by mathematical methods due to the wide variability in the time series.” Risk pooling methods might produce relief here.

Ballou (2004b: 311) suggests to use the reasons for the lumpiness in the forecast, separate forecasting of lumpy and regular demand products, not react quickly to random demand shifts without assignable cause and use slowly reacting forecast methods such as exponential smoothing with a low smoothing constant or a regression model refit annually.


5 Applying Risk Pooling at Papierco

at the most, and maybe make up for forecast inaccuracy by a higher inventory level for low
demand items. Croston (1972) and Johnston and Boylan (1996) recommend an exponential
smoothing constant of 0.05 to 0.20 for lumpy demand. Silver et al. (1998: 127), however,
report pertaining to intermittent and erratic demand that “[t]he exponential smoothing fore-
cast methods […] have been found to be ineffective where transactions (not necessarily
unit-sized) occur on a somewhat infrequent basis. […] Infrequent in the sense that the av-
erage time between transactions is considerably larger than the unit period, the latter being
the interval of forecast updating”.

Lumpy or highly uncertain demand can be coped with by obtaining information directly
from customers, collaborating with other supply chain and channel members, collaborative
forecasting, forecasting total demand and apportioning it by regions, delaying supply re-
response, product differentiation, and forecasting as long as possible, supplying the more
certain products first, developing quick response and flexible supply systems, and applying
the forecasting methods with caution. Most of these suggested solutions rely on risk
pooling.

5.2.4 Distribution Requirements Planning (DRP)

Figure 5.4: 2007 Incoming Goods, Warehouse Sales, and Inventory at
Warehouse Hemmingen

Figures 5.4 and 5.5 illustrate Papierco's demand forecasting and inventory management problems using two standard Papierco warehouses. The inventory level is always around 1,000 to 2,000 tons higher than total warehouse sales. This may be partly explained by the large product variety. The Total Goods Received and Total Warehouse Sales curves often are opposite in phase or time-lagged, i.e. when total warehouse sales go up, often goods receipts go down or vice versa.

Sales departments, product managers, and purchasing departments of the different warehouse locations do not collaborate in planning demand and requirements. The sales departments merely plan the customers' financial development, i.e. sales and contribution margins per customer. On the basis of the product managers' aggregated sales planning on the product group level for all German locations skeleton agreements are centrally negotiated with the most important suppliers. The purchasing departments forecast demand on the product level on the basis of the past six months' sales and order accordingly. These three planning processes are unconnected. The sales departments do not report any expected exceptional demands to the purchasing departments either. The latter only plan products sold via warehouses, without considering substitution effects between similar
products or between warehouse and drop-shipping sales\textsuperscript{726}. Drop-shipping sales are conducted only by the sales departments.

Papierco should create a uniform cross-functional demand planning process, in which sales, product managers, and purchasing collaborate, to contain extraordinary demands through the sales assistants' and product managers' profound market knowledge and enable a better demand forecast and thus order policy. Although Adam and Ebert (1976) show that objective statistical forecasting models produce more accurate results than subjective judgemental forecasts, Bunn and Wright (1991) remark expert forecasts had a higher quality than previous research claims. That is why Silver et al. (1998: 133) suggest combining these two approaches.

The individual locations conduct their distribution requirements planning (DRP) without any coordination, so that inventory reductions at one location strain the transshipment flows and impair other locations' DRP. Thus, one location might deplete another one's stock of a specific product via transshipments. In the following week the latter location might have to obtain this product via transshipments from another warehouse due to a customer demand and so on. Likewise a warehouse may receive a supplier's delivery, although it has plenty of inventory left, while another one does not. This process seems to have taken on a life of its own in a "vicious circle" with increasing transshipment volumes and inventory variability at most warehouse locations.

The increased transshipments did not reduce the aggregate safety stock, although this might be assumed because of the demand balancing effect thanks to the creation of a virtual inventory through transshipments. Allegedly the customer service level increased, which is difficult to verify, as Papierco does not record it in any way.

We will recommend a not necessarily geographically centralized procurement, which forecasts and orders for all of Papierco's German locations on the product level and directs the suppliers' deliveries to the warehouses according to current demand in section 5.3.3.

5.2.5 Demand Forecasting Methods

Increasing forecast accuracy decreases the need for risk pooling\textsuperscript{727} (e. g. emergency transshipments) and safety stock and increases customer service level (product availability).

\textsuperscript{726} Sometimes a drop-shipping sale is converted into a warehouse sale, if the drop-shipping lead times are high.

Today Papierco uses the forecast methods 4 (Moving Average) and 10 (Linear Smoothing) of the twelve ones the ERP software JD Edwards OneWorld offers.

Method 1 (Percent Over Last Year), method 2 (Calculated Percent Over Last Year), method 3 (Last Year To This Year) and method 8 (Flexible Method or Percent Over Months Prior) are so called “naïve estimates” and project sales of previous years into the future either directly or after multiplying them with a factor. These methods are rather inadequate for Papierco, as sales of individual products differ significantly from year to year. Method 12 (Exponential Smoothing with Trends and Seasonality) is not suitable either, as demand for individual products does not follow a trend or seasonal pattern.

Method 4 (Moving Average), Method 7 (Second Degree Approximation), which expresses sales in a curve, method 9 (Weighted Moving Average), method 10 (Linear Smoothing), which assigns weights to the sales numbers linearly decreasingly with a formula, and method 11 (Exponential Smoothing\textsuperscript{729}) are similar. They are suitable for short-term forecasts for mature products without trends or seasonal patterns.\textsuperscript{730} They could enable a good demand forecast for Papierco with an order cycle of two weeks.

Method 5 (Linear Approximation) establishes a trend on the basis of two data points. Small changes influence long-term forecasts strongly. Method 6 (Least Squares Regression) also calculates a linear trend. Turning points and changes in the demand function are recognized late with the Linear Regression. If the sales data form a curve or show strong seasonal fluctuations, systematic forecast errors appear.\textsuperscript{731} Methods 5 and 6 may be suitable for Papierco because of the short order cycle of two weeks, although demand for individual products shows no or only a short-term trend.

Analyzing the forecast methods for the seven standard products, we discovered that a forecast based on sales of the last twelve months leads to improved results compared to the current one with six months. This comes as no surprise as Gibson and Horner (2005: 1ff.) state that JD Edwards OneWorld forecasting accuracy improves with the length of the used sales history. The software is capable of using up to two years of sales history.

Method 11 (Exponential Smoothing) and method 6 (Least Squares Regression) led to the best results most frequently. Ballou (2004b: 311) also recommends these methods for forecasting lumpy demand.

\textsuperscript{728} Oracle (2009).
\textsuperscript{729} Exponential Smoothing automatically uses linearly decreasing weights and is a weighted average of actual sales and the previous period's forecast.
\textsuperscript{730} Oracle (2009).
\textsuperscript{731} Oracle (2009).
The results of method 11 (Exponential Smoothing) might be improved by letting JD Edwards OneWorld determine the smoothing constant alpha based on past sales instead of determining it arbitrarily.

Methods 9 (Weighted Moving Average), 4 (Moving Average), and 10 (Linear Smoothing) also led to good results in order of descending quality. A naïve estimation (projection of the previous year's sales into the current year) did not give good results. The results could be improved by multiplying the previous year's sales with a growth factor.

We used the mean absolute deviation (MAD) of the forecast values from the actual sales in 2006 and 2007 and the forecast error (the sum of the difference of the actual and the forecast sale per week) to measure the quality of the respective forecast method. For other forecast performance measures please refer to Gutierrez et al. (2008: 413f.).

Comparison of the forecast accuracy of forecast methods is difficult\textsuperscript{732}, as the forecast errors of the two methods may be correlated\textsuperscript{733}. Besides “a linear combination of forecasts from two or more [forecasting] procedures can outperform all of those individual procedures”\textsuperscript{734}. According to Kang (1986) a regular average of forecasts of several methods leads to high-quality results.

Tiacci and Saetta (2009) evaluate the impact of usually neglected possible interactions between demand forecasting methods and stock control systems on global system performance. Accordingly, demand forecasting methods cannot be chosen only on the basis of traditional measures of forecast errors. Total costs and service level of the global inventory control system should also be considered. However, this is beyond the scope of this thesis and remains for further research.

The products still have a lumpy demand pattern also according to Ballou's (2004b: 310) definition: “[T]he forecast of the best model that” could “be fit to the time series” was 3.39 times “the standard deviation of the historical data”.

The MAD was on average half the size of the mean actual demand per week, i.e. even with the best tested forecast method, we would have ordered half a week's average demand too much or too little per product per week on average. The absolute forecast error was on average four times the mean actual demand per week, i.e. even though the forecast errors balance each other to a certain extent we would have had four week's average demand too much or too little over the whole year per product on average.

\textsuperscript{732} Silver et al. (1998: 131).
\textsuperscript{733} Peterson (1969).
\textsuperscript{734} Silver et al. (1998: 131).
Methods 11 (Exponential Smoothing), 6 (Least Squares Regression), and 9 (Weighted Moving Average) should be admitted to the DRP forecast run besides today's exclusively used methods 4 (Moving Average) and 10 (Linear Smoothing), as they gave good results. Gibson and Horner (2005: 4) recommend using as many forecast methods as possible “to maximize the chances that the Best Fit forecast that is calculated is really close to what reality will be”. Of course, this has to be traded off with calculation time and software performance.

“The statistical forecast techniques discussed earlier may work well for stable, mature products with significant demand history, whereas qualitative methods based largely on human opinion and direct marketing intelligence (not a part of JD Edwards) usually make more sense for new or unstable demand products. […] In fact, conventional wisdom is that sales and marketing should ‘own the forecast’. Their input is especially important for new products or products with unstable demand. Sales and marketing should participate in the development of forecasts and they should also be formally ‘graded’ on their forecast accuracy performance results. […] And one final comment: always remember that there is far more to be gained by people collaborating and communicating well than there is by using all of the advanced formulas and algorithms yet developed”735.

Since our analysis is only based on seven standard products, as no further data were provided, it should be extended to a larger, more representative number of products before implementation.

Simple forecasting methods outperform statistically sophisticated procedures for individual items. The reverse is true for macro-level data and medium and long-term forecasting. Consequently, sophisticated forecasting methods do not outperform simpler ones in terms of forecast accuracy in general.736 Nevertheless, one could check whether more sophisticated forecasting methods not available in JD Edwards OneWorld and developed for products with lumpy demand lead to more accurate results.

The Croston (1972) method forecasts intermittent demand well737 and is available in forecasting software packages738. It “generates separate forecasts for the demand size and the number of periods between demands, and uses the ratio as an estimate for the expected demand per period. It also updates the mean absolute deviation of the forecast error for the de-

735  Gibson and Horner (2005: 9).
736  Makridakis et al. (1982).
738  Syntetos et al. (2005).
mand size”\textsuperscript{739}. Teunter and Sani (2009: 82) call Croston's method “the standard method for forecasting intermittent demand” and use its forecasts to calculate order-up-to levels that lead to close to target customer service levels. Gutierrez et al. (2008) apply neural network modeling to forecasting lumpy demand. Neural network forecasts generally outperform single exponential smoothing, Croston's method, and the Syntetos–Boylan approximation\textsuperscript{740}. Syntetos and Boylan (2001, 2005) approximately correct an error in the mathematical derivation of and the resulting bias in Croston's estimates of expected demand.

Gutierrez et al. (2008: 418) find neural network models generally perform better than the traditional methods. The Syntetos–Boylan approximation performs better than Croston's and single exponential smoothing methods in lumpy demand forecasting. If the average nonzero demand is considerably smaller in the test than in the training sample, the traditional forecast methods perform better than the neural network forecasts with lower smoothing constants. However, Gutierrez et al. (2008: 412) only consider 24 SKUs.

Analyzing other methods for lumpy demand forecasting not available in JD Edwards OneWorld lies beyond the scope of this thesis. Furthermore, it would be difficult and expensive to integrate these forecasting methods into the current ERP system and DRP.

A better demand forecast leads to a higher product availability (customer service level) at the primary warehouse and thus reduces transshipments. Customer service level can be increased and at least safety stock can be reduced.

Of course it would be desirable to always have the desired product at the right time at the right warehouse, so that no transshipments would be necessary at all. This however is impossible\textsuperscript{741}, as forecasts are generally incorrect\textsuperscript{742}. The longer the forecast horizon, the worse the forecast is\textsuperscript{743}. Aggregate are more precise than individual forecasts\textsuperscript{744}.

As the suggested forecast methods in JD Edwards OneWorld only lead to a limited forecast improvement and the more sophisticated methods for lumpy demand are difficult to implement at least in the short run and their benefit for Papierco is unknown, this company could resort to risk pooling methods that reduce demand uncertainty relying on aggregate forecasting\textsuperscript{745}, such as central ordering.

\textsuperscript{739} Teunter and Sani (2009: 82).
\textsuperscript{741} Evers (2001: 316).
\textsuperscript{742} Anupindi et al. (2006: 168).
\textsuperscript{743} Anupindi et al. (2006: 169).
\textsuperscript{744} Cf. footnote 456.
\textsuperscript{745} Sheffi (2004: 95).
5.3 Solving Papierco's Problems

Papierco could cope with lead time and demand uncertainty and its related forecasting and inventory problems and ensure its competitiveness and economic success by risk pooling.

5.3.1 Determining Suitable Risk Pooling Methods for Papierco

The RPDST developed in section 4.4 is used to determine appropriate risk pooling methods for Papierco, which suffers from customer demand and supplier lead time uncertainty (1). Both demand and lead times fluctuate strongly.

Product variety is important (2) for Papierco's competitive advantage and because its customers, who are mostly printing offices, need all kinds of paper specifications.

Stockout penalty costs are high compared to inventory carrying costs and thus attainable inventory cost savings (3) from e. g. inventory pooling: The stockout cost (209 €) is estimated by the average contribution margin of one ton of warehouse sales to customers minus the sales assistant's premium. The average length of time a ton stays in inventory is estimated by the average inventory level divided by average annual demand. Papierco has an annual average turnover rate of 8, i. e. on average a ton of paper remains in storage for one eighth of a year or one and a half months. Storing one ton of paper costs 22 € per month, so that the cost of holding a ton of paper in storage is 33 € on average.

The supplier lead time means and variabilities are high and therefore their reduction is important to Papierco (4). Papierco declared costs per order did not accrue. However, if all 2007 expenses of the purchasing departments are divided by the total amount of warehouse purchases from suppliers, we arrive at an order cost of 3.31 € per ordered ton. This cost per order is relatively low (5) compared to the average value per ton of 1,058 € in 2007. Demand uncertainty and lead time (uncertainty) reduction and fewer orders are preferred to only lead time pooling, but lower premium transportation cost and in-transit inventory cost (15), as Papierco suffers from both demand and lead time uncertainty, minimum order and saltus quantities have to be observed, and the in-transit carrying cost per unit and emergency transfer cost per unit are low.

Order splitting (16) is not feasible because of among others the required minimum order quantities and full truck load supplier deliveries. The cheaper, faster implementable and changeable, and less cross-functional solution to cope with both demand and lead time uncertainty is preferred to product and/or process redesign of a postponement (14) strategy (10). Besides, manufacturing and assembly postponement can rather be applied by the paper producer, not the paper wholesaler. Papierco could postpone the labeling, packaging (ream
5 Applying Risk Pooling at Papierco

wrapping paper), or delivery of products, e. g. by central ordering the allocation of ordered products can be delayed and conducted according to more current demand information. Mixing printer's ink from base colors can also be postponed to the delivery warehouses until a customer order arrives instead of ordering already mixed colors from the supplier. Cutting paper to the desired format could also be delayed until an order arrives. However, this can only be applied to an insignificant part of the product line. The other postponement options for Papierco will not reduce demand and lead time uncertainty much either.

The paper producers do not possess small-order drop-shipping capabilities (11). They only drop-ship full truck loads to customers. However, there are endeavors of some paper wholesalers to conduct drop-shipping sales via its warehouses to gain the higher profit margin of warehouse sales and of paper producers to drop-ship less than truck load to paper wholesale customers to increase their profit. This causes resentment on both sides.

Virtual pooling (12) by not holding any inventory, only arranging sales, and having all products drop-shipped from the paper producers to the customers is no viable strategy for the paper wholesaler, as it would make him dispensable and the paper producers do not possess the necessary distribution infrastructure. Furthermore, the restriction to deliver to customers usually within 24 hours could not be kept. Therefore lateral transshipments (13) or cross-filling seem to be the risk pooling method of choice for Papierco to deal with both demand and lead time uncertainty.

Order costs may also be considered high in (5), because minimum order and saltus quantities make (placing) an order more expensive, as frequently more than forecast demand minus on hand inventory has to be ordered by the individual locations to meet these order restrictions, which results in unnecessary inventory costs. Increasing the needed order quantity per order by postponement (8) or central ordering (9) for several locations may better exhaust minimum order and saltus quantities and lead to economies of scale in ordering (6) due to price discounts. As Papierco prefers the less expensive, fast implementable and changeable solution and the possibilities for postponement (8) are still limited as described above, central ordering (9) might be a viable risk pooling method to achieve both efficiency and responsiveness to customers. Some of the transportation cost otherwise incurred for emergency transshipments between warehouses may be shifted unto the suppliers who deliver to Papierco's delivery warehouses. Therefore (9) central ordering might make sense, especially against the background of increasing fuel prices.

Today Papierco's average transportation cost to deliver one ton of paper with its truck fleet within Germany is 15.88 €. We arrived at this figure by dividing Papierco Germany's
total transportation cost (driver costs, capital commitment, depreciation, maintenance and repair, motor vehicle tax, insurance, diesel, lubricant, tires, autobahn toll, parking, and miscellaneous operating costs) by the total annual warehouse sales in 2008. The transshipment cost per ton (transportation, shipment documentation, receiving, handling and administration costs) amount to 69.48 € per transshipped ton of paper on average. This is still relatively moderate (6), so that the decision process (10) through (13) can be followed again, which reconfirms transshipments (13) as a favorable risk pooling method.

Papierco’s management thinks that (2) product variety might be reduced in the office paper segment and where product specifications just differ in their format in one or two centimeters. The Paper Technology Research Association Forschungsvereinigung Papiertechnik e. V. (FPT) also denies the necessity of the current large product variety in German paper wholesale. 746 Affirming the importance of lead time (uncertainty) reduction (30) afterwards leads to the same train of thoughts in (31) to (38) as in (5) to (16) without considering postponement (cf. 2), which favors transshipments (36) and perhaps central ordering (33).

If Papierco gives priority to reducing demand uncertainty, as demand variability is more severe and lead times and their variability are not recorded accurately nowadays, and therefore (30) is denied and accommodating demand uncertainty is preferred to inventory reduction (39) due to the fierce competition for customers, then central ordering (33) is favored again: It is less expensive, faster implementable and changeable than capacity pooling (41f.) and permits to achieve economies of scale in ordering (40). Besides, capacity pooling is rather suitable for manufacturing companies than for wholesalers. Papierco's locations cannot pool manufacturing capacity, as they do not produce paper. They could, however, pool or share printer's ink mixing, paper cutting, or ream wrapping capacity. This might not be economically worthwhile, since the costs of shipping mixed paint or cut to fit or ream wrapped paper between locations might destroy the capacity pooling benefits. Furthermore, delivery time to the customer might suffer, and this can only be applied to an insignificant part of the product line. Papierco's locations could pool transportation capacity, which is operationalized by transshipments, and inventory storage capacity, which corresponds to inventory pooling.

Papierco's management would also like to reduce inventory. One has to carefully check whether this intention does not conflict with Papierco's business strategy and competitive

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advantage of being a 24-hour delivery full-range paper wholesaler in Germany and inventory savings outweigh possible lost sales. Remember that Papierco's inventory carrying costs are moderate relative to stockout and transshipment costs per ton. If one concludes that inventory reduction is more important than accommodating demand uncertainty (39), **product pooling** (45) and **inventory pooling** (46) might be suitable. Product pooling keeps inventory close to customers in the delivery warehouses, thus enables the nationwide 24-hour delivery service and product availability (44), pools demands, and improves forecast accuracy, but perhaps degrades product functionality. Because of the mentioned shortcomings and because it only pools demands, product pooling should not be applied on its own but together with another risk pooling method that reduces lead time uncertainty and only within a product segment that can be rationalized without hurting customer service level and product purchase interdependencies substantially. Rationalization in this context means deleting products from the product line or replacing several product variants by a universal product.

Physical inventory pooling in a single central warehouse would preclude the 24-hour delivery service. However, selective stock-keeping in several delivery warehouses may be feasible, pool demands, enable to reduce at least safety stock and maintain the product variety and delivery speed, but increase transportation costs. Fast movers could be stored at every warehouse, while slow movers could be held at a limited number of warehouses only.

If Papierco disavows the importance of lead time (uncertainty) reduction in (30), it may also do so in (4). Papierco's products share common qualities (47). The less expensive, fast implementable and changeable solution is preferred to product and/or process redesign and leagility, and Papierco is a trading company (48). It does not produce its paper products itself and its products neither are modular nor do they share common components besides the raw materials, so that it cannot redesign the products and/or production processes. Hence, component commonality (54) or manufacturing postponement (53) is not sensible for Papierco. Postponing cutting paper to the right format, mixing printer's ink, and labeling and ream wrapping paper are conceivable but not expected to reduce demand or lead time uncertainty significantly.

**Product substitution** (50) can be implemented quickly and cheaply, but displease customers as they do not receive the desired product in case of a stockout, but a substitute. In contrast to product substitution, **central ordering** (33) might reduce lead time (uncertainty) in addition to demand uncertainty and lead to economies of scale in ordering, but be more expensive, particularly since transaction and coordination costs are higher.
On the whole, lateral emergency transshipments seem to be the most suitable risk pooling method for Papierco, followed by central ordering, especially if fuel and transportation costs continue to rise. Both methods may be applied in combination and enable to achieve the seemingly conflicting aims of reducing demand and lead time uncertainty as well as inventory investment and maintaining customer service level in terms of product variety, inventory availability, and delivery speed. Product substitution, product pooling, inventory pooling, and postponement may also be suitable in order of descending favorability, but not as a sole method due to their mentioned drawbacks. They may not reduce lead times or lead time uncertainty by themselves.

In the following we will deal with the suitable risk pooling methods determined for Papierco in more detail.

5.3.2 Emergency Transshipments between Papierco's German Locations

Papierco's German locations exchange products in case of a stockout, which supports the result of the RPDST.

As the quantities exchanged by transshipments have risen over the last years, Papierco's management asked whether these transshipments are economically sound and whether they can be reduced or improved.

In our opinion this stock exchange must not be considered detachedly from sales, demand, demand forecast, order policy and storage policy, as it is influenced by these factors. Therefore the systemic approach of logistics should be accommodated and the interdependencies between single components and the whole should be considered. It is desired to contribute to a preferably spatially and temporally smooth, continuous, and aligned sequence of activities and processes which target satisfying customer needs.

5.3.2.1 Optimizing Catchment Areas

A business policy has evolved historically that if the sales department of one location attends to a customer, the same location's logistics department also delivers products to this customer. Therefore, today some of Papierco's customers in the same five-digit zip code areas are allocated inefficiently to several of the current 21 German warehouse locations. Customers should, however, be supplied standardly by the warehouse closest to them. There is a high potential for

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747 The sales assistant triggers a transshipment order, i.e. he orders stock from another warehouse, if he cannot satisfy a customer's demand from the primary warehouse.
transportation cost degression in switching from today's suboptimal to the determined optimal customer allocation to Papierco's current 21 warehouses. Unfortunately, it cannot be numerализed exactly due to today's inefficient customer allocation to multiple locations, erroneous data management, and ignorance of the number of delivery trips to each customer, delivery routes and quantities, and truck utilization before and after optimization.

Optimizing the customer allocations can lead to cost reductions fast and without much investment burden. The delivery route numbers merely have to be changed for some customers in the customer master data of the ERP software. Furthermore, optimal customer allocations may reduce transshipments.

The optimal customer allocation according to the shortest distance was found with the software NCloc\textsuperscript{750} and Euclidean metric and visualized with the zip code diagram Das Postleitzahlen-Diagramm 3.7\textsuperscript{751} in figure 5.6. The colored areas represent today's, the ones outlined in black the optimal catchment areas.

\textsuperscript{750} ATL (2009).
\textsuperscript{751} Wessiepe (2009).
Figure 5.6: Comparison of Current and Optimal Catchment Areas of Papierco's Warehouses
5.3.2.2 Increase in Transshipments and Its Causes

<table>
<thead>
<tr>
<th>Year</th>
<th>Warehouse Sales to Customers (t)</th>
<th>Transshipments (t)</th>
<th>Transshipments (% of Sales to Customers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>381,694</td>
<td>53,636</td>
<td>14.05</td>
</tr>
<tr>
<td>2006</td>
<td>405,116</td>
<td>58,755</td>
<td>14.50</td>
</tr>
<tr>
<td>2007</td>
<td>428,491</td>
<td>71,967</td>
<td>16.80</td>
</tr>
</tbody>
</table>

Table 5.1: The Extent of Transshipments at Papierco

We can confirm that the transshipment quantities rose from 2005 to 2007 by 34.18% (from 2005 to 2006 by 9.54% and from 2006 to 2007 by 22.49%). The warehouse sales to customers also increased from 2005 to 2007 by 12.26% (from 2005 to 2006 by 6.14% and from 2006 to 2007 by 5.77%). However, this does not fully explain the increase in transshipments, as the percentage of warehouse sales to customers enabled by transshipments increased as well (cf. table 5.1).

In interviews with chief operating officers and directors of purchasing, sales, and logistics at Papierco's different locations it became clear that the increase in transshipments is caused by changing transshipment operations to **direct invoicing** in June of 2006\(^7\), some locations **decreasing** their **inventory levels**, and including more and **more products** in the product line\(^8\). According to one chief executive officer the “dramatic increase” in transshipment volumes was “the manifestation of the sales department's service delusion”. However, thanks to transshipments Papierco had also gained market share in warehouse sales. Papierco's better development compared to its competitors was based on transshipments, as they enabled a higher product availability, broader product assortment, and faster delivery. This confirms that transshipments can lead to a competitive advantage as Guglielmo (1999), Kroll (2006), and Alvarez (2007) already insinuate.

The cost that locations are charged for using an emergency transshipment (transshipment cost rate) is based on quantity units (positions, pallets, and kilograms) and purchase prices and does not reflect the actual logistical costs (picking, transportation, and reloading costs). Within a company group only the costs really incurred by the transshipments should

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\(^7\) Sales people do not search at the own warehouse for an alternative product to the one originally desired by the customer in case of a stockout anymore. Today sales assistants order more via transshipments for reasons of simplicity than prior to the introduction of direct invoicing. This puts a strain on the product exchange flows between warehouses in terms of volume and costs.

\(^8\) These products tend to have small sales volumes and to steal sales from substitutes. Nonetheless, at least small quantities have to be stored at every location, which increases average stock, or the product has to be obtained via transshipments, which increases transshipment quantities.
5 Applying Risk Pooling at Papierco

be charged, so that there is no incentive to prefer or reject the use of transshipments due to inadequate charges.

Although Rudi et al. (2001) find transshipment prices that are supposed to always induce local deciders to make globally optimal inventory and transshipment decisions, Hu et al. (2007) give a counterexample. There may exist coordinating prices for only a small range of problem parameters, e.g. if the two locations are symmetric (both locations have the same cost and revenue coefficients, demand distributions, and capacity constraints, and changes in either demand or capacity distributions are simultaneously implemented in both locations). The higher the capacity uncertainty is, the higher the coordinating prices are. Increasing demand variability may increase or decrease coordinating prices depending on the distribution. A linear transshipment price schedule often will not achieve coordination of two locations' production and transshipment.

Apart from this the transshipment lead time tends to be shorter than the supplier lead time. In Papierco's case the transshipment lead time ranges from a few hours to 4 work days at the most. The supplier lead time for the various products ranges from 14 to 154 days and is 28.49 days on average. Therefore a transshipment from a sister location is preferred to a replenishment from a supplier in case of a stockout, as otherwise the sale is lost due to the usual delivery time restriction of 24 hours.

Some managers remark that for some Papierco locations other ones were their “best customers”, as they made profits by transshipping products. One director of logistics claimed only locations obtaining a lot of products via transshipments criticized the transshipment charge rate as too high. It would be even higher, if the really incurred logistical costs were charged. This supports the call for fair transshipment charge rates.

The transshipment costs ought to be debited to the sales assistants (deducted from the contribution margin which determines the sales assistants' premium) who release a transshipment order or at least made transparent to them. The objection that one should not inhibit the sales assistants in their sales function can be countered that other wholesalers commonly set up guidelines for the sales personnel.

Furthermore, if a sales assistant chooses, for instance, a paper with a one centimeter larger format as an alternative to a stocked out product desired by a customer, the higher purchase price cannot be charged. Therefore, the contribution margin that determines the sales assistant's premium is lower and the sales assistant is enticed to obtain the originally demanded product via transshipment from another warehouse location. This highlights that the implementation of risk pooling methods is influenced by human resource and business
policy factors. Managers should formulate clear guidelines for the usage of transshipments in case a desired item is not available at the primary stocking location.

A software tool should be created to help the sales assistant in deciding whether it is more economical to obtain a stocked out item via transshipments from another warehouse, search for a substitute at the own warehouse, cut paper to the right format, or ream wrap paper at the own location if possible.

5.3.2.3 Transshipments Are Worthwhile for Papierco

A high customer service level at the warehouses can be achieved by either holding sufficient inventory there, which entails high inventory investment and carrying costs, or by postponement through centralized inventory holding, which presumes fast and thus expensive delivery of any amount of any product to any customer. A better alternative might be to hold some inventory at the warehouses and let the warehouses transship products in case of a stockout.754

“A mathematical model of the exact implications […] of transshipments] is extremely complicated”755. Evers (2001), Minner et al. (2003), and Minner and Silver (2005) consider transshipments between two locations for a specific product in a specific situation only and not whether transshipments might be worthwhile for a company with more locations and products in general at all. Minner et al. (2003: 394) note that their model may be extended to multiple locations with no fixed transshipment costs by successively determining which location maximizes the savings for each transshipped unit. The problem becomes more difficult with fixed costs, unless there are only a small number of warehouses as in Tagaras (1999). The structures in all past transshipment research are much simpler than the practical ones.756

If the outlets use complete pooling, the exact form of the lateral transshipment policy does not significantly affect total system performance.757 Deciding between never transshipping or always transshipping as many units as disposable if one location faces a stockout while another one has stock on hand758 is almost as good as a more extensive investigation that considers the transshipment's prospective effect on the transshipping location's cost759. Burton and Banerjee (2005: 169) also find that an ad hoc emergency transshipment approach may lead to lower shortage (higher customer service) and transshipment cost

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756 Chiou (2008: 442).
757 Tagaras (1999).
Applying Risk Pooling at Papierco

(number of lateral transshipments) than a more systematic transshipment technique based on stock level equalization. Transshipping is better than not transshipping, but it increases transportation activity. Backordered demand should not be partially fulfilled by transshipments. In practice pull systems may offer simpler and more practical joint replenishment/transshipment policies than the push systems mostly considered in the literature.

At Papierco the charged transshipment costs (for transportation, shipment documentation, receiving, handling, and administration) amounted to 5 Mio. € in 2007, i.e. about 69.48 € per ton that was delivered via transshipments (5 Mio. €/71,967 t = 69.48 €/t). According to its inventory turnover curve (figure 5.7), Papierco needs around 10,291 t of average inventory for 71,967 t of warehouse sales to customers. This suggests that without transshipments Papierco would have had to store at least 10,291 t of additional average inventory.

This derivation might not be fully justified, as we derive inventory figures for the system without transshipments from the figures for the existing system with transshipments and while safety stocks will be lower in general, regular stocks may increase with cross-filling of demand.

Before transshipments were used, average inventory turnover in German paper wholesale was 5.4 from 1975 to 1984. Therefore one might estimate that Papierco would have needed 13,327 t (= 71,967 t / 5.4) extra average inventory without transshipments. Consequently, Papierco would have incurred approximately 3.5 Mio. € of additional inventory carrying costs in order to sell 71,967 t without transshipments: 13,327 t × 1,058 €/t (average product purchase price in the warehouse sales business division) × 0.25 (average inventory carrying cost rate) = 3,524,992 €. However, these additionally stored tons would not necessarily have been the demanded ones in the right location. As the estimate of additional inventory carrying costs without transshipments is lower than the 2007 total transshipment cost, the latter should be reduced, e.g. by storing fast-movers such as copy papers at all locations (cf. section 5.3.5), avoiding unnecessary and uneconomical transshipments, improving demand forecasts, and using less expensive alternative risk pooling methods.

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760 See, e.g., Jönsson and Silver (1987a).
761 Burton and Banerjee (2005: 169).
762 Wee and Dada (2005: 1529).
Centralizing all inventories in one or several central warehouses would decrease warehouse fixed costs, safety stock and thus inventory holding costs as well as inbound transportation costs to these central warehouses, but also the customer service level due to greater delivery distances to the customers (the stockout costs would be higher and the profit possibly lower) and increase outbound transportation costs to customers. Besides, a central warehousing strategy would conflict with Papierco's corporate strategy of a decentralized full-line 24-hour-delivery distributor.

As stockout costs could not be estimated in the aggregate consideration without transshipments in general, we now consider the costs of transshipping versus not transshipping.

Transshipments entail transportation, shipment documentation, receiving, handling and administration costs, the sending location's cost of reordering the transshipped product from the supplier, as well as an increased probability of a stockout at the sending location.\(^{766}\)

Transportation, shipment documentation, receiving, handling, and administration costs amount to 69.48 € per transshipped ton of paper on average. As derived in section 5.3.1 the order cost per ton amounts to 3.31 €. Even though Papierco's locations order and receive stock regularly about every two weeks and thus it is unlikely to place an order merely to make up for transshipped items, we consider this value as an upper bound to the order cost caused by transshipping.

The increased probability of a stockout at the sending location is difficult to quantify in general and on average. In Papierco's case this cost is rather another transshipping cost again, as the sending location would ask another location for a transshipment, if later it ran out of stock of the product it had just transshipped. The increased stockout likelihood depends on the transshipment quantity, the current on-hand inventory of the transshipped product, customer demand for this item, and the stock receipts of this item (quantity on order and its arrival time).

Transshipments made up 16.8 % of warehouse sales to customers in 2007, i. e. one could assume that Papierco had an average overall stockout probability of 16.8 % and therefore an inventory availability or fill rate before transshipments of 83.2 %. We assume that every location faces a stockout probability of 16.8 % for an item, neglecting the different influencing factors just mentioned, the derivation of this stockout probability from the situation with transshipments, and the difference between alpha and beta service level. If two locations

\(^{766}\) Evers (2001: 312f.).
transship, they face a stockout with a probability of $0.168^2 \cdot 100 = 2.82\%$, three with a probability of $0.168^3 \cdot 100 = 0.47\%$, four with $0.08\%$, five with $0.013\%$, six with $0.002\%$, seven with $0.0004\%$, and 21 with $5.3888354 \cdot 10^{-15}\%$. This affirms that emergency transshipments lead to a high effective fill rate for the customer (97.18\% for two, 99.53\% for three, and 99.92\% for four locations that transship), even if the item fill rate is relatively low (83.2\%). The main benefit (reduced stockouts and safety stock levels) can be reaped having just a few locations transship. It is neither necessary nor economical to have all 21 locations transship due to diminishing marginal returns to transshipping.

If we consider the worst but unlikely case that at every location one after another a stockout occurs for the same item after having transshipped one ton of that item to the preceding location, then the reorder cost due to transshipment only accrues at the last (21st) location. The cost of increased probability of a stockout can be estimated by another transshipping cost of 69.48\€, since the likelihood that one transshipment triggers more than one additional stockout and thus transshipment is negligible as the example above shows.

Therefore the average cost of transshipping can be estimated as: $142.27\text{\€/t} = 69.48\text{\€/t}$ (transportation and related costs) + $3.31\text{\€/t}$ (reorder cost) + $69.48\text{\€/t}$ (increased transshipment usage/stockout probability).

Without transshipments Papierco incurs the cost of a stockout and the cost of holding a ton in inventory until later at the not transshipping location. The stockout cost (209\€) is estimated by the average contribution margin of one ton of warehouse sales to customers minus the sales premium. The impact of stockouts on the future purchasing behavior of customers is difficult to grasp and neglected here. Holding the ton of paper in storage until later costs 33\€ on average (cf. section 5.3.1). Therefore, the cost of not transshipping amounts to approximately $242\text{\€/t}$.

Transshipping is on average economically sensible for Papierco, as it generally is less expensive ($142.27\text{\€}$) than not transshipping ($242\text{\€}$) a ton of paper in case of a stockout.

If only transportation-related costs evoked by transshipments and stockout costs due to not transshipping are considered and the other costs are neglected, a sales assistant should only make a transshipment order in case of a stockout, if the contribution margin is equal to or larger than $69.48\text{\€/t}$. Then at least the average transportation-related costs for the transshipment are covered.

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In order to decide more accurately on emergency transshipments for a specific item in a specific situation the methods proposed by Evers (2001), Minner et al. (2003), and Minner and Silver (2005) can be used, provided that the necessary data are available. Minner et al. (2003: 395) present a heuristic decision rule for the quantity and source of a transshipment. In simulations, Minner et al.'s (2003: 390f., 393) method generally achieves lower average annual costs than Evers' (2001) one. Since the cost parameters are likely to remain constant in the short run, whether or not a particular transshipment is made depends principally on the on-hand inventory level at the shipping location.\(^{769}\)

However, before using transshipments, sales assistants should check their own warehouse for substitutes for the customer wish and try to persuade the customer to buy another product, which only incurs transaction costs (searching for substitutes in the information system). This \textit{product substitution} might cause a slight dissatisfaction on the customer's part, but is certainly cheaper than a transshipment. If the alternative product is more expensive than the original customer wish, a higher profit is gained. If only the sales price for the originally desired product can be charged or the substitute is less expensive than the original purchase wish, Papierco has to accept a lower contribution margin. Of course the product should not be sold beneath cost price.

If no substitute can be found, it should be checked whether the paper can be cut to the right size (\textit{form postponement}\(^{770}\)), which costs around 56.25 €/t (neglecting waste), or ream wrapped (\textit{packaging postponement}) for 33.50 €/t on average. Both options are cheaper than and therefore should be preferred to a transshipment in general.

In order of increasing costs incurred by the considered risk pooling methods, Papierco's sales assistants should first try to substitute an unavailable product, then to customize or differentiate products, and then to resort to transshipments in case of a stockout. This shows that risk pooling methods can be combined effectively.

Although this is a rather crude general average analysis, because exact data (especially probabilities) were not available, and we advert to the perils of using averages as noted e. g. by Savage et al. (2006), it shows some general relationships. Of course a decision for a particular risk pooling method (product substitution, postponement, or transshipment) in a certain situation depends on the specific cost parameters.

\(^{769}\) Evers (2001: 313).
\(^{770}\) See e. g. Chauhan et al. (2008).
5.3.3 Centralized Ordering

5.3.3.1 Papierco's Current Order Policy

At Papierco a replenishment order is placed with a supplier (the daily DRP run generates an order message) whenever the reorder point is reached or in possibly short intervals (every two weeks) within the suppliers' minimum order quantity restrictions. The reorder point is the sum of safety stock, which is set by every Papierco member company independently, and average lead time demand (average sales per day during the lead time times the lead time in days).

The purchase order planning code for a specific product is 1, if it is planned with DRP, and 0, if it is not planned with DRP. The latter case applies to about 20% of the warehouse products, as for them the minimum order quantity is usually higher than the planned order quantity, e.g. if they have fixed order dates or the minimum order quantity is a full truck load. These products are planned manually with order lists.

Safety stock is calculated as the product of average sales per day during the lead time, supplier lead time in days, and a safety factor. Thus double average demand during lead time results in double safety stock. According to experience the safety factor is set to ¼ for ream wrapped paper and 1/3 for not ream wrapped one. The safety factor is not entered into the ERP system for every product, but for parts of the product line manually every three months.

However, safety stock should not be set arbitrarily, but according to a target customer service level (e.g. 90% product availability for A items) and the statistical behavior of demand during lead time or rather the forecast error in the case of Papierco, because demand is forecast. The actual supplier lead time and whether and how often the safety stock is touched is not recorded either. No cost optimal order quantities or times are determined.

Folding Box Board (cf. figure 5.3) has an average demand during one week lead time of 819.23 sheets, a current safety stock of 204.81 (= 819.23 × 1/4) sheets, and a reorder point of 1024.04 (= 819.23 + 204.81) sheets. According to the empirical distribution function this corresponds to a service level of approximately 76% or a stockout probability during lead time of 24%. A reorder point of 1.460 sheets or safety stock of 640.77 (= 1460 - 819.23) sheets would be needed to reach an inventory availability of 80.8% during lead time. According to the respective empirical distribution functions, the Uncoated Cut-Size White Wood-Pulp Paper has an inventory availability during lead time of 86%, one continuous roll of approximately 84%, the other of 73.1%, Woodfree Matte Coated Cut-Size Paper of 72%, the Woodfree White Cut-Size C-Quality Copy Paper of 76.9%, and the Woodfree White Cut-Size A-Quality Copy Paper
of 86.5% with today's calculation of safety stock. The safety stock can be determined more
definedly based on a target customer service level.

According to the nonparametric Kolmogorov–Smirnov test for the second continuous
roll (asymptotic significance (two-tailed) p = 0.700) and the copy papers (p = 0.741 and
0.616) the hypothesis H0 that the sample stems from a population with normally distributed
weekly demands cannot be rejected with a level of significance of 5%. The Kolmogorov–
Smirnov test is also applicable to small samples, but might not be very definite if the un-
known distribution function is not continuous (as in this case) or the data are not metric.\textsuperscript{771}
The hypothesis H0 that the sample stems from a population with uniformly, Poisson, or
exponentially distributed weekly demands is rejected with a level of significance of 5 %
for all products but the second continuous roll (for the exponential distribution p = 0.436).
However, there is one value outside the specified exponential distribution range that is
skipped. In the Kolmogorov–Smirnov test of exponential distribution for the other paper
grades (variables) there are also values outside the specified distribution range that are
skipped.

The used Order Policy Code 4 (Periods of supply) combines the order quantities (fore-
cast demands) for the time period defined in the Value Order Policy (for most Papierco
products 10 days). The JD Edwards OneWorld manual says “This order policy code was
designed to use with high-use/low cost items for which the user is not concerned about
carrying excess inventory”\textsuperscript{772}. This partly explains why Papierco carries so much invento-
ry, although it mainly sells low-turnover and not necessarily low-cost products.

The other available Order Policy Codes are 0 (The DRP system will not plan this item.),
1 Lot-for-lot or as required (The system will create messages for purchase orders for the
exact amount needed.), 2 Fixed order quantity (The system will create messages for pur-
chase orders based on the value entered in the Value Order Policy in the Plant Manufactur-
ing Data. If demand exceeds the fixed order quantity, the system will generate purchase
orders in multiples of the fixed order quantity.), 3 Economic Order Quantity (EOQ), and 5
Rate scheduled item (The system will generate messages based on existing rates and rate
generation rules for parent rate-scheduled items only.).

The order quantity is the maximum of the ten day demand forecast and the minimum
order quantity, which is rounded to the next higher order quantity that is divisible by the
saltus quantity. For instance, if the minimum order and saltus quantity are 500 kg (only

\textsuperscript{772}  Oracle (2009).
complete pallets must be ordered) and forecast demand for ten days is 1,150 kg, then 1,500 kg are ordered. Such a policy that determines and controls the inventory level at each warehouse location in direct proportion to (forecast) demand is called **stock-to-demand**.\(^{773}\)

Papierco's **inventory turnover curve** in grey in figure 5.7 confirms this. For all its warehouses the average annual inventory in dependence of the annual throughput is plotted with green squares. A linear regression line is adequate for these data as the coefficient of determination \(R^2 = 0.8362\) shows. However, it also suggests that not all warehouses execute this order policy consistently.\(^{774}\) Individual turnover rates range from 5 to 21 with an average of 8.24. Deviations of the individual turnover rates might be explained by different service levels or replenishment rules.\(^{775}\) Warehouses, whose data points lie above the turnover curve, might attain a higher turnover and lower inventory holding costs, if they followed the stock-to-demand order policy more consistently. Warehouses, whose data points are plotted beneath the turnover curve, exhibit a higher-than-average turnover rate than attainable by this stock-to-demand policy.

An EOQ policy would lower the average turnover rate to 6.53 as the turnover curve in black shows (a power function with the normative exponent suggested by Ballou (2000: 75) fitted to Papierco's data), probably because the stock-to-demand order policy is not followed consistently today and some warehouses have an unusually high turnover rate of 11, 15, or 21.

Nevertheless, this paper distributor's average inventory levels appear rather high for the annual throughputs. The annual average turnover rate of the German wholesale of paper, cardboard, and office supplies from 1999 to 2006 was 17.3.\(^{776}\) However, this group contains stationary wholesalers, which might raise the average turnover rate and make it unsuitable as a benchmark for just paper wholesalers. The U.S. merchant wholesalers of paper and paper products had an annual average turnover rate from 1992 to 2008 of 12.75.\(^{777}\) Papierco has a rather low average turnover rate of 8.24. This might be explained by the large product variety it offers. Papierco sells at least 7,000 different product specifications. Thus it is difficult to forecast demand for individual products. Furthermore, minimum order and saltus quantities have to be met.

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775 Cf. Ballou (2000: 78f.).
776 Statistisches Bundesamt Deutschland (2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h), calculated by us.
777 U.S. Census Bureau (2009), calculated by us.
Papierco has 196 sum suppliers, but 83 % of the annual procurement quantity is sourced from ten, 52 % from three, 40 % from two suppliers, and 20 % just from a single supplier. With big suppliers a quantity structure is negotiated. There is a one-to-one product-supplier relationship, i.e., every product is sourced from only exactly one supplier.

Therefore, Papierco should collaborate closer with its suppliers, conduct a better supplier management, to enable shorter lead times, a better forecast, inventory policy and product availability. One Papierco member company's director of purchasing had created such a collaboration with Papierco's most important supplier that supplied the highest quantity. A monthly demand forecasting for product groups and a guaranteed maximum lead time of 14 days for fast and 28 days for slow movers was established. Previously this supplier's lead time had been 4 to 6, sometimes 8 to 12 weeks. Inventories could be reduced considerably. Unfortunately, the business relationship to this supplier was broken due to price policy reasons. This concept was neglected, and inventories rose again.

One director of purchasing is against a partner-like collaboration with suppliers for they already took advantage of Papierco due to their big negotiation power. One director of sales remarked, paper wholesalers and manufacturers did not cope with recurring demand peaks correctly, such as in election times. When there were vacation close-downs, they could not prevent supply bottlenecks. This shows again that a close collaboration with

Figure 5.7: Inventory Turnover Curves for Papierco
EOQ = economic order quantity, Pot. = regression power function, Linear = linear regression line.
suppliers is indispensable. Not least Weng and McClurg (2003) showed the value of supplier–buyer coordination (in ordering) in coping with uncertain delivery time and demand.

5.3.3.2 Stock-to-Demand Order Policy with Centralized Ordering and Minimum Order and Saltus Quantities

Risk pooling models are based on economic-order-quantity (trading off inventory holding against order costs) or newsvendor models (trading off overage against underage costs).

In practice, however, a stock-to-demand order policy is followed frequently\textsuperscript{778} as we also detected in interviews with logistics and purchasing managers and at Papierco. Orders and therefore cycle inventories are proportional to demand at each warehouse.\textsuperscript{779} Expected demand at each warehouse location is forecast. Order quantities result from the difference of forecast demand and available inventory. Maister (1976: 132) and Evers (1995: 5) refer to this order policy as the “replacement principle”, where orders are set equal to demand during a certain time period. Such an order policy leads to a constant turnover. It is frequently pursued, as it is simple and easily executable\textsuperscript{780} and because automated ordering systems have very low ordering costs and thus the EOQ is not used\textsuperscript{781}. The replacement principle is followed e. g. in Zinn et al. (1990: 139), Evers (1996: 117, 1997: 59), and Rabinovich and Evers (2003a: 226).

If it is applied, centralization usually does not reduce cycle stocks.\textsuperscript{782} The system wide order quantity of n warehouses and therefore average cycle stock in the decentralized system are equal to the ones in the centralized system, if exactly the forecast demand is ordered.

Following a stock-to-demand order policy, safety stock is often calculated as the product of a safety factor and average demand during lead time at each warehouse as our interviews with logistics and purchasing managers showed. Doubling demand results in double safety stock. Safety stock is not determined by a desired target customer service level and the statistical behavior of demand during lead time or the forecast error. Centralization does not reduce system wide safety stock, if the safety factor is equal for all warehouses.

\textsuperscript{778} Wanke (2009: 108).
\textsuperscript{779} Ballou (2000: 74).
\textsuperscript{780} Ballou (2000: 77f., 2004a: 20f.).
\textsuperscript{782} Maister (1976: 132), Evers (1995: 2, 14f.).
and remains the same. The service level increases, however, due to the risk pooling effect. Perhaps this service level is higher than necessary.

Often the stock-to-demand policy is subject to minimum order and saltus quantity constraints as in the case of Papierco. Then the order quantity $q_i$ for a specific product at warehouse $i = 1, \ldots, n$ results from forecast demand minus available inventory $d_i$, for a specific period at warehouse $i$ and a constant minimum order quantity $m$ and saltus quantity $s$. The saltus quantity demands that only certain multiples are ordered like in Köchel (2007), e. g. only full pallets.

If a stock-to-demand order policy with minimum order and saltus quantities is followed, centralization may lead to a reduction in average cycle stock. The order quantity and therefore average cycle stock in the decentralized system, where every location places orders for itself, is more than or equal to the ones in the centralized system, where a common joint order is placed for all locations\textsuperscript{783}, since often more than forecast demand minus available inventory is ordered in order to meet minimum order and saltus quantities. In the centralized system the constant minimum order and saltus quantities may be exhausted more.

The order quantity $q_i$ for a specific product at warehouse $i$ is

$$q_i = s \cdot \max \left\{ \left\lfloor \frac{d_i}{s} \right\rfloor, \left\lfloor \frac{m}{s} \right\rfloor \right\}. \quad (5.1)$$

The total system wide order quantity in the decentralized system therefore is:

$$q_d = \sum_{i=1}^{n} q_i = \sum_{i=1}^{n} s \cdot \max \left\{ \left\lfloor \frac{d_i}{s} \right\rfloor, \left\lfloor \frac{m}{s} \right\rfloor \right\}. \quad (5.2)$$

The total system wide order quantity in the centralized system is:

$$q_c = s \cdot \max \left\{ \left\lfloor \frac{\sum_{i=1}^{n} d_i}{s} \right\rfloor, \left\lfloor \frac{m}{s} \right\rfloor \right\}. \quad (5.3)$$

The total system wide order quantity in the centralized system is less than or equal to the one in the decentralized system, because the order quantity function (5.1) is subadditive:

$$q_c = s \cdot \max \left\{ \left\lfloor \frac{\sum_{i=1}^{n} d_i}{s} \right\rfloor, \left\lfloor \frac{m}{s} \right\rfloor \right\} \leq q_d = \sum_{i=1}^{n} s \cdot \max \left\{ \left\lfloor \frac{d_i}{s} \right\rfloor, \left\lfloor \frac{m}{s} \right\rfloor \right\}. \quad (5.4)$$

For the proof please refer to appendix E.

The centralized ordering effect (COE), the percent reduction of the order quantity by centralized ordering, is:

\textsuperscript{783} For Özen et al. (2005: 1) inventory centralization also is a byword for joint ordering: “Groups of retailers might increase their expected joint profit by inventory centralization, which means that they make a joint order to satisfy total future demand”.

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Centralized ordering can reduce demand and supply uncertainty and thus inventory and stockouts and increase customer service level by demand pooling, aggregate forecasting across all locations, and postponement of order allocation to the delivery warehouses. This will be shown in the following section.

5.3.3.3 Benefits of Centralized Ordering for Papierco

The example of a woodfree white cutsize A-quality copy paper in table 5.2 demonstrates that the centralized ordering effect for a stock-to-demand order policy with minimum order and saltus quantities can be significant. This copy paper has the highest annual sales and contribution margin in warehouse sales of all products at most Papierco locations.

Table 5.2 shows the actual warehouse sales for this copy paper for Papierco's 22 German locations and one Dutch location per month in 2007. The sales forecasts were obtained with exponential smoothing. The forecast method was initialized with the 2006 actual warehouse sales per month per location, i.e., data from 2006 were used to determine starting values for the exponential smoothing model. The exponential smoothing constant (column O) that minimized the forecast error (the standard error of the forecast (RMSE)) for the monthly forecasts of 2006 warehouse sales for every location was used for forecasting 2007 sales.784

\[
COE = \left(1 - \frac{q_c}{q_d}\right) \cdot 100 = \left(1 - \frac{s \cdot \max\left(\frac{\sum_{i=1}^{n} \frac{d_i}{x_i}}{\sum_{i=1}^{n} \frac{q_i}{x_i}}\right)}{100}\right) \cdot 100. \tag{5.5}
\]

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| 1 | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S |
| 1 | Minimum order quantity | 250 kg | | | | | | | | | | | | | | | | | | |
| 2 | Sales forecast quantity (ton) | 350 kg | | | | | | | | | | | | | | | | | | |
| 3 | Sales order quantity (ton) | 350 kg | | | | | | | | | | | | | | | | | | |
| 4 | Work day | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | | | | | | | |
| 5 | Warehouse | Aalen | | | | | | | | | | | | | | | | | | |
| 6 | Forecast | 5,905 | 6,008 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | | | | | | | |
| 7 | Order forecast | 5,905 | 6,008 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | | | | | | | |
| 8 | Actual sales | 2,707 | 2,406 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | | | | | | | |
| 9 | Minimum order quantity | 250 kg | | | | | | | | | | | | | | | | | | |
| 10 | Sales forecast quantity (ton) | 350 kg | | | | | | | | | | | | | | | | | | |
| 11 | Sales order quantity (ton) | 350 kg | | | | | | | | | | | | | | | | | | |
| 12 | Work day | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | | | | | | | |
| 13 | Warehouse | Aalen | | | | | | | | | | | | | | | | | | |
| 14 | Forecast | 5,905 | 6,008 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | | | | | | | |
| 15 | Order forecast | 5,905 | 6,008 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | 5,905 | | | | | | | |
| 16 | Actual sales | 2,707 | 2,406 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | 2,707 | | | | | | | |
| 17 | Minimum order quantity | 250 kg | | | | | | | | | | | | | | | | | | |
| 18 | Sales forecast quantity (ton) | 350 kg | | | | | | | | | | | | | | | | | | |
| 19 | Sales order quantity (ton) | 350 kg | | | | | | | | | | | | | | | | | | |

5 Applying Risk Pooling at Papierco

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### Table 5.2: Effects of Centralized Ordering at Papierco

The order quantity for every period is the demand forecast for that month minus the net stock (at the end of the period after demand has been satisfied but before the order arrives at the beginning of the next period) left from the previous period plus the quantity to meet the minimum order and safety quantity. Supplier lead time is neglected. If net cycle stock is negative (the actual sales exceeded the order quantity and the cycle stock on hand), this demand is either satisfied via transshipments, covered by safety stock, or backordered.

| Week | Sales | Actual sales | 1/4 Forecast | Order | Lead time | Net stock | 1/4 Sales rate | CS | Average CS | Forecast | CS Forecast | Sales rate | CS Sales rate | Forecast error | Safety stock | MAD | BIAS | RMSE | Safety Stock |
|------|-------|-------------|-------------|-------|----------|-----------|---------------|---|------------|----------|------------|------------|-------------|--------------|--------------|----------|------|------|------------|-------------|
| 1    | 180   | 180         | 170         | 130   | 90       | 0         | 130           |   | 130       | 120      | 20         | 120        | 120         | 120          | 20           | 120      | 120  | 120  | 120       |
| 2    | 180   | 180         | 170         | 130   | 90       | 0         | 130           |   | 130       | 120      | 20         | 120        | 120         | 120          | 20           | 120      | 120  | 120  | 120       |
| 3    | 180   | 180         | 170         | 130   | 90       | 0         | 130           |   | 130       | 120      | 20         | 120        | 120         | 120          | 20           | 120      | 120  | 120  | 120       |
| 4    | 180   | 180         | 170         | 130   | 90       | 0         | 130           |   | 130       | 120      | 20         | 120        | 120         | 120          | 20           | 120      | 120  | 120  | 120       |
| 5    | 180   | 180         | 170         | 130   | 90       | 0         | 130           |   | 130       | 120      | 20         | 120        | 120         | 120          | 20           | 120      | 120  | 120  | 120       |
| 6    | 180   | 180         | 170         | 130   | 90       | 0         | 130           |   | 130       | 120      | 20         | 120        | 120         | 120          | 20           | 120      | 120  | 120  | 120       |
| 7    | 180   | 180         | 170         | 130   | 90       | 0         | 130           |   | 130       | 120      | 20         | 120        | 120         | 120          | 20           | 120      | 120  | 120  | 120       |
| 8    | 180   | 180         | 170         | 130   | 90       | 0         | 130           |   | 130       | 120      | 20         | 120        | 120         | 120          | 20           | 120      | 120  | 120  | 120       |

785 Actually a location might run out of stock before the end of the period and have to wait until the beginning of the next period to place and receive a new order. This time might be seen as a replenishment order lead time. Safety stock is neglected here at first. However, safety stock may also be defined as the average level of the net stock just before a replenishment arrives (Silver et al. 1998: 234, cf. Chopra and Meindl 2007: 305). Here we adhere to the definition "Safety inventory is inventory carried to satisfy demand that exceeds the amount forecasted for a given period" (Chopra and Meindl 2007: 304).
In any case this quantity has to be ordered in addition for the next period to replenish the stock of the location that has transshipped this item or the safety stock or satisfy the backordered demand. It is assumed that there are no available inventories or backorders of the copy paper at the beginning of the year 2007. The net stock of the respective period is the order quantity minus the actual sales plus the previous period's net stock. If the forecast of next period's sales can be met with net stock no order is placed with the supplier (the order quantity is zero). This occurs at the locations Bremen, Dortmund, Ernstroda, Leizen, Lohfelden, Lunteren, Mannheim, Nuremberg, Ottendorf, Sasbach, and Tettang, where the monthly forecasts and actual sales are lower than the minimum order quantity (except in Bremen in August and November and Ernstroda in September).

For central ordering (total demand) the monthly actual sales are the sum of the individual locations' monthly sales (row 191). The total 2007 order quantity of this copy paper with central ordering for all locations (pooled order quantity) 7,847,500 kg (cell N194) is lower than the sum of the total order quantities of the individual locations ordering separately (non-pooled order quantity) 7,974,000 kg (cell N195). The centralized ordering effect (equation (5.5)) amounts to 1.59 %. With central ordering Papierco could have saved ordering 126,500 kg, 117,645 € (= 126,500 kg × 0.93 €/kg) purchasing costs, as well as average cycle inventory and the associated inventory carrying cost just for this one product by improved exhausting of the minimum order and saltus quantity.

For some months the non-pooled order quantity is lower than the pooled one. This is evoked by some locations not placing an order in some months and serving demand from a minimum order quantity and net stock, as the forecasts and actual sales are much lower than the minimum order quantity. However, in these cases higher inventory carrying costs have to be borne, as the ordered minimum order quantity minus sales remains in stock for several periods. Negative net stock also postpones order quantities to later periods. Besides, a higher order quantity than the forecast to meet minimum order and saltus quantities works as a buffer for positive forecast errors (if the actual demand exceeds the forecast): The absolute value of the negative net stock is always less than the forecast error in these cases. Nevertheless, on the whole a lower total order quantity is needed to serve the same total annual demand with central than with decentral ordering.

We approximated the average cycle stock per warehouse location as follows: We calculated the sales rate (actual sales divided by work days). Sales can only occur on work days. We determined the work days per month for the year 2007 (row 5). In case the work days in the different German federal states differed, we took the maximum. We then determined the inventory
level at the end of each working day after sales, deducting the sales rate from the previous end of day inventory. Whenever the end of day inventory was negative we replaced it with zero physical inventory. The inventory level at the beginning of the month is the order quantity plus the previous month's end inventory level. We thus assumed that backordered demand (negative end of month net stock) is satisfied instantaneously at the beginning of the new month when the order quantity arrives. Finally we determined the arithmetic mean of the end of work day inventory levels as the average cycle inventory. This also confirms that today average inventory at Papierco is so high relative to actual sales partly due to minimum order and saltus quantities.

The total average cycle stock with central ordering (row 198) is lower than with decentral ordering (row 199) in every month and for the whole year 2007, because of improved exhausting of minimum order and saltus quantities. For this copy paper Papierco could have saved 131,059 kg of average cycle stock and the corresponding inventory carrying costs of 30,471 € (= 131,059 kg × 0.93 €/kg × 0.25) in 2007.

The sum of the average monthly positive net stock of the individual locations (184,234 kg) in column N is larger than the average monthly positive net stock with central ordering in cell N196 (40,987 kg).

The sum of the forecast error statistics mean absolute deviation (MAD 142,459), bias (BIAS 29,560), and root mean square error (RMSE 190,306) for the individual locations in columns P, Q, and R is higher than the error statistics for the central order (95,502, 13,781, and 130,602 respectively) in cells P, Q, and R192.787

This confirms788 that the aggregate forecast of monthly sales of this copy paper for all 23 considered locations is more accurate than the disaggregate forecast for the individual locations. This leads to a higher inventory availability, i. e. a smaller total stockout or backorder quantity (negative net stock) and thus smaller stockout or backorder costs in the system with central ordering (654,175 kg) than in the system with decentral ordering (845,636 kg), if safety stock is neglected.

According to the One-Sample Kolmogorov-Smirnov Test, the H₀-hypothesis that the forecast error at the locations Aalen, Berlin, Bielefeld, Bremen, Cologne, Dietzenbach, Dortmund, Ernstrøda, Fellbach, Garching, Hemmingen, Kiel, Leizen, Lohfelden, Lunteren, Mannheim, Nuremberg, Ottendorf, Queis, Reinbek, Sasbach, Tettnang, and Trierweiler

787 “MAD is […] the average of the absolute differences between the actual […] and the forecast” sales. “BIAS is the average of the differences between actual and forecast” sales. “RMSE is [the] square root of the average of the squared differences between the actual and the forecast” sales (Ballou 2004c: 5f.).

788 Cf. footnote 456.
and of total demand is normally distributed cannot be rejected with an asymptotic significance (two-tailed) $p$ of 0.984, 0.317, 0.879, 0.872, 0.485, 0.268, 0.582, 0.996, 0.513, 0.974, 0.970, 0.922, 0.973, 0.695, 0.966, 0.984, 0.681, 0.864, 0.832, 0.711, 0.758, 0.991, 0.851, and 0.968 respectively. The One-Sample Kolmogorov-Smirnov Test for the exponential distribution shows a higher asymptotic significance (two-tailed) $p$ of 0.820, Dortmund ($p = 0.936$), Fellbach ($p = 0.824$), Leizen ($p = 0.993$), Lohfelden ($p = 0.911$), Nuremberg ($p = 0.839$), Reinbek ($p = 0.830$), Trierweiler ($p = 0.977$), and total demand ($p = 0.993$). However, for Fellbach and Reinbek there are 3, for Cologne, Dortmund, Lohfelden, Trierweiler, and total demand 6, for Leizen and Nuremberg 7 values outside the specified distribution range. These values are skipped. Kiel shows a higher asymptotic significance (two-tailed) of 0.958 in the One-Sample Kolmogorov-Smirnov Test for the uniform distribution. As Poisson variables are non-negative integers and negative values occur in the data, the One-Sample Kolmogorov-Smirnov Test cannot be performed for the Poisson distribution. In conclusion, the forecast error can be assumed to be rather normally distributed at the different locations. According to Thonemann (2005: 258) most applications assumed a normally-distributed forecast error.

Nevertheless, we use the empirical distribution function of the forecast error to determine the safety stock. The empirical distribution function $F(y)$ gives the probability that the forecast error is less than or equal to $y$, i.e., $F(y) = P(\text{forecast error } Y \leq y)$. In order to have an inventory availability of 91.7%, we determine the $y$ for $P = 91.7\%$. If we carry $y$ as safety stock, this will cover demand that exceeds the forecast with a probability of 91.7%, as the forecast error is less than or equal to this safety stock with the probability of 91.7%. The safety stock that ensures a service level of 91.7% is shown in column S for every location. The sum of the individual locations' safety stocks (245,561 kg) in cell S188 is larger than the safety stock with central forecasting and ordering for all locations (201,579 kg) in cell S191, as the aggregate forecast is more accurate than the disaggregate one. Papierco could have saved 43,982 kg of safety stock and the associated inventory holding cost of $10,226 \, \text{€} = (43,982 \, \text{kg} \times 0.93 \, \text{€/kg} \times 0.25)$ just for this copy paper in 2007. Although Papierco forecasts demand and therefore should use safety stock as protection against the forecast error and not demand uncertainty$^{789}$, it uses the average past demand for the copy paper to determine safety stock.

$^{789}$ Cf. Thonemann (2005: 255f.).
With decentralized ordering there would have been 123,215 kg negative net stock that could not have been absorbed by the safety stock for all locations in 2007. We arrived at this figure by adding the negative net (cycle) stock and safety stock for every location for every month, whenever the absolute value of the former was greater than the one of the latter, and then adding up all the negative sums. With centralized ordering 80,486 kg of demand would have exceeded available inventory (cycle stock and safety stock). In the decentralized system the 123,215 kg of demand could have been satisfied by transshipments from other warehouses, backordered, or lost. In the centralized system, transshipments would not have been possible, as demand would have exceeded the order quantity and safety stock for all locations, and demand could have been only backordered or lost. Therefore one could argue that in this regard the service level in the decentralized system would have been higher. Transshipping 123,215 kg of this copy paper in the decentralized system would have cost at least 8,561 € = 123.215 t × 69.48 €/t (cf. section 5.3.2.3). Losing the contribution margin of selling the 80,486 kg of this copy paper would have cost 80,486 kg × 0.23 €/kg = 18,512 € in the centralized system. Thus the net stockout costs (lost contribution margin in the centralized system minus the transshipment cost in the decentralized one) amount to 9,951 € = 18,512 € - 8,561 € at the most. If all the unsatisfied demand had been backordered in both systems, backorder costs would have been higher in the decentralized than in the centralized system because of the backordered volume.

Overall, Papierco could have saved at least 30,746 € in inventory holding costs just for this one copy paper in 2007, if it had used centralized planning and ordering instead of the current decentralized one: 30,746 € = 30,471 (saved inventory holding costs for average cycle stock) + 10,226 € (saved inventory holding costs for safety stock) - 9,951 € (net stockout costs).

This example highlights that centralized ordering enables to reduce order quantities and thus average cycle inventory and inventory carrying costs by exhausting minimum order and saltus quantities better as well as to reduce safety stock and improve overall customer service level (inventory availability) or reduce negative net stock as the aggregate forecast is more accurate than the disaggregate one.

Therefore, we propose a central distribution requirements planning with aggregate forecasting and central ordering for all Papierco locations. After placing a joint order, central planning would receive a notification of dispatch from the producer when the ordered products are produced and the trucks are ready to deliver them. Then Papierco tells the supplier which warehouses to deliver to according to current demand. Full truck loads can
be delivered to single warehouses or one truck can deliver to several warehouses on a delivery route. The delivery destination decision is postponed until the ordered products are produced and ready to be delivered from the production facility to the delivery warehouses (geographic or logistics postponement).

Today each warehouse location forecasts its warehouse sales and places orders with the suppliers individually. The warehouse receives a dispatch notification from the supplier before the delivery truck leaves the production facility to deliver the ordered products to the warehouse. The delivery destination is determined at the time of placing the order.

With today's decentralized release orders within the centrally negotiated framework contracts every Papierco location orders all products for itself.

With centralized ordering each location or company of the eight ones comprising Papierco could process the orders for one part of the product line, e.g. a main product group, for all considered 23 locations. This would lead to the following advantages:

- Fewer orders at the suppliers (1/23 of today's decentralized orders), lower order costs, improved utilization of minimum order and salton quantities, lower average inventory, higher turnover, lower capital commitment, lower inventory holding costs.
- Only one procurement manager per product line part or product, higher specialist knowledge about this part of the assortment, improved forecasting, improved matching of supply and demand, improved potential utilization (negotiation power), closer collaboration with suppliers, long-term planning with suppliers, cost regression potentials for Papierco and its suppliers, reduced lead times.
- Directing supplier deliveries to certain warehouse locations at short notice (higher flexibility, product availability, and customer service level, reduced transshipments and inventories).

This approach would maintain the importance of the legally independent companies forming Papierco and their decentral locations. The employees of the purchasing departments do not have to relocate to a physically central ordering department, but can remain at their locations. They may become more motivated by their increased responsibility, as they do not place replenishment orders for their own location only anymore, but for all Papierco locations albeit just for a certain part of the product line. Thus possible disadvantages of centralized ordering such as decreased responsiveness and sales due to lacking local know-
ledge\textsuperscript{790} can be mitigated as well. Procurement employees may have more time for improved forecasting and collaboration with suppliers and other departments or their number may be reduced.

The number of the suppliers' trips to the warehouses would probably remain unchanged. Perhaps the supplier would charge a fee for delivery routes, if a truck load is to be transported to more than one Papierco location. This charge is unlikely to outweigh all the other stated benefits. The products, however, have to be managed more intensively by procurement managers. Operations and rules in all locations have to be standardized. Necessary data have to be available and correct.

Orders would still be placed according to order suggestions generated by DRP consistent with customer orders, demand forecasts, inventory levels, and supplier lead time. Of course the ERP software has to be adapted to plan across all Papierco locations.

The paper industry shows long production lead times, expensive holding costs for inventory surplus, and highly random demand at the retailers. Orders can be backlogged only for a few days at the most in case of a stockout or the sale is lost. These conditions favor centralized ordering according to Eppen and Schrage (1981: 51) and Schoenmeyr (2005: 5). Total demand is less variable than demand at the individual stores, which makes consolidated distribution most effective according to Cachon and Terwiesch (2009: 340). The time from placing an order with the supplier until production of the order is finished is longer than the delivery time from the production facility to the delivery warehouses. This corresponds to Cachon and Terwiesch's (2009: 340) observation that consolidated distribution “is most effective […] if the lead time before the distribution center is much longer than the lead time after the distribution center”. Replenishment coordination is most beneficial for high fixed order/transportation cost, large truck capacities, and many retailers.\textsuperscript{791}

The minimum order and saltus quantity restrictions Papierco has to observe can be subsumed under large fixed order or transportation cost and truck capacities, and Papierco has many delivery warehouses in Germany.

In contrast to Eppen and Schrage (1981), Gürbüz et al. (2007: 305), and Cachon and Terwiesch (2009) our considerations do not contain a distribution center (here we follow Schonmeyr's (2005: 4) proposition), Papierco uses a stock-to-demand order policy with minimum order and saltus quantities and transshipments between regional warehouses, weekly demand often does not follow a theoretical distribution (cf. section 5.3.3.1), demand at the

\textsuperscript{790} Ganeshan et al. (2007: 341).
\textsuperscript{791} Gürbüz et al. (2007: 305).
different warehouses is correlated, and supplier lead time is largely neglected. Our centrally
ized ordering model does not increase the distance a unit must travel from the supplier to the
delivery warehouses, unless it is delivered on a delivery route with several stops.

Eppen and Schrage (1981) consider centralized ordering policies in a periodic-review base-stock multi-echelon, multi-period system in the conglomerate for steel industry with independent normally distributed stationary random demands and identical proportional costs of holding and backordering at N warehouses, and no transshipments between the warehouses. In Eppen and Schrage (1981) products are ordered and quantity discounts are possible. Papierco just calls quantities of products from the supplier within the bounds of previously centrally negotiated skeleton agreements. Possible quantity discounts have been granted before.

Diruf (2005, 2007) and Heil (2006: 169) examine only the demand-pooling savings of postponement, centralized ordering, and lateral transshipments between cooperating possibly independent fashion retailers with normal and lognormal\textsuperscript{792} demand, equally big sales areas\textsuperscript{793}, and a newsboy structure. In their model the central ordering system leads to lower costs than the local ordering system with transshipments unless over- and underage costs are equal. In this case both systems achieve the same improvements compared to a system without risk pooling.\textsuperscript{794}

Hu et al. (2005) deal with the impact of emergency transshipments on (s, S) (order-up-to) ordering policies and centralized ordering.

Gürbüz et al. (2007: 296, 305) consider only one outside supplier, but inventory and transportation costs and four order-up-to policies.

Cachon and Terwiesch (2009) consider consolidated distribution in retail with 100 stores, an order-up-to-model, Poisson demand at the retail stores per week\textsuperscript{795}, normally-distributed demand at the retail distribution center\textsuperscript{796}, lead times, and backordering\textsuperscript{797}.

One could still determine an optimal delivery allocation procedure and order policy for Papierco, but this would go beyond the scope of this thesis. The reader is referred to e. g. Silver et al. (1998) for a detailed treatment of inventory control policies.

\textsuperscript{792} Heil (2006: 145f).
\textsuperscript{793} Heil (2006: 169).
\textsuperscript{795} Cachon and Terwiesch (2009: 336).
\textsuperscript{796} Cachon and Terwiesch (2009: 338).
\textsuperscript{797} Cachon and Terwiesch (2009: 336f.).
Alfaro and Corbett (2006: 24) find that within certain quite wide ranges of suboptimality of inventory control policies, risk pooling is better than optimizing the policy. This range expands with the number of SKUs. Papierco carries thousands of SKUs.

Harrison and Skipworth (2008: 193) also find that form postponement in three companies improved responsiveness of manufacturing, although it had not been implemented theoretically ideally.

Finally, risk pooling reduces decision errors, biases, and local suboptimization of boundedly rational decision makers and thus total costs “by pooling decision errors across locations”, even if demands are perfectly positively correlated or deterministic (behavioral benefits of inventory pooling)798.

Therefore, introducing risk pooling methods at Papierco at first, does not hurt.

5.3.4 Product Pooling

For the last years more and more products have been added to Papierco’s product line without dropping any other ones. The product range meanwhile comprises around 20,000 current products, some with few sales, and is planned to be diversified further especially in the business units printing accessories and screens and signs. This diversification leads to higher inventories, as every warehouse has to store at least some units of every product in order to be able to deliver every product specification, or more transshipments. Product availability decreases as forecasts for more and more individual items are less accurate.

“Every firm wishes to be ‘customer focused’ or ‘customer oriented,’” which suggests that a firm should develop products to meet all of the needs of its potential customers. Truly innovative new products that add to a firm's customer base should be incorporated into a firm's product assortment. But if extra product variety merely divides a fixed customer base into smaller pieces, then the demand–supply mismatch cost for each product will increase. Given that some of the demand–supply mismatch costs are indirect (e.g., loss of goodwill due to poor service), a firm might not even realize the additional costs it bears due to product proliferation799.

Already in 1987 Röttgen remarked due to the cut-throat competition fine paper wholesalers are forced to distinguish themselves from their competitors. This is possible by intensifying some selected distribution functions rather than accepting additional ones. Thus paper wholesalers seek to diversify their product line more and more to exhaust the cus-

798 Su (2008: 33).
799 Cachon and Terwiesch (2009: 335f.).
omer potential as much as possible. Fine paper wholesale has to abandon the idea to be a specialist for all paper grades. This implies prioritizing within the product range instead of a sprawling product line diversification. An escalating diversification will lead to disproportionately high costs and continue to keep the return low.

According to the FPT-Workshop No. 4 in Munich on October 24, 2007 the variety of paper grades is narrower in the U.S. and is not demanded by customers (printing offices) in Germany either. The majority of printing offices deny the necessity of the present variety of grades. For them operativeness, color consumption, quality consistency, and mixability of paper grades are decisive and not a new brand or grade.

A FPT study supports this: A change in demand behavior for paper grades seems to gain momentum away from the unclear vast variety of grades towards a homogenization. The printing industry foremost demands good operability and printability of the paper in the printing machine. Paper grades with standard functionality (reproducible operability and printability) and multifunctionality are the focus of the forthcoming development.

Furthermore a too large product variety might backfire, as customers might not like to choose from many alternatives. Toyota's and Nissan's fast introduction of a series of products, for instance, was counterproductive as it confused customers.

For all these reasons Papierco should rationalize its product line by product pooling taking into account its business strategy, demand and buying interdependencies between products, customer needs, and cooperation with suppliers also in order to simplify its procurement planning. Serving “demand with fewer products” reduces “demand variability, which leads to better performance in terms of matching supply and demand (e.g., higher profit or lower inventory for a targeted service level)”.

### 5.3.5 Inventory Pooling

Nowadays there are bilateral agreements between some Papierco member companies to store slow-moving items for one another. However, there is no transparency, which articles are stored at which location, and the partly sought selective stock keeping is not pursued strategically and economically.

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802 FPT (2007b).
If a new product is launched, it is stored at only three locations first. If it has been selling well for half a year, further locations start inventorying it and it may be stocked at every Papierco location in the end.

Papierco's uniform price list suggests immediate availability of all paper grades at every warehouse location. Due to the increasing range of products, however, availability of every product at every location cannot be assured anymore. Some products are only available at one warehouse in Germany. Thus demands for transshipments rise and the 24-hour delivery service cannot be guaranteed anymore. Transshipment errors increase, especially if a product is transshipped via other warehouses. Often truck capacity is exceeded. Papierco's competitive advantage of delivering any paper grade mostly within 24 hours is fading.

The product master record contains 61,132 different products. Thereof merely 23,740 ones show stock on hand at at least one warehouse. Of these only 9,868, of the 61,132 only 14,565 ones, are planned automatically with DRP. The product master record should be rid of inactive products with no sales.

Product purchase planning and storing is distributed unequally between the eight Papierco member companies as figures 5.8 and 5.9 show. If it was distributed more evenly at least for fast movers, product availability could be increased and transshipments decreased (cf. section 5.3.2.3).

Along the same line, Pasin et al. (2002) simulate pooling of equipment for homecare service for a group of local community service centers (CLSCs) in the Montreal, Canada region. Overall pooling reduces shortages (rental costs) with the same inventory level, but the larger CLSCs with considerable equipment overcapacity may lose, because they almost never need to borrow equipment from other CLSCs, but have to bear the disadvantages (wear-and-tear costs). A more even distribution of over-capacity reached by inter-CLSC sales or an equivalent financial compensation is much more effective than minimum stock, maximum contribution or maximum debt rules in producing an overall reduction in costs without penalizing any of the partners in the pooling process.

We would have liked to design an optimal policy of strategic stock-keeping (inventory pooling through selective stock keeping). However, the necessary data such as the turnover or (average) inventory per SKU were not available.
Figure 5.8a: Product Purchase Planning at Papierco’s Member Companies

- Number of products planned with DRP (planning code = 1)
- Number of products not planned with DRP (planning code = 0), but with stock on hand

Figure 5.8b: Product Purchase Planning at Papierco’s Member Companies
5.3.6 Challenges in IT and Organization

Today too little process-oriented information exchange between departments inhibits business processes. Data are not transparent enough. If they are recorded at all, often they can only be obtained from the diverse, little integrated electronic data processing (EDP) systems with great effort. Too many subsystems and interfaces result in data transfer problems, too much data maintenance, and high costs. A lot of workarounds were programmed in the standard ERP system for Papierco, as many locations wanted to keep some unique business processes. However, the standard ERP system should standardize the business processes or one does not derive the full benefit from the standard software. CLM (1995: 6) also concludes that “the vast majority of available technology capable of facilitating process integration is underutilized”.

Papierco’s different data analysis tools often show different numerical results for the same data query specifications. Data are often not available on a disaggregate individual product basis, but only for product groups. Analyses are hampered by different product codes for the same product for drop-shipping and warehouse sales, different periods (days, weeks, and months), units (sheets and kilograms), and product groupings and levels in dif-

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Figure 5.9: Stockkeeping at Papierco’s Warehouses in February 2008

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different parts of the EDP system, too little knowledge about the analysis tools at Papierco's locations, as well as a bad data structure and maintenance. The delivery situation is not transparent enough: There are customer and delivery addresses. The delivery addresses are not assigned to customers uniquely. Sales can only be attributed to customer and not to delivery addresses. Some data are not recorded at all, such as cycle, safety, and average stock, as well as turnover per product, utilization of safety stock, cycle time, actual supplier lead times, and actual transshipment costs. Some computerized reports give wrong (calculated, not actual) safety stock levels for product groups, so that often the shown safety stock is higher than the actual total inventory on hand. Certain costs can only be obtained by checking every single cost unit. Higher cost awareness might lead to higher return. Setting up a systematic controlling might be worthwhile.

Data and information are passed on by employees only hesitantly and after direct request. Important extra information to get a complete idea often is omitted. This might be interpreted as a defense strategy to secure the job and power position by exclusive knowledge. Any criticism can be invalidated by pointing out that certain information had not been considered. Similar “micropolitical games” were observed e. g. by Reihlen (1997: 3) in a heating technology company. Change in logistical practices often faces resistance. This can be remedied with a company culture that promotes transparency.

Papierco consists of eight different and legally independent companies, but is and wants to be seen as a single uniform company. However, employees rather feel obliged to their individual member companies that pay their salaries. This sometimes leads a member company to transship products for its own warehouse locations first and leave the goods bound for other member companies' locations behind. Products ought to be transshipped according to urgency and not company affiliation. Papierco should not optimize locally but globally.

Logistics is seen very restrictively within Papierco as storing, handling, and transporting goods. Taking on its interdepartmental function, logistics should collaborate closely with and support management, sales, purchasing, finance, accounting, and controlling.

During this study differences in managing Papierco's different locations became obvious. Papierco should standardize its operational policy, measure performance uniformly, and restructure its distribution system cautiously. For this a consistent and faultless data maintenance and accessibility is essential. Some data are deficient for logistical management.

Most of these challenges are common in a lot of companies. Papierco is addressing them successfully and is a profitable company.

5.4 Summary

The paper wholesale company Papierco can increase its competitiveness and reduce customer demand and supplier lead time uncertainty by the risk pooling methods transshipments, product substitution, postponement, centralized ordering, product pooling, and inventory pooling.

The proposed optimization of the customer allocation to the individual warehouses can lead to considerable transportation cost savings near-term and without much investment burden. Customers should be served by the warehouse nearest to them.

The following suggestions can be made to reduce inventory and transshipments, which have increased for the last years, and maintain or improve the customer service level and profitability:

(1) The organizational structure and logistics should support the business processes as well as possible.
(2) The company culture should promote transparency and a process view.
(3) Improve the fragmented, little integrated, little standardized, not process- but function-oriented system landscape. This would also lower the disproportionately high IT costs.
(4) Necessary data should be collectable faultlessly.
(5) The demand planning and purchasing policy should be improved, as this will result in higher product availability (customer service level) and less transshipments and inventory.
(6) Create a uniform cross-functional demand planning process, in which sales, product managers, and purchasing collaborate to contain extraordinary demands through the sales assistants' and product managers' profound market knowledge and enable a better demand forecast and thus order policy.
(7) Communicate and coordinate inventory reductions at the different member companies and warehouses. If a company is member of a purchasing group, it cannot act autonomously anymore.

Methods 11 (Exponential Smoothing), 6 (Least Squares Regression), and 9 (Weighted Moving Average) should be admitted to the DRP forecast run besides today's exclusively used methods 4 (Moving Average) and 10 (Linear Smoothing), as they gave good results. The forecast should be based on the last 12 to 24 months of sales history, if system performance permits this.
5 Applying Risk Pooling at Papierco

(8) Establish (not necessarily physically) centralized procurement, which forecasts and orders for all of Papierco's German locations on the product level and directs the suppliers' deliveries to the warehouses according to current demand (consolidated distribution with pooling over the outside-supplier lead time).

(9) Foster a close, reliable, long-term collaboration and exchange of information between suppliers, Papierco, customers, and individual departments.

(10) Safety stock and transshipments can be reduced without hurting product availability by decreasing lead time (uncertainty) through improved collaboration with suppliers and reducing demand uncertainty by better forecasts and information gathering and usage.

(11) Determine safety stocks more definedly according to the target customer service level, forecast error, supplier lead time, and lead time variability.

(12) Enable determining the correct inventory levels per product and utilization of safety stock.

(13) Rationalize the product line considering the business strategy, customer needs, product interdependencies, and cooperation with suppliers (product pooling).

(14) Establish transparency regarding the storage locations of products.

(15) Pursue selective stock keeping (inventory pooling) strategically economically.

(16) Use alternatives to transshipments (product substitution and form postponement).

(17) Papierco's emergency transshipments are economically worthwhile on average.

(18) However, they should only be used, if the contribution margin of a sale is at least 69.48 €/t.

(19) Establish transshipment cost rates that reflect the true costs.

(20) Set up clear rules for the sales assistants for using transshipments.

(21) Transshipment costs should be made transparent to the sales assistants and perhaps be deducted from the premium-determining contribution margin.

We would have liked to always evaluate the cost savings attainable by these suggestions for improvement in money units, but necessary cost data and information were not provided. A consultancy described similar problems of obtaining data at Papierco.
Human resource factors, transaction costs, and local suboptimization seem to be important in risk pooling and transshipments. These factors are commonly neglected in the risk pooling literature.

This application shows that risk pooling can be used effectively as a guiding umbrella principle in systematically restructuring a distribution system to cope with supplier lead time, customer demand, and forecast uncertainty, as well as product variety and reduce costs and inventory, increase customer service, and make a company more competitive.

Risk pooling methods can be used side by side to take advantage of their benefits, while making up for disadvantages of other ones.

Our Risk Pooling Decision Support Tool is suitable to determine appropriate risk pooling methods for a company that faces lead time and demand uncertainty. Some of the methods determined with the help of this tool are already applied by Papierco nowadays (transshipments, product substitution, inventory pooling, and postponement), but can and should be improved. The other ones still make sense after a more thorough investigation (centralized ordering and product pooling).

Centralized ordering can reduce average cycle inventory, even if a stock-to-demand order policy is followed and minimum order and saltus quantities have to be observed. It also enables to decrease safety stock and improve inventory availability, as the aggregate forecast for the central order is more accurate than the disaggregate one for the decentral orders.
6 Conclusion

Our main novel contributions lie in the (1) comprehensive and concise definition of risk pooling distinguishing between variability, uncertainty, and risk, (2) holistic review and value-chain-oriented structuring of the plethora of research on risk pooling methods in business logistics, especially on inventory pooling, according to their uncertainty reduction abilities, (3) developing tools to help in comparing and choosing appropriate risk pooling methods and models for different economic conditions based on a contingency approach, (4) applying these tools to German paper wholesale, and (5) conducting a survey on the recognition and usage of the various risk pooling concepts and their associations in 102 German trading and manufacturing companies.

Risk pooling in business logistics can reduce total variability of demand and/or lead time and thus uncertainty and the possibility of not achieving business objectives (risk) by consolidating individual variabilities (measured with the standard deviation) of demand and/or lead time. These individual variabilities are consolidated by aggregating demands (demand pooling) and/or lead times (lead time pooling).

This reduction in uncertainty allows to reduce inventory without reducing the customer service level (product availability) or to increase the service level without increasing the inventory or a combination of both and to cope with product variety. Risk pooling is explained by the Minkowski-inequality, the subadditivity property of the square root of non-negative real numbers, and the balancing effect of higher-than-average and lower-than-average values of a random variable.

Risk pooling usually shows increasing returns, but diminishing marginal returns. Its benefit generally increases with decreasing correlation of pooled demands and/or lead times and concentration of uncertainty as well as increasing variability.

Risk pooling in business logistics comprises well over 600 publications mostly containing modeling research. After the concept borrowed from modern portfolio and insurance theory has been mainly applied to inventory pooling, meanwhile research focuses on postponement, transshipments, and the coordination of risk pooling arrangements and cost and profit allocation through contracts. The researchers are of different backgrounds, orientation, and prominence, so that they use inconsistent terms, frameworks, and structures and make our thorough literature review, structuring, and definitions essential.

We identified ten risk pooling methods: (1) inventory pooling, (2) virtual pooling, (3) transshipments, (4) centralized ordering, (5) order splitting, (6) component commonali-
(1) Inventory pooling is the consolidation of inventories, e.g., by inventory or warehouse system centralization or selective stock keeping, in order to reduce inventory holding and shortage costs through risk pooling. Its risk pooling effect in terms of inventory savings can be quantified with the square root law (SRL), portfolio effect (PE), and inventory turnover curve.

The SRL states that the total system wide stock of \( n \) decentralized warehouses is equal to that of a single centralized one multiplied with the square root of the number of warehouses \( n \). Despite confusion in the literature it applies to regular stock, if an economic order quantity (EOQ) order policy is followed, the fixed cost per order and the per unit stock holding cost, demand at every decentralized location, and total system demand is the same both before and after centralization. It is valid for safety stock, if demands at the decentralized locations are uncorrelated, the variability (standard deviation) of demand at each decentralized location, the safety factor, and average lead time are the same at all locations both before and after consolidation, average total system demand remains the same after consolidation, no transshipments occur, lead times and demands are independent and identically distributed random variables and independent of each other, the lead time variance is zero, and the safety-factor approach is used to set safety stock for all facilities both before and after consolidation. It applies to total stock (the sum of regular and safety stock), if the assumptions stated above of the SRL both as applied to regular and safety stock hold (cf. appendix B). It does not hold, if its assumptions are not fulfilled.

If an EOQ policy is followed and constant fixed costs per order, holding costs, and total demand are assumed for all locations before and after centralization, the total order fixed
cost usually is lower because of less orders and the inventory holding cost is lower due to a smaller total EOQ in the centralized than in the decentralized system (cf. appendix C). Savings in safety stock through inventory pooling stem from balancing demand variabilities (risk pooling).

Although some researchers\textsuperscript{811} claim the SRL estimated real savings well, in 13 of 14 practical cases we reviewed it overestimated actual inventory savings often significantly. This means its assumptions are not fulfilled in these cases or there were other inventory- or service-related changes. In a survey that we conducted with eleven companies from different countries and industries (see table D.1) only one fulfilled all, two fulfilled none of the five assumptions necessary for applying the SRL to regular stock. The participants fulfilled at least two and at the most seven of the eleven assumptions of the SRL when applied to safety stock.

It seems that seldom is it appropriate to apply the SRL, because mostly not all its assumptions are fulfilled. Nonetheless, the other SRL- and PE-models that we synoptically compared in terms of their assumptions in table D.2 might be applied as their assumptions are fulfilled.

Researchers questioning the SRL either question its assumptions or do make other assumptions and therefore arrive at different results.

Zinn et al.'s (1989) PE shows the reduction in aggregate safety stock by centralizing several warehouses' inventories in one warehouse in percent, if lateral transshipments are not usual, there is no lead time uncertainty, customer service level is not affected by a change in the warehouse number, demand at each warehouse is normally distributed, and the order quantity equals demand during lead time.

The inventory turnover curve shows average inventory in dependence of the inventory throughput for a specific company. It can be constructed from a company's stock status reports and be used to estimate the average inventory (not only safety stock as with the PE) for any (planned) warehouse throughput without the limitations of the SRL.

(2) Virtual pooling extends a company's warehouse or warehouses beyond its or their physical inventory to the inventory of other own or other companies' locations by means of information and communication technologies, drop-shipping, and cross-filling.

(3) Transshipments are inventory transfers among locations (e. g. between warehouses or stores) for example in case of a stockout.

\textsuperscript{811} For example Sussams (1986: 10), Pfohl (1994: 141).
(4) **Centralized ordering** places joint orders for several locations and later allocates the orders (perhaps by a depot) to the requisitioners or distribution points in consolidated distribution according to current demand information.

(5) **Order splitting** is partitioning a replenishment order into multiple orders with multiple suppliers or into multiple deliveries.

(6) **Component commonality** designs products sharing parts or components. This reduces the variability of demand for these components.

(7) **Postponement** delays decisions in production, logistics, or distribution as long as possible, e.g. developing, purchasing, ordering, fulfillment assignment, production, manufacturing, assembly, packaging, labeling, pricing, and shipping. Because of a shorter forecast period and an aggregate forecast more accurate information can be used.

(8) **Capacity pooling** is consolidating production, service, or inventory capacities of several facilities. Without pooling every facility fulfills demand just with its own capacity. With pooling demand is aggregated and fulfilled by a single (perhaps virtually) joint facility. A higher service level can be attained with the same capacity or the same service level can be offered with less capacity.

(9) **Product pooling** is unifying several product designs to a single generic or universal design or reducing the number of products thereby serving demands that were served by their own product variant before with fewer products.

In (10) **product substitution** one tries to make customers buy another alternative product, because the original customer wish is out of stock or although it is available (demand reshape).

Using **contingency theory**, we explored conditions that favor these individual risk pooling methods, their advantages and disadvantages, and basic trade-offs in detail. Based on this synopsis the **Risk Pooling Decision Support Tool** (RPDST) was developed for choosing an appropriate risk pooling strategy for a specific situation.

This tool was effectively utilized to choose suitable risk pooling methods for a large German **paper distributor**. This application showed that risk pooling can be used effectively as a guiding umbrella principle in systematically restructuring a distribution system to cope with supplier lead time, customer demand, and forecast uncertainty, as well as product variety and reduce costs and inventory, increase customer service, and make a company more competitive. Human resource factors, transaction costs, and local suboptimization seem to be important in risk pooling and transshipments. These factors are commonly neglected in the risk pooling literature. Risk pooling methods can be and are used
side by side to take advantage of their benefits, while making up for disadvantages of other ones. This is in line with our survey findings.

Centralized ordering can reduce average cycle inventory even if a stock-to-demand order policy is followed and minimum order and saltus quantities have to be observed. It also enables to decrease safety stock and improve inventory availability as the aggregate forecast for the central order is more accurate than the disaggregate one for the decentral orders.

The literature review and this application showed the theoretical benefits risk pooling can bring. However, survey research on the knowledge and application of risk pooling is scarce. Therefore, we explored whether the different risk pooling concepts are known, applied, and associated in a survey of 102 German manufacturing and trading companies:

A lot of respondents do not perceive all the questioned concepts as risk pooling ones. It appears that mainly transshipments and postponement are associated with risk pooling.

Although at least in our sample the risk pooling concepts are known fairly well (central ordering, product substitution, and selective stocking the most), only selective stocking, transshipments, and central ordering are widely applied. Transshipments are more, postponement and product pooling less applied than suggested by some publications mostly for other regions.

Less sample companies have centralized their warehouse system than European ones. For our sample we cannot confirm a major decentralization trend as one may expect due to increasing fuel costs. Companies seem to be consistent in their strategy of centralization, decentralization, or no change in warehouse number over time.

The utilization and knowledge of a risk pooling concept are correlated. This suggests that improving the knowledge of risk pooling may increase its application. Research needs to convey under what conditions and how the different risk pooling concepts can be applied successfully. This research constitutes one step in this direction.

Prominently associated is past decentralization with future decentralization, the utilization of product substitution and demand reshape, past centralization and decentralization (the only negative correlation), the application of the inventory turnover curve and transshipments, commonality and product pooling, risk pooling and transshipments, turnover curve and order splitting, selective stocking and virtual pooling, transshipments and virtual pooling, risk pooling and postponement, product substitution and transshipments, product substitution and virtual pooling, as well as postponement and commonality and vice versa.
We can support Rabinovich and Evers' (2003b) finding that time postponement (emergency transshipments and inventory centralization) contributes to the implementation of form postponement at best only weakly for our sample.

Trading companies seem to apply product substitution and transshipments more than manufacturing companies. The opposite is true for commonality and postponement. This was considered in the RPDST. In contrast to Van Hoek (1998b) our sample shows no significant difference in the application of postponement by electronics, automotive, food, and clothing manufacturers.

More large companies appear to use risk pooling and postponement than smaller ones, perhaps because they can better afford to invest in expensive risk pooling methods as suggested by Huang and Li (2008b: 12). More small companies have centralized their warehouse or logistics system in the past than large ones in our sample.

The survey is of limited representativeness and generalizability, as a genuine simple random sample of the relevant population of German manufacturing and trading companies could not be drawn. Survey research is very laborious and prone to many biases and errors and has low response rates that disappoint the researcher and impair the results. Our experience supports that face-to-face methods tend to achieve higher response rates.

As this treatise constitutes a first attempt to structure the vast risk pooling research in business logistics, develop tools to choose between the various risk pooling methods, and get an idea about their recognition and application in German companies, we make the following suggestions for further research:

Our RPDST and its underlying contingency factors should be empirically validated with additional companies in different industries. Conditions and implementation modalities favoring the different risk pooling methods should be further explored, especially for product pooling, central ordering, (particularly non-manufacturing) capacity pooling, virtual pooling, and substitution/demand reshape, as our considerations are not exhaustive. The effectiveness and efficiency of the different methods should be compared. Evers (1999), Swaminathan (2001), Eynan and Fouque (2005), and Wanke and Saliby (2009) made a good start here.

Perhaps a normative model could be developed that integrates and compares the ten identified methods in terms of their costs and benefits in order to choose an optimal one. However, such a model might be either too complex or simple. Perhaps combining simulation and analytic frameworks may better account for the complicated interaction effects
among various factors.\textsuperscript{812} Centralized ordering and transshipments at Papierco could be simulated as well.

In general, risk pooling models should become more realistic in terms of their assumptions, accessibility for practitioners, and allowing (practitioners) to quantify the benefits of risk pooling.\textsuperscript{813}

We considered choosing suitable risk pooling methods for individual companies for certain economic conditions and sometimes their relation to their immediate supply chain members at the most. However, a risk pooling strategy that is beneficial for an individual supply chain member might not be profitable for others or the whole supply chain.\textsuperscript{814}

Therefore, it should not be implemented by one company unilaterally and further research should focus on the supply chain as a whole: Which conditions render a risk pooling method or a combination of risk pooling methods beneficial for all members of a supply chain? How do you get independent parties to agree on or join a risk pooling strategy? If some supply chain members are better and other ones worse off after risk pooling, how do you distribute the gains to encourage risk pooling and make it beneficial for everybody? The contracting side of risk pooling still leaves room for further research.

Another interesting question to explore would be whether the risk pooling methods make individual companies and the whole supply chain more resilient to external uncertainties other than demand and lead time uncertainty. Sheffi (2006, 2007) explores this question for several risk pooling methods and individual companies\textsuperscript{815}. Snyder and Shen (2006: 42) conclude that “[s]upply chain resilience [to supply disruptions and demand uncertainty] can be improved significantly without large increases in cost” by centralization (risk pooling) and decentralization (risk diversification). How should supply chains or logistics systems be designed, so that risk pooling is exploited optimally and uncertainties are minimized?

\textsuperscript{812} Cf. Hwarng et al. (2005).
\textsuperscript{813} Cf. Heil (2006: 81, 169).
An empirical analysis of risk pooling in the German auto industry might be interesting, because of the current changes in model mix (high gas prices), production volume (recession), and steel prices. How can you prepare your production system for something like this?

How does the current economic downturn affect risk pooling? We already noted that this might have contributed to increased research and implementation of risk pooling.

How do increased transportation costs affect risk pooling? If they are lasting and warehouse networks are therefore decentralized, how is this decision affected by risk pooling and how does network redesign affect risk pooling?

Another more representative survey with a higher response rate could also shed light onto the companies' reasons for and against as well as the manner, degree, benefits, and costs of applying the risk pooling concepts, as we intended in the six-page version of our survey that yielded a uselessly low response rate. As risk pooling can affect the whole supply chain, another survey could consider a supply chain wide perspective rather than single companies.

Risk pooling is usually shown or proved with the standard deviation. For other measures of dispersion, such as the variance of independent random variables or the range, there might be no risk pooling effect. Therefore one could consider risk pooling with measures of dispersion other than the standard deviation. Risk pooling should also be further explored with different order policies.

Finally, the SRL- and PE-models can be extended to include further assumptions. One should also check whether the conditions or assumptions necessary for the SRL to hold (necessary conditions) are also sufficient conditions, i. e. if the SRL holds, these conditions also automatically apply.
Appendix A: A Survey on Risk Pooling Knowledge and Application in 102 German Manufacturing and Trading Companies
1 Introduction

After reviewing the limited recent survey research in OR, business logistics, SCM, and particularly risk pooling mostly with low response rates, we describe our findings from a survey on risk pooling knowledge and application we conducted among 102 German manufacturing and trading companies. Such a survey has been demanded by some researchers and – to our knowledge – has not been conducted before.

1.1 Motivation: Scarce Survey Research on Risk Pooling

There is little empirical and especially survey research in OR, business logistics, and risk pooling. The samples and response rates are usually small or not mentioned.

No surveys have been conducted on risk pooling in business logistics in general yet. Only few surveys touch types of risk pooling. Most of these surveys deal with postponement, although the majority of empirical research on postponement relies on case stu-

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817 Griffis et al. (2003: 237).
Appendix A


Whereas some researchers find postponement application has increased, will increase, or postponement is widely applied\textsuperscript{821}, others state it is not applied as much (as expected)\textsuperscript{822} and will be even less used in the future\textsuperscript{823}. This is explained by “a general lack of understanding of postponement” regarding its conception, gains, and costs\textsuperscript{824}, perceived technology limitations, ineffective organization alignment\textsuperscript{825}, as well as difficulties in managing the relations to suppliers and customers\textsuperscript{826} and in estimating the costs and benefits of postponement\textsuperscript{827}.

Van Hoek (1998b: 513) finds that “[d]ownstream activities such as distribution and packaging are largely postponed (56.93 per cent of the flow of goods and 53.95 per cent). Upstream activities such as engineering and purchasing are postponed to a lesser extent (37.49 per cent of the flow of goods and 37.42 per cent). Overall however, the findings indicate that postponement is applied at multiple points in the chain and to a significantly high share of the flow of goods”. Yang et al. (2005b: 1000) remark that postponement is mostly applied as make to order and ship to order.

\textsuperscript{820} Van Hoek (2001).
\textsuperscript{821} CLM (1995: 213), Morehouse and Bowersox (1995), Van Hoek (1998b, 2000b), Van Hoek and Van Dierdonck (2000), McKinnon and Forster (2000: 7f.), Chiou et al. (2002), Huang and Li (2008b). CLM (1995: 213) finds “Research clearly supports the generalization that firms are rapidly adopting both form and time postponement”, although 10.3 % of North American and 85 % of non-North American world class companies have decreased or substantially decreased the use of postponement and 31 % of North American and 0 % of non-North American (European/Pacific Basin) world class companies have increased or substantially increased the use of postponement (Workbook Section 4: Organization, Question 31, “Electronic Appendix” Disk to CLM 1995). Yet, only few non-North American companies completed the workbook (CLM 1995: 384).
\textsuperscript{823} “Postponement applications are still not as widespread as expected. […] The respondents also expected postponement to be less used in three years” (Yang et al. 2005b: 991).
\textsuperscript{824} Oracle (2004: 2, 7).
\textsuperscript{825} Capgemini (2003), Matthews and Syed (2004: 30).
\textsuperscript{826} Yang et al. (2005b: 991), Waller et al. (2000), Van Hoek et al. (1998).
\textsuperscript{827} Van Hoek et al. (1998).
Rabinovich and Evers (2003b: 41f.) find that time postponement (emergency transshipments) contributes to the implementation of form postponement.

Huang and Li (2008b: 5, 16f.) discover that the degree of postponement application is higher in China than CLM (1995), Yang et al. (2005a), and Van Hoek (1998b) remarked in Western countries and increases. Chiou et al. (2002: 122) also conclude “that form postponement strategies are practiced widely by IT firms in Taiwan”. Huang and Li (2008b: 12) sent their questionnaires only to 411 companies that had confirmed on the phone that they applied postponement. They, Chiou et al. (2002), and Yang et al. (2005b) do not state how many companies in their research countries actually apply postponement. In a personal correspondence on September 4, 2009 Dr. Biao Yang, The York Management School, University of York, UK, explained that speaking from their experience, given the working definitions of different postponement strategies they provided828, very few companies would claim that they are not using any postponement.

The Council of Logistics Management (CLM) conducted a base-line survey in North America (Canada and the U.S.), Europe (France, Germany, the Netherlands, Norway, Sweden, and the UK), and the Pacific Basin (Australia, Japan, and Korea) from May to September 1993. Of the 21,592 mainly manufacturing companies contacted, 3,693 answered (response rate: 17.1 %). In Germany 3,000 surveys were mailed and 322 returned (response rate: 10.7 %).829

It also did interviews with 111 companies from 17 countries in North America, Europe, and the Pacific Basin from early 1994 until spring 1995 that were believed “by a group of logistics experts to have a high potential to possess world class logistical capabilities” and asked them to complete a 24-page workbook.830

35.3 % of North American and 29.1 % of non-North American world class companies consider **location flexibility** (“the ability to service customers from alternative warehouse locations”, i.e. in our opinion transshipments or virtual pooling) less or least impor-

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828 In their survey Yang et al. (2005b: 1002f.) ask for “the percentages of goods related to” engineer, purchase, make, final manufacturing/assembling, package/label, and ship to order to elicit the extent of postponement application in the respondents’ companies. Thus they equate make-to-order with postponement or delayed differentiation, while Cachon and Terwiesch (2009: 344) distinguish these strategies: Although “they are conceptually quite similar”, “[d]elayed differentiation is thought of as a strategy that stores nearly finished product and completes the remaining few production steps with essentially no delay. Make-to-order is generally thought to apply to a situation in which the remaining production steps from components to a finished unit are more substantial, therefore involving more than a trivial delay. Hence, delayed differentiation and make-to-order occupy two ends of the same spectrum with no clear boundary between them”.


tant, 35.3% or 37.5% respectively more or most important. The North American and non-North American world class companies see mostly the logistics department as responsible for location flexibility (77.19 and 74.76% responsibility). Fifty-one percent of North American and 58.3% of non-North American world-class companies believe they perform better or much better than their competitors in terms of location flexibility.831

According to McKinnon and Forster (2000: 17), “the proportion of retail sales bypassing conventional shops and being delivered directly to the home is likely to increase significantly” until 2005. “Direct distribution to the home from nationally based suppliers is likely to experience the fastest growth”832. That means that virtual pooling in the form of drop-shipping is expected to increase.

In a small phone survey by Randall et al. (2006) of 64 (56 responses, 54 usable responses, response rate: 84.4%) publicly held e-tailers that made up 60% to 70% of U.S.-wide e-tailing revenue, 36 companies (67.7%) chose to hold inventory. That means 33.3% of the surveyed e-tailers conducted virtual pooling.

In the CLM baseline survey, 62.81% of North American, 68.31% of European, and 47.26% of Pacific Rim companies agree or strongly agree that on an equal volume basis they had inventory located at fewer sites in 1993 (today) than in 1988 (five years ago).833 That means that 68.31% of the surveyed European companies conducted inventory pooling.

The world class companies’ “[l]ogistics strategy includes a priority to reduce […] [t]he number of logistics facilities” more so in Europe and the Pacific Basin, where the mean answer was 3.55 than in North America, where the mean answer was 3.23 on a scale from 1 (Strongly Disagree) to 5 (Strongly Agree).834

McKinnon and Forster (2000: 6f.) find “The centralisation of inventory is likely to outstrip that of production. At a European level, the degree of inventory concentration is forecast to increase by a third, twice as much as at a national level. A significant minority of the panel (around 15%) indicated that within countries there would be net decentralisation of inventory, with firms increasing their number of stockholding points. The prevailing view, however, was that inventory centralisation, which has been one of the main logistical trends over the past 30 years, would continue apace for at least the next 5 years”.

832 McKinnon and Forster (2000: 9).
A Warehousing Education and Research Council survey with 139 U.S. participants in manufacturing, retail, wholesale, public utilities and government showed that the number of warehouses continues to shrink, although there are a few new large facilities in West or Mid Atlantic regions.\(^{835}\)

Contrarily, according to a survey by Lemoine and Skjoett-Larsen (2004) among logistics managers of mechanical, electronic, and medical equipment companies in Denmark in 2001 (46 usable questionnaires, response rate: 10 \%) the number of suppliers, production facilities and warehouses has not been changed in the last three to five years in Europe, but has been increased or will be increased outside Europe.

Bandy (2005) conducts an anonymous survey among 24 students that shows that a simple spreadsheet in-class simulation helps students understand the impact of pooling safety stock.

Reviewing literature and interviewing Belgian companies, Naesens et al. (2007) find that companies are reluctant to implement inventory pooling in a horizontal collaboration.

Nonetheless, companies seem to have conducted inventory pooling within companies to a broad extent.

Twenty-seven percent of North American and 29.1 \% of non-North American world-class companies consider **substitution flexibility** (“the ability to substitute product or service offerings in the event of a delay or stockout versus backorder or line cancellation”) less or least important, 46.2 \% or 25 \% respectively more or most important. Responsibility for substitution flexibility rests 49.9 \% with logistics, 35.63 \% with marketing according to North American, or 48.41 \% or 42.95 \% respectively according to non-North American world-class companies. 44.2 \% of North American and 37.5 \% of non-North American world-class companies believe they perform better or much better than their competitors in terms of substitution flexibility.\(^{836}\)

Only few surveys provide information on how many companies apply the respective risk pooling method.

Nearly 50 \% of more than 350 companies from all over the world have not implemented postponement strategies.\(^{837}\) Hence, about half of these companies use postponement.

More than 40 \% of the companies surveyed by Kiperska-Moroñ (2003: 131) gear total production towards customer orders. Surveyed companies manufacture on average 16 \% to

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\(^{835}\) Modern Materials Handling (2002).


\(^{837}\) Oracle (2004).
stock and 84 % to order, engineering 97 %, metal 74 %, plastic products 83 %, and electro-
technical companies 77 % to order. Thus one could infer that about 40 % of the surveyed 
companies in Upper Silesia, Poland apply manufacturing postponement.

From 1988 to 1993 inventory was centralized or pooled by 68.31 % of the European 
companies surveyed by the CLM.838

Virtual pooling is applied by 33.3 % of the U.S. e-tailers that Randall et al. (2006) in-
terviewed.

None of the surveys gives detailed information on Germany, although Germany is the 
fourth largest economy in the world according to its nominal GDP in USD in 2008839 and 
is very progressive, advanced, and sophisticated in logistics, especially in “operating effi-
ciency and cost” and customer service, and, like other European countries, in the “func-
tional integration of logistics work within the firm” and “environmental issues” like “re-
verse logistics”840. European countries have opportunities for improvement in “the external 
integration of logistics systems and development of supply chain relationships throughout 
Europe”841.

1.2 Objective

We would like to determine to what extent the different risk pooling concepts are known and 
applied by 102 German manufacturing and trading companies and examine for our sample the 
following remarks, suggestions, and demands:

Van Hoek (1998b) finds that postponement is extensively applied in electronics and au-
tomotive and less extensively applied in food and clothing. We would like to find out 
whether this applies to our sample as well.

Alfaro and Corbett (2003: 12f., 15) observe that “several approaches to the widely rec-
ognized challenge of managing product variety rely on the pooling effect. Pooling can be 
accomplished through the reduction of the number of products or stock-keeping units 
(SKUs), through postponement of differentiation, or in other ways [component commo-
nality and inventory pooling]. These approaches are well known and becoming widely 
applied in practice”. However, there are no studies yet whether product pooling and com-
ponent commonality really are widely applied in practice.

839 IMF (2009).
Herer et al. (2006) remark “Transshipments are not widely adopted in practice because the IT infrastructure is inadequate and there are no realistic models to take advantage of transshipment benefits”. However, there are no studies yet whether transshipments really are not widely used in practice.

Thomas and Tyworth (2006) demand a survey to determine whether order splitting is employed in practice\textsuperscript{842}.

Boone et al. (2007) review postponement literature published from 1999 to 2006 and conclude research should be extended to non-manufacturing postponement and investigate the slow rate of postponement adoption among practitioners.

Huang and Li (2008b: 12) only surveyed large electronic/information technology, clothing, and electric appliances companies. They remark large companies may apply postponement more than small ones, since they may be better able to afford the redesign of products and/or processes usually required by postponement\textsuperscript{843}. “Hence, further studies could compare the differences of postponement application between large-scale and small and medium companies”\textsuperscript{844}.

\textsuperscript{842} “Yet, despite the impressive amount of past and present work on pooling lead-time risk by order splitting, it is difficult to find any substantive evidence of successful applications in academic or practitioner literature” (Thomas and Tyworth 2006: 246). “Although studies in both tracks provide hypothetical evidence that pooling lead-time risk by splitting orders simultaneously may be worthwhile, it is difficult, if not impossible, to find substantive empirical validation of the proposition” (Thomas and Tyworth 2006: 254). “Collectively, these limitations make the value proposition rather dubious. Thus future research in this area should include case studies, simulations, and surveys to determine whether companies use such order splitting methods and the business setting where successful applications appear” (Thomas and Tyworth 2006: 254f.).

\textsuperscript{843} Ernst and Kamrad (2000), Aviv and Federgruen (2001b).

\textsuperscript{844} Huang and Li (2008b: 19).
2 The Survey

There has not been a survey on how many companies know and apply the various risk pooling methods yet, especially not in Germany. In order to respond to the aforementioned demands and remarks, we conducted a survey among German manufacturing and trading companies from September 2008 to August 2009 and obtained 102 completed questionnaires (response rate: 21.3%) from logistics or supply chain management professionals. Since an earlier six-page survey that was e-mailed to 3,600 companies had a response rate of only 0.3%, we asked 478 manufacturing and trading company representatives in person to complete the one-page questionnaire in figure A.4 or forward it to the appropriate person mainly on company and job fairs in various German cities.

Respondents were promised a summary of the survey results as an incentive. Our experience supports that face-to-face methods usually achieve higher response rates.

2.1 Research Design

The respondents worked for companies from the following branches of economic activity according to the German Classification of Economic Activities Edition 2003 of the German Federal Statistical Office (Statistisches Bundesamt Deutschland):

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Table A.1: Comparing Respondents with the Total Population of Manufacturing and Trading Companies in Germany

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
<th>The whole population</th>
<th>Responding companies</th>
<th>Variance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Number</td>
<td>%</td>
<td>Number</td>
</tr>
<tr>
<td>11</td>
<td>Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction, excluding surveying</td>
<td>17</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>Manufacture of food products and beverages</td>
<td>5,189</td>
<td>4.46</td>
<td>4</td>
</tr>
<tr>
<td>16</td>
<td>Manufacture of tobacco products</td>
<td>24</td>
<td>0.02</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>Manufacture of wearing apparel; dressing and dyeing of fur</td>
<td>378</td>
<td>0.32</td>
<td>1</td>
</tr>
<tr>
<td>21</td>
<td>Manufacture of pulp, paper and paper products</td>
<td>817</td>
<td>0.70</td>
<td>2</td>
</tr>
<tr>
<td>22</td>
<td>Publishing, printing and reproduction of recorded media</td>
<td>2,456</td>
<td>2.11</td>
<td>2</td>
</tr>
<tr>
<td>24</td>
<td>Manufacture of chemicals and chemical products</td>
<td>1,405</td>
<td>1.21</td>
<td>3</td>
</tr>
<tr>
<td>25</td>
<td>Manufacture of rubber and plastic products</td>
<td>2,635</td>
<td>2.26</td>
<td>2</td>
</tr>
<tr>
<td>26</td>
<td>Manufacture of other non-metallic mineral products</td>
<td>1,677</td>
<td>1.44</td>
<td>1</td>
</tr>
<tr>
<td>27</td>
<td>Manufacture of basic metals</td>
<td>897</td>
<td>0.77</td>
<td>1</td>
</tr>
<tr>
<td>28</td>
<td>Manufacture of fabricated metal products, except machinery and equipment</td>
<td>6,175</td>
<td>5.31</td>
<td>4</td>
</tr>
<tr>
<td>29</td>
<td>Manufacture of machinery and equipment n.e.c.</td>
<td>5,990</td>
<td>5.15</td>
<td>13</td>
</tr>
<tr>
<td>30</td>
<td>Manufacture of office machinery and computers</td>
<td>164</td>
<td>0.14</td>
<td>1</td>
</tr>
<tr>
<td>31</td>
<td>Manufacture of electrical machinery and apparatus n.e.c.</td>
<td>1,922</td>
<td>1.65</td>
<td>7</td>
</tr>
<tr>
<td>32</td>
<td>Manufacture of radio, television and communication equipment and apparatus</td>
<td>542</td>
<td>0.47</td>
<td>5</td>
</tr>
<tr>
<td>33</td>
<td>Manufacture of medical, precision and optical instruments, watches and clocks</td>
<td>2,067</td>
<td>1.78</td>
<td>2</td>
</tr>
<tr>
<td>34</td>
<td>Manufacture of motor vehicles, trailers and semi-trailers</td>
<td>1,001</td>
<td>0.86</td>
<td>14</td>
</tr>
<tr>
<td>35</td>
<td>Manufacture of other transport equipment</td>
<td>314</td>
<td>0.27</td>
<td>3</td>
</tr>
<tr>
<td>36</td>
<td>Manufacture of furniture; manufacturing n.e.c.</td>
<td>1,484</td>
<td>1.27</td>
<td>2</td>
</tr>
<tr>
<td>37</td>
<td>Recycling</td>
<td>168</td>
<td>0.14</td>
<td>3</td>
</tr>
<tr>
<td>40</td>
<td>Electricity, gas, steam and hot water supply</td>
<td>1,196</td>
<td>1.03</td>
<td>2</td>
</tr>
<tr>
<td>45.2</td>
<td>Building of complete constructions or parts thereof; civil engineering</td>
<td>6,352</td>
<td>5.46</td>
<td>1</td>
</tr>
<tr>
<td>51.46</td>
<td>Wholesale of pharmaceutical goods</td>
<td>3,148</td>
<td>2.70</td>
<td>2</td>
</tr>
<tr>
<td>51.47.8</td>
<td>Wholesale of paper and paperboard, stationery, books, newspapers, journals and periodicals</td>
<td>2,259</td>
<td>1.94</td>
<td>3</td>
</tr>
<tr>
<td>51.53.1</td>
<td>Non-specialized wholesale of wood, construction materials and sanitary equipment</td>
<td>1,254</td>
<td>1.08</td>
<td>2</td>
</tr>
<tr>
<td>51.88</td>
<td>Wholesale of agricultural machinery and accessories and implements, including tractors</td>
<td>1,333</td>
<td>1.15</td>
<td>1</td>
</tr>
<tr>
<td>52.11</td>
<td>Retail sale in non-specialized stores with food, beverages or tobacco predominating</td>
<td>24,790</td>
<td>21.30</td>
<td>7</td>
</tr>
<tr>
<td>52.42</td>
<td>Retail sale of clothing</td>
<td>25,896</td>
<td>22.25</td>
<td>10</td>
</tr>
<tr>
<td>52.46</td>
<td>Retail sale of hardware, paints and glass</td>
<td>11,279</td>
<td>9.69</td>
<td>1</td>
</tr>
<tr>
<td>52.48.6</td>
<td>Retail sale of games and toys</td>
<td>3,564</td>
<td>3.06</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>116,393</strong></td>
<td><strong>100</strong></td>
<td><strong>102</strong></td>
</tr>
</tbody>
</table>

As 78.7% of the sampling frame population did not respond and the sample is small, it is not too representative of neither the whole population in the different branches of economic activity the respondents’ companies belong to in table A.1 nor of the target population of German manufacturing and trading companies. Not all areas of domestic production and trade are covered. Our sample consists of too many manufacturing companies, especially from vehicle construction (34, 35), although this is an important industry in Germany, manufacture of machinery (29, 31, 32), and recycling (37) and too few trading companies, particularly in food (52.11), clothing (52.42), and hardware retail (52.46) as the variance in the last column shows.

Deviations of responding companies from the whole population in Huang and Li (2008b: 13) are of similar magnitude. In contrast, the responding companies in Yang et al. (2005b: 997) closely reflect the whole population. Of the 28 mentioned surveys in this section only Huang and Li (2008b) and Yang et al. (2005b) (7.14 %) compare the responding companies' characteristics to the whole population (retrospective quota sampling).

We have to highlight that the whole population in table A.1 only consists of companies with 20 or more employees, while our sample encompasses three companies (respondents 2, 65, and 100 from industrial sectors 52.42, 27, and 51.47.8) with less than 20 employees. If we omitted them, the variance would increase and the representativeness decrease even more. A detailed classification of the branches of economic activity with all German companies with any number of employees is not publicly available. The German Federal Statistical Office told us we could apply for a special query with charges. A retrospective quota sampling with more detailed subgroups of industrial economic activity than in table A.1 and all German companies, which cannot be conducted due to lacking data, might reveal that our sample is more representative of these subgroups.

The size of the responding companies ranges from 5 to 182,739 employees. 2 % have less than 10, 9 % less than 50, 31 % less than 250, 32 % less than 500, and 68 % have 500 employees.

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847 There were 52,362 manufacturing (9.94 % of manufacturing and trading companies) and 474,065 (90.06 %) trading companies in general 20 or more employees in Germany in 2007 or 2006 respectively (Statistisches Bundesamt Deutschland 2009i: 409, 371). In our sample there are 75 (73.53 %) manufacturers and 27 (26.47 %) trading companies.

or more employees. The majority of the sample consists of larger companies, while the majority of the whole population comprises small ones. 849

Nevertheless our survey can at least show the risk pooling knowledge and activities of the surveyed companies for a given moment in time. They are relatively heterogeneous in terms of industry membership and number of employees (size), so that risk pooling knowledge and activities of a wide company spectrum and size specific specialties can be detected. 850 Besides, the respondents do not deviate from the overall population extremely regarding the branches of activity. Therefore, the absence of data from the nonrespondents may not contaminate the conclusions drawn from the sample too much. 851

The questionnaire was scrutinized by three academics and three logistics managers, pretested among eleven companies, and adjusted according to the suggestions and detected problems before the final distribution to insure content validity. 852 Validity measures whether the questions capture what they are intended to capture. 853 Of the 28 surveys mentioned previously 28.57 % deal with their validity. Reliability measures “whether respondents are consistent or stable in their answers” 854. Only 17.86 % of the 28 surveys mentioned address their reliability. We did not measure reliability as respondents usually are not willing to be interviewed twice or to answer a questionnaire enlarged by asking for the same construct twice. 855 We could not check for “systematic reporting errors” (response bias), as external data, which the survey responses could be compared to, are not available 856. None of the 28 surveys mentioned refers to their response bias.

We did not check for non-response bias, because we could not collect the nonrespondents' characteristics. 858 Non-response bias is the distortion of the sample and therefore the basic population because some people do not respond or do not answer certain questions. The answers of respondents may differ from the ones of nonrespondents. There is no consensus on when nonresponse reduces survey quality and therefore on appropriate response

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849 In 2006 there were 4,307 (0.63 %) active industrial and 1,362 (0.18 %) trading companies with 250 and more, 680,561 (99.37 %) or 735,820 (99.81 %) ones respectively with less than 250 employees subject to social security (Statistisches Bundesamt Deutschland 2009i: 493). In our sample 74.67 % of the industrial and 51.85 % of the trading companies have 250 and more employees.


856 Groves et al. (2004: 259).


response rate is above the unfavorable response rates below 20%, within the 10% to 30% of the past mean, and the 4% to 32.7% of large samples in the Journal of Business Logistics from 1997 to 2001, and higher than a lot of the mentioned surveys' ones.

Nonresponse rates often are ignored, because it is assumed that the reason for the nonresponse is not associated with the measured statistical values and therefore it does not affect the quality of the survey's results. Of the 28 surveys we mentioned ten (35.71%) deal with their nonresponse bias. Most of these determine the nonresponse bias, checking whether the answers of first respondents and late respondents differ, although late respondents may not be an appropriate estimate for nonrespondents.

Nonetheless, the answers of our 51 first and 51 last respondents are independent (the null hypothesis that there is no significant relationship between the answers cannot be rejected) in Pearson's and Yates' chi-square and Fisher's exact test at the 5% level, except for the question about their risk pooling knowledge and centralization in the past. In all other cases the distribution of the answers within the two groups does not differ significantly: The two-sided asymptotic significance of the respective test statistic is greater than 0.05 in each case, so that it is safe to say that any differences are due to chance variation, which implies that the two groups answered equally.

With our sample size of 102 the confidence interval or margin of error is 9.7 on the 95% confidence level for an estimated percentage of 50%, i.e., one can be 95% certain that if 50% of the sample picks an answer between 40.3% (50-9.7) and 59.7% (50+9.7) of the whole population would have also picked that answer. However, the true percentage of the population only is the sample's percentage plus/minus the confidence interval, if a genuine simple random sample of the relevant population was drawn. This cannot be confirmed for our sample, so that this confidence interval is an underestimate. No errors and “biases of coverage, sampling, nonresponse, or measurement […] are included in the margin of error.” When random sampling is not used, one has to depend on logic apart from

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860 Yu and Cooper (1983).
861 Flynn et al. (1990).
862 Griffis et al. (2003: 242).
865 In this case Pearson's chi-square test gives \( \chi^2 = 9.046 \) with \( df = 1 \) and \( p = 0.00263 \), Yates' correction for continuity \( \chi^2_{Yates} = 7.880 \) with \( df = 1 \) and \( p = 0.004998 \), and Fisher's exact test \( p \) (two-tailed) = 0.004728.
866 In this case \( \chi^2 = 4.752 \) with \( df = 1 \) and \( p = 0.029264 \), \( \chi^2_{Yates} = 3.928 \) with \( df = 1 \) and \( p = 0.047432 \), and \( p = 0.046973 \) in Fisher's exact test.
867 Groves et al. (2004: 382).
mathematical probability to assess to what extent the sample deviates from the population it was drawn from.\textsuperscript{868}

2.2 Data Analysis and Findings

2.2.1 Risk Pooling Knowledge and Utilization in the German Sample Companies

The most known concepts related to risk pooling in the whole sample are central ordering, product substitution, selective stocking, transshipments, and order splitting, followed by product pooling, commonality, virtual pooling, capacity pooling, “risk pooling”, postponement, demand reshape, the portfolio effect (PE), inventory turnover curve, and square root law (SRL) in order of descending percentage of respondents that know these concepts.

Surprisingly, the SRL (28 \%) is less known than the PE (54 \%), although it is the simpler concept and there are more and earlier publications on it in business logistics. Perhaps the PE is more popular, as it is a generalization of the SRL and originated in finance.

\textsuperscript{868} Vockell and Asher (1995: ch. 8).
A lot of respondents obviously did not realize that risk pooling may comprise all these different concepts. Otherwise they would have noted that they know and apply risk pooling, whenever they checked to know or apply any of these concepts. Risk pooling is a hypernym and not a risk pooling concept itself.

The most applied risk pooling concepts in the whole sample are selective stocking, transshipments, central ordering, commonality, and centralization, followed by product substitution, virtual pooling, capacity pooling, product pooling, postponement, order splitting, “risk pooling”, the PE, inventory turnover curve, demand reshape, decentralization, and the SRL in order of descending percentage of surveyed companies applying these concepts.

While the knowledge of the different risk pooling concepts is fairly good (only the SRL and the inventory turnover curve are known by less than 50 %), they are not widely applied. Only the well established concepts selective stocking, transshipments, and central ordering show application rates over 50 %, namely 66 %. This disagrees with Herer et al. (2006), who remark “Transshipments are not widely adopted in practice because the IT infrastructure is inadequate and there are no realistic models to take advantage of transshipment benefits”. Some companies which do not employ central ordering remarked it increased transportation and delivery costs too much. This could be counteracted with a centralized ordering system like the one we designed for Papierco earlier. Transportation costs do not increase (substantially) or the supplier incurs them.

Postponement is only applied by 35 % of the companies. Thus we cannot conclude “that firms are rapidly adopting both form and time postponement” and widely apply it in Germany as CLM (1995: 209) reports for North America and Europe, McKinnon and Forster (2000: 5) for Europe, and Chiou et al. (2002) and Huang and Li (2008b) for China. More sample companies in Germany (65 %) have not implemented postponement strategies than suggested by Oracle (2004) (nearly half of 358 mainly manufacturing companies from all over the world). We agree with Van Hoek et al. (1998), Bowersox et al. (1999), Battezzati and Magnani (2000), Brown et al. (2000: 78), Oracle (2004), Yang et al.

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869 Wazed et al. (2009: 70) find “Although the benefits of commonality are widely known, many companies are still not taking full advantage of it when developing new products or re-designing the existing ones”. We can agree with them for our sample.

870 Alfaro and Corbett (2003: 12f., 15) already remark that risk pooling approaches such as product pooling, postponement, component commonality, and inventory pooling “are well known […] in practice”.


(2004, 2005a, 2005b, 2007), and Boone et al. (2007) that postponement is not applied as much (as expected).

Some respondents told us they did not use postponement as it entailed completely different production and storage concepts and therefore usually was uneconomical. Research has to determine more clearly the changes necessary for postponement, methods for calculating the costs of postponement, and conditions that render postponement economical. Practice seems to lack the knowledge to implement postponement economically. Perhaps more concepts have to be developed that may make postponement less expensive, such as operations reversal. This is in line with Oracle (2004: 7f.). Our survey suggests that the reason for the low application may not lie in the basic knowledge of this concept (55% know it), but it is less known than most of the other concepts except for demand reshape, the PE, inventory turnover curve, and SRL.

**Component commonality** is well known and applied by nearly every second surveyed company. Thus, we can support Kim and Chhajed (2001: 219), who remark “The use of commonality in product line extensions is a growing practice in many industries”, and Alfaro and Corbett (2003: 12, 15), who observe it is “becoming widely applied in practice”. Nevertheless some companies who do not use it pointed out it was too expensive. This confirms that the cost of common components can be high.

Location flexibility achieved by transshipments and **virtual pooling** seems to be more important in the sample companies in Germany than suggested by CLM for North American and non-North American world class companies. McKinnon and Forster (2000: 9, 17) predicted virtual pooling in the form of drop-shipping to increase. Randall et al. (2006) found that 33.3% of the 56 interviewed U.S. e-tailers relied on virtual pooling. More generally we find that 46% of the surveyed manufacturers and traders apply virtual pooling in Germany. Our sample only contains a single toy e-tailer.

Fewer German sample companies (48%) have centralized their stockholding than European ones overall (68.31%)875. Our findings agree with McKinnon and Forster (2000: 6f.), Modern Materials Handling (2002), and Alfaro and Corbett (2003: 12f.) that inventory **centralization** is an important trend. However, we can also confirm the minority opinion of 15% of the panelists in McKinnon and Forster (2000: 6f.) that there will be a slight net decentralization of inventory in Germany in the future. Thirty-five percent of the German

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sample companies have not changed the number of warehouses or production facilities in the past. Lemoine and Skjoett-Larsen (2004) reached a similar result in Denmark. Some of the companies that did not or will not centralize declared it increased transportation costs too much.

Most companies have already centralized or to a lesser extent decentralized their warehouse or logistics system in the past. Only six percent intend to centralize their logistics system in the future. Merely seven percent plan to increase the number of warehouse or production locations in the future. This is in opposition to the expectation that the increasing fuel and transportation costs induce companies to decentralize their warehouse or logistics systems. The risk pooling advantages derived from physical inventory pooling may outweigh the increased transportation costs.

Product substitution flexibility seems to be more important in Germany than suggested by CLM\textsuperscript{876} for North American and non-North American world class companies. Companies applying demand reshape mostly indicated they persuaded customers to buy another substitute product even though the original customer wish was available to increase the profit margin and not for risk pooling reasons as intended by Eynan and Fouque (2003, 2005).

We have to disagree with Alfaro and Corbett (2003: 12) who observe “the reduction of the number of products or stock-keeping units (SKUs)”, also known as product pooling\textsuperscript{877}, and “postponement of differentiation” are “becoming widely applied in practice”. Product pooling is applied by 40 % and postponement by 35 % of the companies in our sample.

We can answer the call of Thomas and Tyworth (2006: 254f.) for empirical research “to determine whether companies use such order splitting methods”, pointing out that only 35 % of German companies in our sample do apply them. However, our survey does not inform about the conditions and success of these order splitting applications.

Some interviewees said they did not know when and how it was favorable to apply the various risk pooling concepts. Research needs to address these issues further. More research is needed to convey to practice when and how the different risk pooling concepts may be implemented successfully. Our research constitutes one step in this direction.

\textsuperscript{876} Workbook Section 3: Relative Performance Competencies, Question 29, “Electronic Appendix” Disk to CLM (1995)

\textsuperscript{877} Cachon and Terwiesch (2009: 330, 467).
2.2.2 Association between the Knowledge of Different Risk Pooling Concepts

The knowledge of risk pooling is significantly associated with the knowledge of postponement (Goodman and Kruskal's Tau ($\tau$) = 0.147, approximative significance based on chi-square approximation ($p$) = 0.000), product pooling ($\tau$ = 0.104, $p$ = 0.001), transshipments ($\tau$ = 0.091, $p$ = 0.002), the turnover curve ($\tau$ = 0.087, $p$ = 0.003), commonality ($\tau$ = 0.066, $p$ = 0.010), demand reshape ($\tau$ = 0.061, $p$ = 0.013), and virtual pooling ($\tau$ = 0.050, $p$ = 0.025) in order of descending significance.

**Goodman and Kruskal's Tau** was chosen, as it offers advantages over all other measures of association for nominal variables. It can be interpreted easily, its maximum is one, it takes the value 0, if the variables are independent, and it is suitable, if the number $k$ of the independent variable $x$'s categories is not equal to the number $m$ of the dependent variable $y$'s categories. Its only disadvantage is its complicated calculation, which is remedied with modern statistics software. $^878$ Goodman and Kruskal's Tau measures the association of two categorical variables in terms of an improvement of prediction relative to a random distribution of people (or responding companies in this case) based on the marginal distribution. $^879$ It is a measure of proportional reduction of error (PRE). $^880$

The above Tau of 0.147, for instance, means that the postponement knowledge of 14.7% more of responding companies is predicted correctly, if we predict the postponement knowledge of a company not only according to the general distribution of postponement knowledge, but according to the conditional distribution of postponement knowledge that is distinguished by the risk pooling knowledge. $^881$ Postponement might be the most popular type of risk pooling, as its recognition shows the highest correlation with the knowledge of risk pooling. Forty-two of the 59 responding companies who know risk pooling also know postponement. Twenty-nine of the 43 logistics professionals not knowing risk pooling do not know postponement either. The knowledge of risk pooling is also highly significantly associated with knowing product pooling ($\tau$ = 0.104, $p$ = 0.001) and transshipments ($\tau$ = 0.091, $p$ = 0.002).

Further significant correlations at least at the 5% level between the knowledge of the different risk pooling concepts can be read from table A.2 at the end of this section.

Most significantly **correlated** is the knowledge of product pooling and transshipments ($\tau = 0.163, p = 0.000$), risk pooling and postponement ($\tau = 0.147, p = 0.000$), transshipments and capacity pooling ($\tau = 0.139, p = 0.000$), as well as transshipments and postponement ($\tau = 0.135, p = 0.000$) and vice versa in order of descending strength of correlation.

In this sample the knowledge of postponement and capacity pooling ($\tau = 0.116, p = 0.001$), product substitution and demand reshape ($\tau = 0.112, p = 0.001$), product pooling and demand reshape ($\tau = 0.104, p = 0.001$), postponement and order splitting ($\tau = 0.101, p = 0.001$), selective stocking and transshipments ($\tau = 0.098, p = 0.002$), as well as demand reshape and transshipments ($\tau = 0.095, p = 0.002$) is relatively strongly correlated. These concepts seem to be related and therefore to be known together: Postponement and capacity pooling are popular and applied together e. g. in the auto industry. Both in product substitution and demand reshape goods are substituted. One can offer a limited number of products by product pooling or offer a variety of products (but not store all of them) and apply demand reshape or transshipments. In order splitting certain steps in the order and supplier delivery process may be postponed. If SKUs are only stocked at certain locations (selective stocking), transshipments may be necessary between these locations.

Usually, we call a correlation in the social and economic sciences strong, if the measure of correlation is $> 0.5$. In social and economic sciences any two characteristics are in general only weakly connected, i. e. the measure of correlation is $< 0.3$ for a lot of bivariate distributions of socio-scientific data, because social and economic interrelations are not transparent at first glance, but multidimensional, flexible, and versatile.\(^{882}\) Furthermore, the other nominally scaled measures of correlation show much higher values than Tau, but are difficult to interpret except for Lambda. However, Lambda has the disadvantage of taking the value 0, even if both variables are not independent.\(^{883}\) In our research the Tau values are one half to one third of the other measures' ones.

A statistical correlation does not necessarily mean that there is a real cause and effect relationship between two variables: First of all, with a 95 % confidence interval there is still a 5 % chance that a measured correlation is coincidental. Secondly, without a theory one cannot determine the cause and the effect. Thirdly, there might be a spurious causation, i. e. two characteristics change in the same way, although they are not connected. They both are connected to and influenced by a third characteristic. In order to elucidate these effects also statistically one has to analyze more than two variables collectively by

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\(^{882}\) Müller-Benedict (2007: 197f.).

\(^{883}\) Müller-Benedict (2007: 203ff.).
**Multivariate data analysis**. Multivariate analysis methods for only nominal data seem less powerful and clear than the ones for metric data and are not widely available in software packages. If all variables are nominal, contingency table, configuration frequency, log-linear, latent structure (if additional latent variables are used), and cluster analysis can be employed. Most multivariate analysis methods require higher scales of measurement. They should not be used without understanding them, their assumptions, controversies, and theoretical foundations as modern software facilitate and some researchers do.

Knowledge of a risk pooling concept certainly is not only connected to the knowledge of other risk pooling concepts and a company's industrial sector and size (number of employees), but also to other factors. Likewise, the application of a risk pooling concept might be correlated to additional factors besides the awareness of this and other concepts, the application of other concepts, and a company's sector of economic activity and size. These other factors remain subject to further research.

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887 Holtmann (2007).
888 Breakwell (2007: 441ff.).
There is a strong highly significant correlation between the knowledge of a risk pooling concept and its application as the diagonal in the correlation matrix in Table A.3 at the end of this section shows. This suggests that increasing practitioners' knowledge and understanding of risk pooling by praxis-oriented research may increase its application. The strongest correlation exists between the knowledge and the application of virtual pooling ($\tau = 0.431$, $p = 0.000$). That means the error of predicting the variable utilization of virtual pooling can be reduced by 43.1 %, if the distribution of the variable knowledge of virtual pooling is known. Forty-six of the 65 respondents who know virtual pooling also apply it. Of the 37 respondents who do not know virtual pooling 36 also do not apply it. Consequently, one professional did not recognize the concept perhaps by its name, but when reading the explanation he came to realize that his
company applies this concept. There are a few cases like that pertaining to the other risk pooling concepts as well.

The next highest correlations exist between the knowledge and application of the SRL ($\tau = 0.319, p = 0.000$) and of commonality ($\tau = 0.317, p = 0.000$).

The recognition of transshipments is significantly correlated with both the application of selective stocking ($\tau = 0.088, p = 0.003$) and risk pooling ($\tau = 0.071, p = 0.008$), the knowledge of postponement with the use of risk pooling ($\tau = 0.079, p = 0.005$). This highlights again that the respondents seem to mainly associate the popular concepts of postponement and transshipments with risk pooling. The knowledge of transshipments might favor the implementation of selective stocking, since products have to be exchanged between locations as they are only stored at few locations for economical reasons.

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</thead>
<tbody>
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<td>0.319 (0.000)</td>
<td>0.291 (0.000)</td>
<td>0.292 (0.000)</td>
<td>0.202 (0.000)</td>
<td>0.047 (0.022)</td>
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<td>Order Splitting</td>
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Table A.3: Significant Correlations at the 5 % Level (except in the case Product Substitution/Demand Reshape) between Knowledge and Utilization of Risk Pooling Concepts

a. Goodman and Kruskal’s Tau
b. Approximative significance based on chi-square approximation.
2.2.4 Association of the Utilization of Different Risk Pooling Concepts

Most significantly and strongly associated is past decentralization with future decentralization ($\tau = 0.253, p = 0.000$), the utilization of product substitution and demand reshape ($\tau = 0.212, p = 0.000$), past centralization and decentralization ($\tau = 0.185, p = 0.000$), the application of the inventory turnover curve and transshipments ($\tau = 0.132, p = 0.000$), commonality and product pooling ($\tau = 0.127, p = 0.000$), risk pooling and transshipments ($\tau = 0.121, p = 0.000$), the turnover curve and order splitting ($\tau = 0.117, p = 0.001$), selective stocking and virtual pooling ($\tau = 0.113, p = 0.001$), transshipments and virtual pooling ($\tau = 0.113, p = 0.001$), risk pooling and postponement ($\tau = 0.109, p = 0.001$), product substitution and transshipments ($\tau = 0.096, p = 0.002$), as well as product substitution and virtual pooling ($\tau = 0.096, p = 0.002$) and vice versa as shown in Table A.4 at the end of this section.

Eighty-four (99%) of the 85 companies which did not decentralize in the past do not intend to decentralize in the future. Eleven of the 17 companies which did decentralize will continue to decentralize in the future. Eighty-four (88%) of the 95 companies which do not intend to decentralize their warehouse or logistics system, did not decentralize in the past either. Six (86%) of the seven companies planning to decentralize in the future, already decentralized in the past. It seems that these companies follow their warehouse or logistics system strategy of decentralization or no decentralization consistently over time.

Fifty-one (94%) of the 54 respondents who do not apply product substitution do not apply demand reshape either. Twenty of the 48 respondents using product substitution use demand reshape as well. Fifty-two of the 80 companies which do not reshape demand do not substitute products in case of a stockout either. Twenty of the 22 demand reshaping companies also use product substitution. It seems that companies which do not persuade customers to buy a substitute product in case of a stockout mostly do not do so either, if the desired product is available. This might occur, if a company does not sell substitute products. Ninety-one percent of demand reshapers also apply product substitution, perhaps because both strategies are similar in that they both substitute products.

If a company centralized in the past (49 companies), there was absolutely no decentralization in the past. If a company conducted no centralization in the past, there was mostly no decentralization either: Of the 53 companies which did not centralize in the past only 17 decentralized in the past, 36 ones (68%) did not. Past centralization and decentralization thus show a rather negative correlation as the Phi value of $-0.430$ ($p = 0.000$) sug-
gests. Forty-nine (58%) of the 85 companies which did not decentralize centralized in the past and none of the 17 companies which decentralized centralized in the past. It appears that decentralization excludes centralization and vice versa. The strategy of decentralization, centralization, or no change is followed fairly consistently over time.

Thirty-four (97%) of the 35 companies which do not transship do not use the inventory turnover curve. Forty-three of the 67 transshipping companies utilize the turnover curve. Thirty-four of the 77 responding companies which do not use the inventory turnover curve do not take advantage of transshipments either. Twenty-four (96%) of the 25 companies using the turnover curve transship. One could assume that companies using the inventory turnover curve attach great importance to inventory turnover. If therefore they tend to mainly store fast movers at every location, this might explain why they also use transshipments to exchange e.g. slow movers between locations.

Forty (77%) of the 52 companies which have not implemented component commonality do not use product pooling. Twenty-nine of the 50 companies using common components also use product pooling. Forty of the 61 companies which have not implemented product pooling have not implemented component commonality either. Twenty-nine (71%) of the 41 product pooling companies use common components as well. This comes as no surprise as product pooling may rely on common components to satisfy customers that were previously offered their own product variant with a single common product. Furthermore, both methods take advantage of standardization. “[S]tandardization enables risk pooling across products, leading to lower inventories, and allows firms to use the information contained in aggregate forecasts more effectively.”

Thirty-one (89%) of the 35 companies not relying on transshipments likewise declared that they did not apply risk pooling. Thirty-one of the 67 companies using transshipments also use risk pooling. Thirty-six of the 67 companies which indicated that they are not using risk pooling do not use transshipments either. Thirty-one (89%) of the 35 ones using risk pooling do use transshipments as well. This highlights again that the responding professionals strongly associate risk pooling with transshipments.

Fifty-seven (74%) of the 77 companies which do not use the turnover curve do not apply order splitting either. Sixteen of the 25 companies employing the turnover curve split orders as well. Fifty-seven (86%) of the 66 companies not splitting orders do not use

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889 Although we deal with nominal variables, we can exceptionally refer to a negative correlation here (cf. Schulze 2007: 127).
the turnover curve. Sixteen of the 36 companies that utilize order splitting use the inventory turnover curve as well. Splitting an order into multiple orders or goods receipts may not only decrease supplier lead time variability but also reduce average inventory and therefore increase inventory turnover. The inventory turnover is reflected in the inventory turnover curve. Inventory policies, which may be determined and controlled with the inventory turnover curve, might lead to order splitting.

Twenty-seven of the 55 not virtually pooling companies do not store SKUs selectively at warehouses. Thirty-nine (83 %) of the 47 companies which apply virtual pooling also apply selective stocking. Twenty-five (71 %) of the 35 logistics professionals indicating that their company does not rely on selective stocking do not pool virtually either. Thirty-nine of the 67 companies using selective stock-keeping also apply virtual pooling. Virtual pooling may entail selective stocking and vice versa: On the one hand, access to other locations' inventories via virtual pooling may favor a specialization in stock holding. On the other hand, stocking products only at few locations due to cost considerations may necessitate that these locations can access each other's inventories. For instance, a company may choose to stock only fast movers at all regional warehouses and have slow movers dropped-shipped to customers or cross-filled. Thus inventories and demands at different locations are pooled virtually.

Seventy-seven percent (27) of the companies not using transshipments (35), do not pool virtually either. Fifty-eight percent (39) of the companies transshipping (67) use virtual pooling in addition. Twenty-seven of the 55 responding companies which do not use virtual pooling do not use transshipments either. However, thirty-nine (83 %) of the 47 virtually pooling companies rely on transshipments. Extending a company's warehouse or warehouses beyond its or their physical inventory to the inventory of other own locations or of other companies' locations via information technology and the internet (virtual pooling) often entails stock transfers between locations (transshipments). Virtual pooling resembles transshipments, if it comprises drop-shipping\(^{892}\) or cross-filling\(^{893}\).

Of the 67 respondents who indicated not having implemented risk pooling 51 ones (76 %) have not implemented postponement either. Twenty (57 %) of the 35 ones who use risk pooling also use postponement. Fifty-one (77 %) of the 66 survey participants indicating no postponement utilization also denied the use of risk pooling. Twenty (56 %) of the 36 companies having implemented postponement also confirm the usage of risk pool-

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\(^{892}\) Netessine and Rudi (2006: 845).
ing. Consequently, the responding logisticians strongly associate risk pooling with postponement.

Twenty-six (74%) of the 35 companies that do not use transshipments do not substitute products either. Thirty-nine of the 67 transshipping companies also use product substitution. Twenty-six of the 54 companies not substituting products do not use transshipments either. Thirty-nine (81%) of the 48 product substitutionists use transshipments in addition. This shows that product substitution and transshipments can be applied side by side just like in the case of Papierco. For this company product substitution is the cheaper option, so that it should only use transshipments as an alternative, if it is not possible to substitute products in case of a stockout.

The same applies to virtual pooling: Thirty of the 48 companies which rely on product substitution pool virtually as well. Thirty-seven (69%) of the 54 ones not substituting products, do not apply virtual pooling either. Thirty-seven (67%) of the 55 companies not pooling virtually do not use product substitution either. Thirty of the 47 ones pooling virtually also substitute products.

We can support Rabinovich and Evers' (2003b) finding that time postponement (emergency transshipments and inventory centralization) contributes to the implementation of form postponement at best only weakly for our sample: Postponement is only weakly and at the 5% level just not statistically significantly associated anymore with transshipments ($\tau = 0.035, p = 0.059$) and selective stocking ($\tau = 0.035, p = 0.059$). Twenty-eight (42%) of the 67 companies stocking selectively thereby centralizing inventory also apply postponement. Twenty-seven (77%) of the 35 ones not using selective stocking do not use postponement either. The same applies to transshipments.

Postponement is statistically significantly independent of past ($\tau = 0.000, p = 0.903$) and future centralization ($\tau = 0.009, p = 0.350$). The contrary is true for its association with risk pooling ($\tau = 0.109, p = 0.001$) and component commonality ($\tau = 0.068, p = 0.009$). Forty of the 66 not postponing companies do not use component commonality. Twenty-four (67%) of the 36 postponing companies also employ common components. Forty (77%) of the 52 companies not applying component commonality do not apply postponement either. Twenty-four of the 50 users of common components also rely on postponement. This shows that the implementation of postponement and commonality may go hand
in hand\textsuperscript{894} as we already highlighted describing the Risk Pooling Decision Support Tool. The implementation of postponement may even require component commonality.\textsuperscript{895}

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Table A.4: Significant Correlations at the 5 % Level between the Utilization of Risk Pooling Concepts

a. Goodman and Kruskal’s Tau
b. Approximative significance based on chi-square approximation.


2.2.5 Risk Pooling Knowledge and Utilization in the Responding Manufacturing and Trading Companies

Figure A.2: Risk Pooling Knowledge and Utilization in the Sample Manufacturing and Trading Companies
When we subdivide the original sample for subanalyses in this section, we decrease our sample size and therefore enlarge our confidence intervals\(^{896}\).

At the 5 % level Pearson’s and Yates’ chi-square and Fisher’s exact test revealed significant differences between manufacturing and trading companies in employing product substitution (Pearson’s chi-square \(\chi^2 = 8.01\), degrees of freedom df = 1, \(p = 0.004652\)), commonality (\(\chi^2 = 7.84\), df = 1, \(p = 0.00511\)), and transshipments (\(\chi^2 = 6.19\), df = 1, \(p = 0.012847\)), in the knowledge of commonality (\(\chi^2 = 5.47\), df = 1, \(p = 0.019346\)), and in the utilization of postponement (\(\chi^2 = 4.52\), df = 1, \(p = 0.033501\)^{897}) in descending order of asymptotic significance (two-sided).

The 75 manufacturing companies surveyed know central ordering, product substitution, selective stocking, and order splitting the most, followed by transshipments, product pooling, commonality, capacity pooling, virtual pooling, risk pooling, postponement, demand reshape, the PE, inventory turnover curve, and SRL.

The 27 trading companies recognize central ordering, product substitution, selective stocking, transshipments, order splitting, product pooling, the PE, virtual pooling, capacity pooling, demand reshape, commonality, risk pooling, the inventory turnover curve, postponement, and the SRL in decreasing order of awareness.

The manufacturing and trading companies do not differ statistically significantly at the 5 % level in their knowledge of the various risk pooling concepts, except for commonality. Seventy-six percent of the manufacturing and 52 % of the trading companies are aware of this concept.

Selective stocking (63 %), central ordering (61 %), transshipments (59 %), and commonality (57 %) are the concepts most frequently applied by the manufacturers. Capacity pooling (47 %), centralization, virtual pooling, product pooling, postponement, product substitution, order splitting, risk pooling, the PE, inventory turnover curve, demand reshape, the SRL, and decentralization follow in order of descending employment.

Trading companies apply transshipments (85 %), central ordering (78 %), selective stocking (74 %), and product substitution (74 %) the most, followed by centralization (63 %), virtual pooling, order splitting, risk pooling, the PE, product pooling, demand reshape, commonality, capacity pooling, the inventory turnover curve, postponement, decentralization, and the SRL.

896 Vockell and Asher (1995: ch. 8).
897 However, in this case \(\chi^2_{\text{Yates}} = 3.58\) with df = 1 and \(p = 0.058479\), but \(p = 0.037049\) in Fisher’s exact test.
All concepts are more widely used in the trading companies than in the manufacturing companies, except for the SRL, commonality, the inventory turnover curve, product pooling, postponement, and capacity pooling. As already mentioned above, this relationship is statistically significant only for product substitution, commonality, transshipments, and postponement at the 5 % level. This supports our hypothesis from the Risk Pooling Decision Support Tool that component commonality, postponement, and capacity pooling are rather applied by manufacturers and might be more suitable in a manufacturing environment. However, the utilization of capacity pooling in manufacturing and trading companies is just not statistically significantly different at the 5 % level anymore ($\chi^2 = 3.53, \text{df} = 1, p = 0.060268$).

Forty-one percent of the manufacturing companies apply postponement. This matches the more than 40 % of the manufacturers surveyed by Kiperska-Moroñ (2003: 131) in Upper Silesia, Poland that gear total production towards customer orders.

Thirty-seven percent of the 27 electronics (classification numbers 30, 31, and 32) and automotive (34) and 40 % of the five food (15) and clothing (18) manufacturers employ postponement. Consequently, with our sample we cannot support at the 5 % level Van Hoek (1998b), who finds that postponement is extensively applied in electronics and automotive and less extensively applied in food and clothing. The utilization of postponement by electronics and automotive and food and clothing manufacturers in our sample is independent in the Fisher Exact Probability Test\(^ {898}\) ($p (\text{two-tailed}) = 1$). It differs neither in these two nor in the four groups significantly at the 5 % level. However, Van Hoek's (1998b) observation may apply to the whole population, as the confidence interval for the aforementioned conditions is very broad with 18.86 for electronics and automotive and 43.83 for food and clothing. For the same reasons as given earlier this confidence interval can only serve as a crude estimate here. Only five answers from food and clothing manufacturers are probably not enough to compare postponement application between different industrial sectors.

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\(^{898}\) The Fisher Exact Probability Test is used, because some contingency table (crosstab) cells have expected counts less than 5. Nevertheless, Pearson's and Yates' chi-square test led to the same conclusion.
2.2.6 Knowledge and Utilization of the Different Risk Pooling Concepts in Small and Large Responding Companies

Figure A.3: Knowledge and Utilization of the Different Risk Pooling Concepts in Small and Large Responding Companies
The answers of the 33 small (having less than 500 employees) and 69 large companies (having 500 or more employees according to the Deutsches Institut für Mittelstandsfororschung (German Institute for Midium-sized Businesses Research)) are independent (the null hypothesis that there is no significant relationship between the answers cannot be rejected) in Pearson's and Yates' chi-square and Fisher's exact test at the 5 % level, except for the usage of risk pooling ($\chi^2 = 5.63, \text{ df} = 1, p = 0.017656$), centralization in the past ($\chi^2 = 4.75, \text{ df} = 1, p = 0.029298$), and postponement ($\chi^2 = 4.24, \text{ df} = 1, p = 0.039482^{899}$). This means only for these last three variables the distribution in the two groups of small and large companies differs statistically significantly$^{900}$, most significantly for risk pooling.

The small companies tend to have more knowledge of selective stocking, demand reshape, central ordering, product pooling, and order splitting, while a higher percentage of large ones know the SRL and postponement. The large companies apply all concepts more than small companies (especially risk pooling, postponement, transshipments, capacity pooling, the PE, and product pooling) except for centralization in the past, demand reshape, commonality, product substitution, and central ordering in order of descending percentage difference of companies applying the respective concept. Hence, we can agree with Huang and Li (2008b: 12) that large companies may apply postponement more than small ones, since they may be better able to afford the redesign of products and/or processes usually required by postponement$^{901}$.

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899 However, in this case $\chi^2_{Yates} = 3.37$ with df = 1 and p = 0.066394, but p = 0.047623 in Fisher's exact test.

900 This means that one can be certain that this statistic is dependable, the difference is genuine and not by coincidence. It does not mean that the difference is large, important, or useful (Walonick 2009).

3 Critical Appraisal

We need to point out that the assumption of the significance test of random sample data may be violated. For population data any crosstable differences are real and thus significant. With non-random sample data we cannot establish significance.\textsuperscript{902} However, significance tests are sometimes used as rough approximations.\textsuperscript{903} For criticism of significance testing you may e. g. refer to Carver (1978), Cohen (1994), and Thompson (1996). Statistical significance does not tell if a research's results will reoccur\textsuperscript{904} or the strength and generalizability of relationships in a sample and hence may divert attention from more crucial concerns\textsuperscript{905}.

Although a thorough research process was followed, the limited representativeness of this survey has to be acknowledged. This should be remedied in another survey by a higher response rate. However, this might be difficult, as response rates for academic studies are low\textsuperscript{906} and have been declining over the last years\textsuperscript{907}. Perhaps there are so few surveys in logistical research, since it is very difficult to obtain a random or at least representative sample because of low response rates as we experienced. A lot of companies are swamped with surveys and/or have a policy of not answering surveys. Some researchers pay companies to take part in surveys or give them other perquisites, which might also lead to a response bias. Practitioners should not criticize business research as too theoretical on the one hand and not take part in surveys on the other hand.

As it is laborious to design and administer surveys, the usually low response rates disappoint the researcher and “imperil the strength of the research findings”\textsuperscript{908}, and survey research is prone to so many biases and errors\textsuperscript{909}, one perhaps should consider other empirical research. Netessine (2005: 6), for instance, suggests using university research database, publicly available, consulting company, or industry journal data. Still for a Ph.D. student with little funds it is difficult to access some of these data sources that are subject to charges.

Besides, some specific data are not available at all or insufficient. For example, we could not obtain any information about the number of warehouses from business and logis-

\textsuperscript{902} Garson (2009).
\textsuperscript{903} Dorofeev and Grant (2006: 253f.), Garson (2009).
\textsuperscript{904} Carver (1978).
\textsuperscript{905} Thompson (1994).
\textsuperscript{906} Bickard and Schnittlein (1999), Goldsby and Stank (2000).
\textsuperscript{907} Baruch (1999).
\textsuperscript{908} Griffis et al. (2003: 237).
\textsuperscript{909} Groves et al. (2004: 39ff., 377f., 380).
tics associations and federal statistical offices in Germany and the U.S. to derive how inventories changed in dependence of the number of warehouses compared to SRL predictions or how the number of warehouses changed over time. Some researchers expected the number of warehouses to increase with increasing fuel costs.

Furthermore, the number of companies in the industrial sectors in different publications of the German Federal Statistical Office differs, as it receives its information from different data sources. If the industrial sectors are broken down further, only companies with 20 or more employees are considered.\textsuperscript{910} If all companies with any number of employees are considered, they are not subdivided into detailed industrial sectors.\textsuperscript{911} This impaired our retrospective quota sampling.

Another survey could also shed light onto the companies' reasons for and against as well as the manner, degree, benefits, and costs of applying the risk pooling concepts, as we intended in the six-page version of this survey that yielded a uselessly low response rate. As risk pooling can affect the whole supply chain, another survey could consider a supply chain wide perspective rather than single companies.

A lot of respondents do not perceive all the questioned concepts as risk pooling ones. It appears that mainly transshipments and postponement are associated with risk pooling.

Although at least in our sample the risk pooling concepts are known fairly well (central ordering, product substitution, and selective stocking the most), only selective stocking, transshipments, and central ordering are widely applied. Transshipments\textsuperscript{912} are more important and applied, postponement\textsuperscript{913} and product pooling\textsuperscript{914} less than suggested by some publications mostly for other regions.

Nearly half the sample centralized its warehouse or logistics system in the past. This is less than overall in Europe\textsuperscript{915}. In contrast to the expected trend to decentralize due to increasing transportation costs, only seven percent will increase, six percent even decrease the number of warehouse or production locations in the future. It seems that the companies are very consistent in their strategy of centralization, decentralization, or no change over time.

\textsuperscript{910} For example Statistisches Bundesamt Deutschland (2009i: 371).
\textsuperscript{911} For example Statistisches Bundesamt Deutschland (2009i: 378).
\textsuperscript{912} CLM (1995), Herer et al. (2006).
\textsuperscript{914} Alfaro and Corbett (2003: 12).
\textsuperscript{915} CLM (1995).
The utilization and knowledge of a risk pooling concept are correlated. This suggests that improving the knowledge about risk pooling may increase its application. Research needs to convey to practitioners under what conditions and how the different risk pooling concepts can be applied successfully. This research constitutes one step in this direction.

Prominently associated is past decentralization with future decentralization, the utilization of product substitution and demand reshape, past centralization and decentralization (the only negative correlation), the application of the inventory turnover curve and transshipments, commonality and product pooling, risk pooling and transshipments, the inventory turnover curve and order splitting, selective stocking and virtual pooling, transshipments and virtual pooling, risk pooling and postponement, product substitution and transshipments, product substitution and virtual pooling, as well as postponement and commonality and vice versa.

We can support Rabinovich and Evers' (2003b) finding that time postponement (emergency transshipments and inventory centralization) contributes to the implementation of form postponement at best only weakly for our sample.

Trading companies seem to apply transshipments and product substitution more than manufacturing companies. The opposite is true for commonality and postponement. In contrast to Van Hoek (1998b) our sample shows no significant difference in the application of postponement by electronics, automotive, food, and clothing manufacturers.

More large companies appear to use risk pooling and postponement than smaller ones, perhaps because they can afford to invest in expensive risk pooling strategies as suggested by Huang and Li (2008b: 12). More small companies have centralized their warehouse or logistics system in the past than large ones in our sample.

Our survey shows that different risk pooling methods are and can be applied together as we already suggested in the Risk Pooling Decision Support Tool and the Papiroco example.
### Questionnaire

Survey on Risk Pooling in Business Logistics  
by Dipl.-Kfm. Gerald Oeser

<table>
<thead>
<tr>
<th>Question</th>
<th>Known?</th>
<th>In use?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4 Risk Pooling</strong> (Demand and/or lead time variability is reduced, if one aggregates demands and/or lead times e.g. across locations, because it becomes more likely that higher-than-average demands and/or lead times will be offset by lower-than-average ones. This reduction in variability allows to reduce safety stock and therefore reduces average inventory without reducing the service level.)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>5 Square Root Law</strong> (Total (safety) stock in (n) warehouses = (safety) stock in 1 centralized warehouse (\times) square root of the number of warehouses (n).)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>6 The Portfolio Effect</strong> shows the reduction in aggregate safety stock by consolidating several warehouses’ inventories in one warehouse in percent.</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>7 Selective Stock Keeping/Specialization</strong> (Reducing inventory carrying cost treating products differently without reducing the service level substantially. For example, products with a low turnover might only be stocked at few locations due to cost considerations.)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>8 Component Commonality</strong> (Products are designed sharing components. This reduces the variability of demand.)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>9 The Inventory Turnover Curve</strong> shows average inventory in dependence of the inventory throughput for a specific company. It can be used to estimate the average inventory for any (planned) warehouse throughput (shipments from the warehouse or sales).</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>10 Product Pooling</strong> (Unification of several product designs to a single generic or universal design or reducing the number of products thereby serving demands that were previously served by their own product version with fewer products.)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>11 Product Substitution</strong> (One tries to make customers buy another alternative product, because the original customer wish is out of stock or although the original customer wish is available (Demand Reshape). This reduces variability of demand and inventory costs.)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>12 Transshipments/Inventory Sharing</strong> Inventory transfers among locations (e.g. between warehouses or stores) for example in case of a stockout.</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>13 Delayed Product Differentiation and Postponement</strong> (Postponement of e.g. manufacturing, assembly, packaging, labeling, or delivery. Product customization should be delayed as long as possible. This allows to ship a single generic product further down the supply chain and to change it later into individual products according to recent demand information. Demand for individual products is aggregated to the demand for the generic product on preceding supply chain stages. Aggregated demand for the generic product fluctuates less, since stochastic fluctuations of the individual demands are offset to a certain extent. Inventory carrying costs and stockouts can be reduced.)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>14 Capacity Pooling</strong> (Consolidation of production, service, or warehouse capacities of several facilities. Without pooling every facility fulfills demand just with its own capacity. With pooling demand is aggregated and fulfilled by a single (perhaps virtually) joint facility. A higher service level can be attained with the same capacity or the same service level can be offered with less capacity.)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>15 Virtual Inventory/Warehouse/Pooling:</strong> A company extends its warehouse(s) beyond the physical inventory to the inventory of other own locations or of other companies’ locations using information and communication technologies, drop-shipping, and cross-filling.</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>16 Central Ordering</strong> for several locations and later allocation of the orders (perhaps by a depot) to the distribution points or requisitioners according to recent demand information.</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>18 Order Splitting</strong> is partitioning a replenishment order into multiple orders with multiple suppliers or into multiple deliveries.</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question</th>
<th>Known?</th>
<th>In use?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>19 a) Did you centralize your warehouse/logistics system</strong> (reduce the number of warehouse or production locations)?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>b) Do you intend to centralize your warehouse/logistics system?</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>20 a) Did you decentralize your warehouse/logistics system</strong> (increase the number of warehouse or production locations)?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>b) Do you intend to decentralize your warehouse/logistics system?</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

---

Please push to send answers

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Figure A.4: Questionnaire
<table>
<thead>
<tr>
<th>Industry Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction, excluding surveying</td>
</tr>
<tr>
<td>15</td>
<td>Manufacture of food products and beverages</td>
</tr>
<tr>
<td>16</td>
<td>Manufacture of tobacco products</td>
</tr>
<tr>
<td>18</td>
<td>Manufacture of wearing apparel; dressing and dyeing of fur</td>
</tr>
<tr>
<td>21</td>
<td>Manufacture of pulp, paper and paper products</td>
</tr>
<tr>
<td>22</td>
<td>Publishing, printing and reproduction of recorded media</td>
</tr>
<tr>
<td>24</td>
<td>Manufacture of chemicals and chemical products</td>
</tr>
<tr>
<td>25</td>
<td>Manufacture of rubber and plastic products</td>
</tr>
<tr>
<td>26</td>
<td>Manufacture of other non-metallic mineral products</td>
</tr>
<tr>
<td>27</td>
<td>Manufacture of basic metals</td>
</tr>
<tr>
<td>28</td>
<td>Manufacture of fabricated metal products, except machinery and equipment</td>
</tr>
<tr>
<td>29</td>
<td>Manufacture of machinery and equipment n.e.c.</td>
</tr>
<tr>
<td>30</td>
<td>Manufacture of office machinery and computers</td>
</tr>
<tr>
<td>31</td>
<td>Manufacture of electrical machinery and apparatus n.e.c.</td>
</tr>
<tr>
<td>32</td>
<td>Manufacture of radio, television and communication equipment and apparatus</td>
</tr>
<tr>
<td>33</td>
<td>Manufacture of medical, precision and optical instruments, watches and clocks</td>
</tr>
<tr>
<td>34</td>
<td>Manufacture of motor vehicles, trailers and semi-trailers</td>
</tr>
<tr>
<td>35</td>
<td>Manufacture of other transport equipment</td>
</tr>
<tr>
<td>36</td>
<td>Manufacture of furniture; manufacturing n.e.c.</td>
</tr>
<tr>
<td>37</td>
<td>Recycling</td>
</tr>
<tr>
<td>40</td>
<td>Electricity, gas, steam and hot water supply</td>
</tr>
<tr>
<td>45.2</td>
<td>Building of complete constructions or parts thereof; civil engineering</td>
</tr>
<tr>
<td>51.46</td>
<td>Wholesale of pharmaceutical goods</td>
</tr>
<tr>
<td>51.47.8</td>
<td>Wholesale of paper and paperboard, stationery, books, newspapers, journals and periodicals</td>
</tr>
<tr>
<td>51.53.1</td>
<td>Non-specialized wholesale of wood, construction materials and sanitary equipment</td>
</tr>
<tr>
<td>51.88</td>
<td>Wholesale of agricultural machinery and accessories and implements, including tractors</td>
</tr>
<tr>
<td>52.11</td>
<td>Retail sale in non-specialized stores with food, beverages or tobacco predominating</td>
</tr>
<tr>
<td>52.42</td>
<td>Retail sale of clothing</td>
</tr>
<tr>
<td>52.46</td>
<td>Retail sale of hardware, paints and glass</td>
</tr>
<tr>
<td>52.48.6</td>
<td>Retail sale of games and toys</td>
</tr>
</tbody>
</table>

**Table A.5: Survey Participants' Answers to the Questionnaire**
Appendix B: Proof of the Square Root Law for Regular, Safety, and Total Stock

Based on a numerical example in Ballou (2004b: 379f.) and in a manner different from the flawed\(^{916}\) one in Maister (1976), we formally prove that under certain assumptions the SRL applies to regular, safety, and total stock.

Let average regular stock at location \(i\) be the economic order quantity (EOQ) \(Q_i\) divided by two:

\[
R S_i = \frac{Q_i}{2} = \frac{\frac{2d_iS}{TC}}{2}, \tag{B1}
\]

where \(d_i\) is demand at warehouse \(i\), \(S\) the fixed order cost, \(I\) the inventory carrying cost rate and \(C\) the product value per unit. Regular system inventory for \(n\) decentralized warehouses equals

\[
R S_d = \frac{\sum_{i=1}^{n} \frac{2d_iS}{TC}}{2} = \frac{\sum_{i=1}^{n} \sqrt{R S_i}}{2} \tag{B2}
\]

Regular stock in one centralized warehouse is

\[
\frac{\sum_{i=1}^{n} \frac{2d_iS}{TC}}{2} = \frac{\sum_{i=1}^{n} \sqrt{R S_i}}{2}
\]

\(^{916}\) Das (1978: 334) correctly remarks “But Maister’s proof is incorrect due to a combination of faulty algebra and possible misprints” without pointing out the mistakes. Indeed, we found e. g. that it is supposed to be \(\sigma_D = \sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2 = \sum (\sigma_i^2)\) instead of \(\sigma_D = \sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2 = \sum (\sigma_i^2)\) (Maister 1976: 129) and \(\frac{\sum (\sigma_i^2)}{\sqrt{\sum (\sigma_i^2)}}\) instead of \(\frac{\sum (\sigma_i^2)}{\sum (\sigma_i^2)}\) (Maister 1976: 130). The expression \(\frac{\sum (\sigma_i^2)}{\sum (\sigma_i^2)}\) \(\frac{1}{\sqrt{\sum (\sigma_i^2)}}\) (Maister 1976: 130) is also incorrect. Furthermore, it has to be \(\frac{1}{8} \cdot (0.2)^2 = 0.005\) instead of \(\frac{1}{8} \cdot (0.02)^2 = 0.005\) (Maister 1976: 129).

Changing a three-location to a one-location system reduces inventory by 42 (not 43) % and changing a ten-location to a four-location system reduces inventory by 37 (not 38) % according to the SRL (Maister 1976: 131). Maister (1976: 132) wrongly states \(\frac{\sum (\sigma_i^2)}{\sum (\sigma_i^2)} = \frac{\sqrt{\sum (\sigma_i^2)}}{\sqrt{\sum (\sigma_i^2)}}\), although he earlier notes that \(\sum d_i = 1\) (Maister 1976: 127). He also explains “If the original decentralised system had 16 locations, and inventory costs account for one-half of total costs in this system, then inventory savings from centralisation equal \(\frac{1}{2} \left( 1 - \frac{1}{16} \right) TC = \frac{3}{8} TC\). But transportation must represent \((1-x)TC\), or \(\frac{1}{2} TC\) in the decentralised system. Hence, we can afford to almost double transportation expenses and still retain a system cost less than in the original system” (Maister 1976: 133). However, we can only afford 1.75 times and not almost double the transportation cost or, in other words, we could only increase transportation cost by 75 % at the most. But if all inventory savings were spent on increased transportation costs, we would not retain a system cost less than in the original system. The centralized and decentralized system costs would be equal and we would be indifferent between them. Nevertheless, Das (1978: 333) also misprinted \(d_i = 1\) and incorrectly uses the equality instead of the approximation sign, although the power (square root) function cannot equal a linear one. Furthermore, \(\sigma_1, \sigma_2, \ldots, \sigma_n\) should be \(\sigma_1, \sigma_2, \ldots, \sigma_n\) and \(\sum (\sigma_i^2)\) should be \(\sum (\sigma_i^2)\) (Das 1978: 334). Das (1978: 332) also refers to a proof to his solution in the appendix, but the journal does not contain it. Professor emeritus Chandrasekhar Das, College of Business Administration, University of Northern Iowa, Department of Management, agreed with us and kindly rewrote the proof, as it was not available at the publisher anymore in 2009 (personal correspondence on February 27, 2009).
Appendix B

\[ RS_c = \frac{\sqrt{\frac{\sigma^2}{n} d_i}}{2} = \frac{\sqrt{\sigma^2 \sum_{i=1}^{n} d_i}}{2}. \quad \text{(B3)} \]

Regular stock in one centralized warehouse times a factor \( \alpha \) equals regular system stock in \( n \) decentralized warehouses:

\[ RS_c \cdot \alpha = RS_d \iff \frac{\sqrt{\sum_{i=1}^{n} d_i}}{2} \cdot \alpha = \frac{\sqrt{\sum_{i=1}^{n} d_i}}{2} \iff \alpha = \frac{\sqrt{\sum_{i=1}^{n} d_i}}{2} = \frac{\sqrt{\sum_{i=1}^{n} d_i}}{2}. \quad \text{(B4)} \]

If demand at each warehouse is equal (d), the regular system inventory for \( n \) decentralized warehouses equals the one in one centralized warehouse times the square root of the number of warehouses \( n \):

\[ RS_c \cdot \frac{n \sqrt{d}}{\sqrt{\sum_{i=1}^{n} d_i}} = RS_d \iff RS_c \cdot \frac{n \sqrt{d}}{\sqrt{\sum_{i=1}^{n} d_i}} = RS_d \iff RS_c \cdot n \sqrt{\frac{n \sqrt{d}}{\sqrt{\sum_{i=1}^{n} d_i}}} = RS_d \iff RS_c \cdot \sqrt{n} = RS_d. \quad \text{(B5)} \]

This means the SRL applies to regular stock, if an EOQ order policy is followed, the fixed cost per order and the per unit stock holding cost (inventory carrying cost rate times the product value per unit), demand at every location, and total system demand is the same both before and after centralization.\(^{917}\) However, according to Maister (1976: 128f.) the SRL can also be “a good approximation when demand rates at all the field locations are not equal”.

If regular inventory in each of \( n \) locations in the decentralized system (\( RS_d \)) is considered the following relationship holds:

\[ \frac{RS_c \cdot \sqrt{\sum_{i=1}^{n} d_i}}{n} = RS_s \iff \frac{RS_c \cdot \sqrt{\sum_{i=1}^{n} d_i}}{\sqrt{n \sum_{i=1}^{n} d_i}} = RS_s \iff \frac{RS_c}{\sqrt{n}} = RS_s \iff RS_c = RS_s \cdot \sqrt{n}. \quad \text{(B6)} \]

This corresponds to equation 9-28 in Ballou (2004b: 380): \( AIL_T = AIL_i \sqrt{n} \).

Safety stock in warehouse \( i \) is

\[ SS_i = z s_{d_i} \sqrt{LT}, \quad \text{(B7)} \]

where \( z \) is the same safety factor for every warehouse, \( s_{d_i} \) the standard deviation of demand at warehouse \( i \), and \( LT \) the constant replenishment lead time for every warehouse.

System safety stock in \( n \) decentralized warehouses is

\[ SS_d = z \sqrt{LT} \left( \sum_{i=1}^{n} s_{d_i} \right). \quad \text{(B8)} \]

If the demands are uncorrelated, safety stock in the centralized warehouse is

$$SS_c = z\sqrt{LT \sum_{i=1}^{n} (s_{di})^2}. \quad (B9)$$

Safety stock in one centralized warehouse times a factor $$\alpha$$ equals systemwide safety stock in n decentralized warehouses:

$$SS_c \cdot \alpha = SS_d \iff (z\sqrt{LT \sum_{i=1}^{n} (s_{di})^2}) \cdot \alpha = z\sqrt{LT \sum_{i=1}^{n} s_{di}}$$

$$\iff \alpha = \frac{z\sqrt{LT \sum_{i=1}^{n} s_{di}}}{\sqrt{LT \sum_{i=1}^{n} (s_{di})^2}} \iff SS_c \cdot \frac{\sum_{i=1}^{n} s_{di}}{\sqrt{\sum_{i=1}^{n} (s_{di})^2}} = SS_d. \quad (B10)$$

If the standard deviation of demand at each warehouse is equal ($$s_d$$), the systemwide safety stock in n decentralized warehouses is equal to the safety stock in one centralized warehouse times the square root of the number of warehouses n:

$$SS_c \cdot \frac{\sum_{i=1}^{n} s_{di}}{\sqrt{\sum_{i=1}^{n} (s_{di})^2}} = SS_d \iff SS_c \cdot \frac{n \cdot s_{d}}{\sqrt{n \cdot (s_{d})^2}} = SS_d \iff SS_c \cdot \frac{n \cdot s_{d}}{\sqrt{n}} = SS_d \iff SS_c \cdot \sqrt{n \cdot s_{d}} = SS_d \iff SS_c \cdot \sqrt{n} = SS_d. \quad (B11)$$

This means the SRL applies to safety stock, if demands at the decentralized locations are uncorrelated918, the variability (standard deviation) of demand at each decentralized location919, the safety factor (safety stock multiple)920 and average lead time are the same at all locations both before and after consolidation, average total system demand remains the same after consolidation921, no transshipments occur922, lead times and demands are independent and identically distributed random variables and independent of each other923, the variances of lead time are zero924, and the safety-factor (k$$\sigma$$) approach is used to set safety stock for all facilities both before and after consolidation925.

If demands at the warehouses are correlated, the SRL does not even yield an approximation. The safety stock savings through centralization decrease with increasing correlation between demands at the warehouses and become zero with perfectly positive correlation.926

Total inventory is the sum of regular and safety stock.927 Therefore total inventory in the decentralized system TI_d with n warehouses equals total inventory in one centralized warehouse TI_c times the square root of the number of warehouses n:

919 Maister (1976: 130).
926 Maister (1976: 130).
The SRL applies to total inventory, if the assumptions stated above of the SRL both as applied to regular and safety stock hold. For a critical review of these assumptions please refer to Maister (1976: 125, 132f.), Das (1978: 331f.), McKinnon (1989: 102ff.), and Evers (1995: 2, 14f.).

It should be checked whether the conditions or assumptions necessary for the SRL to hold (necessary conditions) are also sufficient conditions, i.e. whether, if the SRL holds, these conditions also automatically apply. This analysis, however, is beyond the scope of this thesis.

Ballou (2004b: 380) incorrectly states “The square-root rule […] measures only the regular stock reduction, not both regular and safety stock effects […]. Assuming that an inventory control policy based on the EOQ formula is being followed and that all stocking points carry the same amount of inventory, the square-root rule can be stated as follows:

\[ AIL_T = AIL_I \sqrt{n} \]  

where

- \( AIL_T \) = the optimal amount of inventory to stock, if consolidated into one location in dollars, pounds, cases, or other units
- \( AIL_i \) = the amount of inventory in each of \( n \) locations in the same units as \( AIL_T \)
- \( n \) = the number of stocking locations before consolidation”.

Traditionally the SRL has been mainly applied to safety stock, but as proven above it is also valid for regular stock or both regular and safety stock, if the respective necessary assumptions stated above hold. If it is only applied to regular stock as in Ballou’s case, all the assumptions of the SRL as applied to regular stock enumerated above must apply, not only the two mentioned by Ballou here. Ballou’s formulation of the second assumption may confuse, as Maister (1976: 125) assumes “the demand rates at all the field locations are equal”.

---

927 Ballou (2004b: 380). Total inventory might also include pipeline, speculative, and obsolete stock (Ballou 2004b: 330f.), which is neglected here.
928 Professor emeritus Ronald H. Ballou, Weatherhead School of Management, Case Western Reserve University, agreed with us in a personal correspondence on May 15, 2007.
Appendix C: What Causes the Savings in Regular Stock through Centralization Measured by the SRL?

The total EOQ in the decentralized system is

$$Q_d = \sqrt{\frac{2S}{ic}} \sum_{i=1}^{n} \sqrt{d_i}.$$  \hspace{1cm} (C1)

The EOQ in the centralized system is

$$Q_c = \sqrt{\frac{2S}{ic}} \sum_{i=1}^{n} d_i.$$  \hspace{1cm} (C2)

Due to the subadditive property of the square root, the sum of the square root of the demands at the locations $i$ is greater than or equal to the square root of the sum of these demands:

$$\sum_{i=1}^{n} \sqrt{d_i} \geq \sqrt{\sum_{i=1}^{n} d_i}.$$  \hspace{1cm} (C3)

Therefore, the total EOQ in the decentralized system (the sum of the EOQs of the locations $i$) is greater than or equal to the EOQ in the centralized system:

$$Q_d = \sqrt{\frac{2S}{ic}} \sum_{i=1}^{n} \sqrt{d_i} \geq Q_c = \sqrt{\frac{2S}{ic}} \sum_{i=1}^{n} d_i.$$  \hspace{1cm} (C4)

However, the total EOQ in the decentralized and centralized system are only equal, if demands or demand forecasts at at least $n-1$ locations are zero$^{929}$, which is unusual:

$$\sum_{i=1}^{n} \sqrt{d_i} = \sqrt{\sum_{i=1}^{n} d_i} \Leftrightarrow (\sum_{i=1}^{n} \sqrt{d_i})^2 = \sum_{i=1}^{n} d_i$$  \hspace{1cm} (C5)

$$\Leftrightarrow \sum_{i=1}^{n} d_i + 2 \sum_{i=1}^{n} \sum_{i<j} \sqrt{d_i d_j} = \sum_{i=1}^{n} d_i \Leftrightarrow \sum_{i=1}^{n} \sum_{i<j} \sqrt{d_i d_j} = 0.$$

If $n-1$ $d_i$ equal zero, (C4) becomes

$$Q_d = \sqrt{\frac{2d_i S}{ic}} = Q_c$$  \hspace{1cm} (C6)

for this single non-zero $d_i$. If all $d_i$ are zero, (C4) becomes

$$Q_d = 0 = Q_c.$$  \hspace{1cm} (C7)

Therefore, if demands (at at least two locations) are larger than zero, the EOQ and therefore the average regular inventory and thus the inventory holding costs are lower in the centralized system. However, under the above condition the EOQ per decentralized location $i$ is less than the one for the centralized one, as $n > 1$.

$^{929}$ This theoretically questions Wanke and Saliby's (2009: 680) general statement that “[t]he cycle stock savings are based on the fact that the square-root of the aggregate demand is always smaller than the sum of the square roots of individual demands”.

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The total number of orders in the decentralized system is

\[ N_d = \sum_{i=1}^{n} \frac{d_i}{q_i} = \frac{\sum_{i=1}^{n} d_i}{\sqrt{\frac{2\sigma_i^2}{Ic}}} \leq \frac{1}{\sqrt{Ic}} \cdot \frac{1}{\sqrt{\sum_{i=1}^{n} d_i}} \leq \frac{1}{\sqrt{Ic}} \cdot \sqrt{\sum_{i=1}^{n} d_i} \]  

The number of orders in the centralized system is

\[ N_c = \frac{\sum_{i=1}^{n} d_i}{q_c} = \frac{\sum_{i=1}^{n} d_i}{\sqrt{\frac{2\sigma_i^2}{Ic}}} \leq \frac{1}{\sqrt{Ic}} \cdot \sqrt{\sum_{i=1}^{n} d_i} \leq \frac{1}{\sqrt{Ic}} \cdot \sqrt{\sum_{i=1}^{n} d_i} \]  

Due to the subadditive property of the square root, the total number (the sum of the numbers) of replenishment orders in the decentralized system is greater than or equal to the number of orders in the centralized one:

\[ \sum_{i=1}^{n} d_i \geq N_c \leq \sqrt{\sum_{i=1}^{n} d_i} \]

In analogy to (C5)-(C7), if demands (at at least two locations) are larger than zero\(^{930}\), the total number of replenishment orders in the decentralized system is greater than the number of orders in the centralized one resulting in lower total order fixed costs in the centralized system. However, in this case the number of orders (lead times) per decentralized location \(i\) is smaller than the number of orders for the centralized one\(^{931}\), as \(n > 1\):

\[ N_i = \frac{d_i}{q_i} = \frac{d_i}{\sqrt{2d_i\sigma_i}} < N_c \leq \frac{\sum_{i=1}^{n} d_i}{q_c} \leq \frac{1}{\sqrt{2\sigma_i}} \cdot \sqrt{\sum_{i=1}^{n} d_i} \leq \frac{1}{\sqrt{2\sigma_i}} \cdot \sqrt{\sum_{i=1}^{n} d_i} \]  

The savings in regular stock stem from the assumption of an EOQ order policy, constant fixed costs per order, holding costs (inventory carrying cost rate times product value per unit), and total demand for all locations before and after centralization. In the centralized system, usually the total order fixed cost is lower because of less orders and the inventory holding cost is lower due to a smaller EOQ than in the decentralized system.\(^{932}\)

\(^{930}\) Ronen (1990), Zinn et al. (1990), and Evers (1995) neglect this.

\(^{931}\) Cf. Ronen (1990: 132). Zinn et al. (1990: 139) state that “inventory centralization will increase the number of lead times per year if an EOQ ordering quantity is used”. “[A]n increase in the number of lead times with the same expected annual demand decreases the average base stock” (Zinn et al. 1990: 141). This is true for the centralized warehouse compared to each decentralized one.

\(^{932}\) Evers (1995: 5).
### Table D.1: Fulfillment of the SRL's Assumptions by Eleven Surveyed Companies

<table>
<thead>
<tr>
<th>Survey respondents</th>
<th>Number</th>
<th>Country</th>
<th>Industry</th>
<th>Employees</th>
<th>Position</th>
<th>Central warehouses</th>
<th>Regional warehouses</th>
<th>Assumptions of the SRL when applied to</th>
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<td>1</td>
<td>Denmark Paper wholesale</td>
<td>Paper wholesale</td>
<td>65</td>
<td>Logistics Manager</td>
<td>2</td>
<td>100</td>
<td>Demands iid (are independent and identically distributed random variables)</td>
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<td>Paper production</td>
<td>40,000</td>
<td>Logistics Analyst</td>
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<td>0</td>
<td>Locations' demands uncorrelated</td>
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<td>Germany Paper production</td>
<td>Reusable packaging</td>
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<td>Locations' demand variance the same</td>
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<td>Locations face same average lead time</td>
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<td>Safety Stock/Regular Stock</td>
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|                    |        | Average total system demand remains the same after consolidation |        | 0                  | 1                  | 1                  | Safe Stock                                             |
|                    |        | Locations' demands the same                                      |        | 0                  | 1                  | 0                  | Regular Stock                                           |
|                    |        | EOQ Order Policy                                                  |        | 0                  | 1                  | 0                  |                                                         |
|                    |        | Locations' fixed order cost the same                              |        | 1                  | 0                  | 1                  |                                                         |
|                    |        | Locations' per unit holding cost the same                         |        | 1                  | 0                  | 1                  |                                                         |

1=Yes, 0=No
## Table D.2: Comparison of Important Inventory Consolidation Effect, Portfolio Effect, and Square Root Law Models

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</table>

✓ Evers and Beier (1993: 110) and Evers (1995: 4) list these additional assumptions of the square root law when applied to safety stock.

(✓) On the one hand this assumption is made, on the other hand in another consideration or formula it is dropped or unnecessary.

This table contains only assumptions explicitly stated in the respective papers.
<table>
<thead>
<tr>
<th>Pioneers</th>
<th>Critics</th>
<th>Variable lead time</th>
<th>Transshipments</th>
<th>Optimal consolidation</th>
<th>Network design</th>
</tr>
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</table>

1. Maister (1976) is the first to prove the square root law (SRL) for safety stock (SS) and cycle stock (CS) under certain assumptions, but with faulty algebra and possible misprints.
2. The SRL “is an exception rather than a law [...]. A totally centralized system is [...] the best purely from the point of view of inventory costs” (Das 1978: 335).
3. Expected holding and penalty costs are smaller after centralization. These savings decrease with increasing demand correlation. If demands are identical and unrelated, one arrives at the SRL (Eppen 1979).
4. The portfolio effect (PE) depends on the sales correlation and magnitude (the relative sizes of the standard deviations of demand). The SRL is a special case of the PE, if the magnitude is equal to 1 and the sales correlation is equal to 0 (Zinn et al. 1989).
5. Defining service level as “the desired fraction of demand supplied from stock” “no general results can be derived concerning the desirability of inventory centralization/decentralization without knowing the order quantities and the probability distributions involved” (Ronen 1990: 134).
6. Mahmoud (1992) describes the Portfolio Quantity Effect (PQE), the Portfolio Cost Effect (PCE), and an optimal consolidation scheme. Super-consolidation is not always optimal.
7. Evers and Beier (1993) consider lead time uncertainty, unequal average lead times, and centralization to several locations (multiple consolidation points). The equation on page 115 is incorrect: It should read: k = sqrt(1/(1-beta)) (personal correspondence with Professor Evers on July 6, 2009).
8. Tallon (1993) considers variable demand and replenishment lead times and correlation of demand during lead time. SS savings from centralization depend on the correlation of sales and the ratio of the standard deviations of demand during lead time (magnitude).
9. Evers (1995) considers the Consolidation Effect (CE) under various assumptions. The CE shows the impact of inventory pooling on both SS and CS (Evers 1995: 1). CS determined by the EOQ approach can be decreased through centralization, but primary savings result from reductions in SS. Generally, there are no reductions in SS, if the replacement principle is followed. The assumptions are not likely to be found in practice collectively. Inventory increases with the number of locations.
11. The last concluding bracket in the numerator is missing in Evers and Beier (1993: 114).
12. With equal partitioning of demand in addition to Maister’s (1976) assumptions, Evers and Beier (1993) arrive at a revised SRL: There are no further savings in SS after the first consolidation. The reduction in SS depends only on the number of decentralized facilities.
13. Eppen (1979) considers the end-of-period inventory before a new order arrives, which may be seen as the safety stock (Silver et al. 1998: 234), and only “statistical economies of scale”, not the order quantity effect. Holding and shortage costs are proportional to the standard deviation of demand.
15. In Eppen (1979), at the beginning of every period location i raises its inventory to the level minimizing its expected holding and shortage costs for the respective period, which is the corresponding newsvendor problem’s optimal solution. This is called base-stock, order-up-to-level, or (R, S) policy.
16. “If the level of inventory on hand plus on order is less than the reorder point, a reorder is placed with an outside source and the on-order inventory level is increased” (Evers 1996: 117).
17. Ronen (1990: 130) considers an “Order Quantity/Reorder Point (Q,R) inventory control policy. Demand during stock replenishment lead time has some statistical distribution due to variability of demand, lead time, or both. The order quantity is determined by the Economic Order Quantity (EOQ) and the reorder point, R, consists of average demand during lead time plus a safety stock, which is a certain number (k) of standard deviations of demand during lead time”. Such an order policy is also called (s, q).
18. All locations control inventories by the Wilson Lot Size Formula or EOQ before and after pooling (Maister 1976: 131).
19. The order quantity is equal to the average demand during lead time (Evers 1995: 14). The replacement principle or stock-to-demand policies can be subsumed under order-up-to-level models (Wanke and Saly 2009: 680).
22. All locations utilize the safety-factor (kR) approach to set safety stock before and after pooling (Maister 1976: 129).
23. All locations use the same safety stock multiple k before and after pooling (Maister 1976: 132).
24. All locations offer the same service level (Ronen 1990).
25. Zinn et al. (1989) use the probability of not running out of stock during lead time as the customer service level measure.
26. Ronen (1990) uses the fraction of demand supplied from stock during lead time as the customer service level measure.
Appendix D

Continuation of Table D.2

Eppen (1979) considers a single-period single product multi-location newsboy problem with normal demand at each of N warehouse locations with mean \( \mu_i \) and standard deviation \( \sigma_i \) and identical linear holding and penalty cost functions at each location. All locations have the same fixed cost per order before and after pooling (Maister 1976: 131). In case of a stockout demand is backordered by the offending location (Evers 1996: 117).

Evers (1997: 59) assumes that suppliers have enough available inventory to satisfy all locations' demands from inventory. "[D]emands are independent and identically distributed random variables" (Evers and Beier 1993: 110).

"Average total system demand remains the same after consolidation" (Evers and Beier 1993: 110, cf. Maister 1976: 131).

"[D]emand rates at all the field locations are equal" (Maister 1976: 125). Each location has the same proportion of total system demand (Maister 1976: 127f.). "The proportion of demand facing each decentralized facility is the same" (Evers 1995: 14).

All decentralized facilities face the same variance (variability) of demand (Maister 1976: 130).

Each location's coefficient of variation of demand \( \sigma_i/\mu_i \) is supposed sufficiently small, so that negative demand is insignificantly likely (Eppen 1979: 498).

"Demands at the decentralized locations are uncorrelated" (Maister 1976: 132).

Demand at each decentralized facility is allocated equally to all centralized facilities (Evers and Beier 1993: 119). The "consolidation effect is maximized when all \( W_j \) are equal to 1/m" (Evers 1995: 109).

Location i requires a minimum fraction or allocation of total demand (Das 1978: 332).

If the minimum demand allocation requirement are the same for all locations, Das (1978: 332f.) arrives at formula \( T^* \), and the approximation \( \Delta_{\text{approx}} \).

"Lead times and demands are independent of each other" (Evers and Beier 1993: 110).

"Lead times [...] are independent and identically distributed random variables" (Evers and Beier 1993: 110).

The average lead time is equal for all locations before and after pooling (Evers and Beier 1993: 110).

Caron and Marchet (1996) consider two-echelon distribution systems with 1 central and N remote warehouses. The correlation coefficients are the same for all pairs of remote warehouses. Value added during transit and demand served by the central warehouse is negligible. \( R_2 \) is the ratio of SS in an independent system (the central warehouse holds safety stock against demand variations during production or procurement lead times (P) and remote warehouses against demand variations during transit lead times (T)) and a coupled system (only remote warehouses hold buffer against variations in demand during the procurement and transit lead times (P+T)). The independent system is favorable, if local demands are independent. The coupled system is favorable, when there is high positive correlation.

Evers (1996) shows that the PE is applicable to nonemergency transshipments. Savings through transshipments increase with demand variability and decrease with lead time variability and increasing average lead time at each market. There are decreasing marginal returns to transshipment with increasing number of locations transshipping.

The PE underestimates the benefits of emergency transshipments, as it does not consider the number of locations, lead times, and fill rates adequately. Compared to a centralized system a decentralized system with one or more "location strategy" transshipment leads to less stockouts for the same system inventory. Emergency transshipments pool both demand and lead time uncertainty, while preserving market presence. There are decreasing marginal returns to transshipment with increasing number of locations transshipping (Evers 1997).

Evers and Beier (1998) consider the effect of lead time in consolidation at a single facility, correlation of demand between centralized facilities, differences in average lead time, and lead time variation at different facilities. Supplier lead times do not change with centralization. The model of Evers and Beier (1998) is more precise than Tallon's (1993) one, because it allows for specific exogenous lead time means and standard deviations at the centralization location, while Tallon (1993) implicitly assumes the lead time at the centralization location is related to those at the decentralized locations.

Tyagi and Das (1998) consider unequal demand variances and possibly unequal capacities of centralized locations. Maximum savings in aggregate SS by allocating SS among any number of centralized locations are achieved, if each centralized location provides the same proportion of each decentralized location's demand with equal or unequal variances. Savings in aggregate SS do not depend on the number of centralized locations or their size, but on the relative magnitudes of the variances of decentralized demands. The PE is larger, if variances are of similar magnitude.

Complete centralization of safety stock is not always optimal for correlated demands. Das and Tyagi (1999) suggest an optimal centralization scheme for grouping safety stocks for different customer demands.

Crockett and Zinn (2005) include inventory cost by means of the SIRL (a discrete inventory function) into the standard network design model mixed-integer program, which minimizes transportation and fixed warehousing costs subject to supplier (not warehouse) capacity, demand, and flow balance constraints. The model allows different network configurations for different product classes. The service level, average demand, and variability of demand may vary for each class. Including inventory in network design reduces the total network cost and the number, but not the location of warehouses in the solution.
Appendix D

Continuation of Table D.2

Wanke (2009: 108) considers where and when cycle and safety stock should be consolidated, if lead times, demands, their variability, fixed order and per-unit holding costs may differ at the alternative consolidation locations and demand may be correlated. He demonstrates that Tyagi and Das' (1998) demand allocation rule is valid in this environment: “[T]he consolidation effect is maximal when a given centralized facility supplies the same fraction of demand to each decentralized location. Under different lead times and demand variability conditions and in the presence of cycle stocks, this fraction is equal to 1, therefore implying consolidation in one single facility.” Consolidation is mainly influenced by the ratio of the standard deviations of lead time at the potential locations.

Wanke and Saliby (2009) present a framework for deciding whether and how (via inventory centralization or regular transshipments) inventories should be pooled, using the consolidation effect to measure inventory costs, service levels, and total costs. They relax Tyagi and Das' (1998) and Ballou and Burnetas' (2000) assumptions regarding lead time variabilities, demand correlations, and stock-related costs.

Centralized Ordering Effect (see section 5.3.3.2).

Caron and Marchet (1996: 233) consider order-point systems ((s, q), (s, S), (R, s, S), (R, s, Q) policies, or any other non-standard order policy that places a new order whenever the review reveals that the inventory status reached or fell below the order point), but only “the overall safety stock required independently of the order quantity and the target level of inventory availability” (238).

“If the level of inventory on hand plus on order is less than the reorder point, a reorder is placed with an outside source and the on-order inventory level is increased. [ ... ] In addition, each facility is assumed to place orders with an outside source equal to the expected demand during lead time (in other words, the order quantity is directly related to the average demand)” (Evers 1996: 117).


Wanke (2009: 110) assumes an (s, q) policy.

Wanke and Saliby (2009: 681) assume an (s, q) policy.

The order quantity is “equal to the expected demand during lead time” (Evers 1996: 117).

“The order quantity is set equal to the average demand during lead time. Since the order quantity is directly related to average demand, since average total demand remains unchanged, and since all locations are identical, the effect of emergency transshipments on systemwide cycle stocks should be negligible” (Evers 1997: 59).

No transshipments between facilities take place before pooling (Evers 1996: 116).

No transshipments between facilities take place before pooling (Evers 1996: 120).

No transshipments between facilities take place before pooling (Evers 1997: 59).

Wanke and Saliby (2009: 679, 688) consider regular transshipments, i.e., all centralized locations satisfy demands at all decentralized ones. A primary location supplies part of the demand, a secondary one the rest.

Demand during lead time is normally distributed (Evers 1997: 64).

“Demand, lead time and demand during lead time are normally distributed variables” (Wanke 2009: 110).

“Average total system demand remains the same after pooling” (transshipment times are negligible) (Evers 1996: 116).

“Total system demand is assumed to remain the same” (Evers 1996: 120).

“[T]he variability of demand, defined as the value of standard deviation within a given time interval, is the same for all N remote warehouses (this assumption will be discarded at a later stage)” (Caron and Marchet 1996: 249).

Caron and Marchet (1996: 241) assume that “demand at each remote warehouse (as well as overall demand) shows no significant time-correlation (i.e., demand fluctuations in succeeding time intervals are independent of one another).”

The “proportions of demand reassigned (transshipped)” are the same for all facilities (Evers 1996: 117).

“[W]hen emergency transshipments are used, demand can be filled from any location; hence, it can be asserted that demand is evenly pooled over all locations and that WI=1/N is the appropriate value” (Evers 1997: 60).

Wanke and Saliby (2009: 681) use Tyagi and Das’ (1998) allocation rule, if inventory is centralized, i.e., each centralized location provides the same proportion of demand to each decentralized one. In case of regular transshipments or independent systems, Ballou and Burnetas’ (2003) allocation rule is used, i.e., each centralized location provides the same proportion of demand to its primary decentralized one.

“Lead times and demands are independent random variables” (Wanke 2009: 110).

Caron and Marchet (1996: 241) assume that “transit lead time (T) from the central warehouse is the same for all N remote warehouses.”
Table D.2 shows the different SRL and PE models and the assumptions they are based upon. With the help of this table one can choose the model best fit for assessing inventory changes from centralization or decentralization for given conditions. The corresponding formulae for calculating the inventory savings achievable by inventory pooling can be found on the respective publication's page noted in the first or second row of this table.

In order to facilitate readability the assumptions are grouped according to the rubrics stock-, inventory-policy-, demand-, and lead-time-related. The columns or models are arranged chronologically according to their year of publication, so that the development and adding or dropping of assumptions over time can be retraced where possible.

The models are also grouped by colors according to their main contribution or focus, although this is not too definite, as they are very different or overlapping and the terms SRL and PE are sometimes used interchangeably.


Of course all researchers may be considered critical pioneers as they all contribute something novel and critically review previous work, which is the essence of scientific research. Mahmoud (1992: 198, 212) also considers the optimal consolidation scheme and criticizes that the PE is not sufficient to define it. Evers and Beier (1993) and Evers (1995) criticize Maister's (1976) SRL. Evers and Beier (1993) and Tyagi and Das (1998) consider multiple consolidation points and the equal partitioning of demand assumption. Wanke and Saliby (2009) also deal with regular transshipments. Important distinguishing assumptions made or not made by the various models are highlighted in grey.

933 Ronen (1990) and Zinn et al. (1989, 1990) have a scientific dispute. For details please refer to the respective publications.
<table>
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<tr>
<th>Possible Favorable Conditions</th>
<th>Inventory Pooling</th>
<th>Virtual Pooling</th>
<th>Transshipments</th>
<th>Central Ordering</th>
<th>Order Splitting</th>
<th>Component Commonality</th>
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<td>Stockout/backlog penalty cost high</td>
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Table D.3: Conditions Favoring the Various Risk Pooling Methods
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<th>Possible Favorable Conditions</th>
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<th>Virtual Pooling</th>
<th>Transshipments</th>
<th>Central Ordering</th>
<th>Order Splitting</th>
<th>Component Commonality</th>
<th>Postponement</th>
<th>Capacity Pooling</th>
<th>Product Pooling</th>
<th>Product Substitution</th>
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<td>Optimal OP (implementation)</td>
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<td>Central depot as close as possible to supplier</td>
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<td>Possible Favorable Conditions</td>
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<td>Virtual Pooling</td>
<td>Transshipments</td>
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<td>Order Splitting</td>
<td>Component Commonality</td>
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5. “Theoretical conditions conducive to order splitting include relatively low transportation costs and incremental ordering costs coupled with relatively high demand rates and variability, fill rates, in-transit and facility holding-cost factors, unit values, and lead-time uncertainty” (Thomas and Tyworth 2007: 178). “[A] single supplier […] might reserve an order and then split it into smaller shipments released sequentially to take advantage of actual information about future deliveries and reduce the variability of the demand process” (Thomas and Tyworth 2007: 189).
6. Kelle and Miller (2001: 407) find dual sourcing may decrease stockouts, if there is no “single, reliable supplier […] and the variability of the lead-time demand is considerable”, but is only suitable, if lead time uncertainty cannot be reduced.
12. Evers (1999: 123). “It appears […] that the two-delivery model performs better under lower levels of […] standard deviation of demand or service level”. This is because there are two stockout possibilities (one more than [sic] the single-delivery model) during each order cycle in the two-delivery model. Thus the two-delivery model is less vulnerable to stockouts if demand variability or service level is low” (Chiang 2001: 73, cf. Chiang and Chiang 1996).
16. Transshipments are valuable for locations that face similar mean demands per period (Jönnson and Silver 1987a, Dikl and de Koks 1996: 378) and standard deviations of demand (Tagaras 1999, Herer et al. 2002, Tagaras and Vlahos 2002).

The value of capacity sharing increases with similar demand variability (Iyer and Jain 2004, Jain 2007), similar customer classes (Cachon and Terwiesch 2009: 151), similar work content, demand rates, or delay costs for independent companies sharing capacity (Yu et al. 2008), and low demand fluctuation for products in the North American automotive industry (Goyal and Netessine 2006, Goyal et al. 2006).

The value of SKUs rationalization increases with increasing equality of standard deviations (low concentration of uncertainty) of demand (Alifaro and Corbett 2003: 18f., 24).

The benefit of demand reshaping increases with customers switching from the product to the larger one with the smaller standard deviation of demand (Eymann and Fouque 2003: 712, 2005: 96), which suggests different product demand variabilities. Weng (1999) finds a modular product design enables to use the most capable and also expensive product as joint buffer stock to substitute for other products (“Weng 1999: 75) in case of a stockout. The resulting savings are maximal, if the “variance of end-of-period net inventory is identical for all retailers and all products” (Weng 1999: 76, 80).


A C E M can aggregate demand from many OEMs, thus increase capacity utilization, and lower uncertainty, stock levels, and cost for a given service level thanks to risk pooling (Plambeck and Taylor 2003, Simchi-Levi et al. 2008: 281, Cachon and Terwiesch 2009: 351).

Evers (1999: 128, 132), Hu et al. (2005). However, future material availability and requirements should be of low uncertainty (Tagaras and Coen 1992). Furthermore, Evers (1996) finds the percentage reduction in safety stock obtained by using non-emergency transshipments decreases with increasing coefficient of variation of lead time (lead time variability) and average lead time at each market (Evers 1996: 126ff.).


Wanke (2009: 122). “The safety inventory savings on aggregation increase with the replenishment lead time” (Chopra and Meindl 2007: 319). Inventories should be pooled by inventory centralization, if lead time means are high and homogeneous (Wanke and Saliby 2009: 690).

Continuation of Table D.3

Long production lead times favor centralized ordering (Sippel and Schrage 1981: 11; Schoenmeyr 2005: 5). In consolidated distribution the lead time before the DC should be much longer than the backorder period (Cachon and Terwiesch 2009: 349).

"The potential reduction in inventory is greatest where order lead times are short, keeping cycle stocks low, and demand is highly variable, creating the need for large safety stock" (McKinnon 1989: 104).

Thomas et al. (2003: 307).


It is preferable to form pooling groups that consist of locations facing asymmetric replenishment lead times (Tagaras 1999). However, Tagaras and Vlachos (2002) find that non-identical ordering times of two locations which transship do not significantly affect optimal performance.


A longer allowed delivery time enables drop-shipping from the factory to consumers (Bucklin 1965: 28).

Short delivery times require speculation (Bucklin 1965: 28). If the relative delivery time (average delivery time divided by average manufacturing and delivery time) is long and customers demand a medium or low delivery frequency, a postponement strategy can be pursued (Pagh and Cooper 1998: 24). "If the required lead times are very short, it is not possible to perform final manufacturing activities in a postponed manufacturing structure" (Van Hoek 2004: 176).

Capacity pooling is more valuable for a short planned lead time (Weng 1998: 587).


Chang and Lin (1991). In general, the outbound transportation distance and cost to customers increase more with decreasing number of inventory locations than the inbound transportation distance and cost to the stocking locations are reduced. Thus the total transportation distance and cost generally increase with centralization or inventory pooling (Evers 1999: 122, Kim and Benjaafar 2002: 16, Ballou 2004b: 574, Keln 2005, Durand 2007: 8, Keln and Brodin 2008) and transportation costs (per distance unit) should be low (compared to inventory cost savings), if inventories are pooled (Fawcett et al. 1992: S67, Schulte 1999: 80, Vahrenkamp 2000: 31f).


Order splitting is only appropriate for low incremental transportation costs (Thomas and Tyworth 2007: 178, 185).


Low pipeline inventory holding costs make “risk-pooling over outside-supplier leadtimes” worthwhile (Schwarz 1989: 828, 839).

Evers (1999: 132). However, Thomas and Tyworth (2007: 178) contend relatively high in-transit and facility holding cost factors theoretically encourage order splitting, but do not investigate the effect of varying in-transit holding-cost on the value of order splitting in their computational experiments.

Order splitting should only be applied, if there are no transportation or order economies of scale (Evers 1999: 122f., Thomas and Tyworth 2006, 2007, Saadneh and Elshibli 2009).

Large economies of scale in manufacturing or logistics processes rather recommend a full speculation or logistics postponement strategy (Pagh and Cooper 1998: 24).


Order splitting is valuable for high fill rates (service levels) (Thomas and Tyworth 2007: 178, 189). Higher service levels provide a richer opportunity for safety-stock savings” (Thomas and Tyworth 2007: 171).

Gretzinger et al. (1993: 532f.).


Chen and Chen (2003), Chen and Ben (2007), Yu et al. (2008: 1).


Centralized ordering is valuable, if orders are backlogged at some penalty in case of a stockout (Eppen and Schrage 1981: 51, Schmenner 2005: 5).

Evers (1999: 132) recommends order splitting for high stockout costs per unit.

Substitution is profitable, if the stockout and backorder cost is high (higher than the substitution cost) (Liu and Lee 2007: 1, 41).

Inventory pooling is suitable for low stockout costs, as it increases the distance between the inventory and the buyer and delivery time and therefore might increase stockouts (Bowen 1986: 279, McKinnon 1988: 194, Fawcett et al. 1992: 360f, Evers 1999: 122f, Schulte 1995: 80, 377, Valuetronics 2000: 31f, Ballou 2004: 573f, Schnitt 2005: 14, Cachon and Terwiesch 2008: 336). However, in Dai et al. (2008: 467, 410f) a central inventory at a supplier shared by two retailers (inventory pooling) instead of separate reserved inventories for each retailer tends to be beneficial for the supplier and retailers, if the lost-sale penalty cost is high, customer demand is random, independent, normally-distributed, and price-sensitive and the wholesale price constant. For high backlogging costs only the supplier's total profit is larger under inventory pooling. Inventory pooling is more beneficial, if the stockout and delay costs for different demand classes are similar (Deshpande et al. 2003).

Maister (1976: 132) considers the EOQ, Eppen (1979, newsvendor model) and Cachon and Terwiesch (2009: 322) order-up-to or base-stock (R, S) models, i.e. the inventory status is reviewed every R time units. An order is placed to increase the inventory position (on-hand plus on order minus backorders) to the order-up-to or base-stock level S. The order arrives after a lead time (Silver 1998: 239–240, 267–268). If a replacement principle is followed, generally cycle stock levels in the centralized and decentralized system are equal (Maister 1976: 132, Evers 1995: 2, 14f). If safety stock is calculated as the product of a safety factor and average demand during lead time, it does not change either with centralization provided that the safety factor is equal for all warehouses before and after centralization.

Eppen and Schrage (1981: 51), Gurbitz et al. (2007: 296), and Cachon and Terwiesch (2009: 336) consider an (R, S) policy, Gurbitz et al. (2007: 296) also (s, S) policies, Hu et al. (2005: 31) an (R, s, S) policy. In the s, S policy the inventory status is reviewed continuously. A new order is placed to increase the inventory position to the order-up-to level S whenever the order drops to or below the reorder-point s (Silver 1998: 238–239). Following a (R, s, S) policy the inventory status is reviewed every R time units. A new order is placed to increase the inventory position to the order-up-to level S, if the inventory has dropped to or below the reorder-point s (Silver 1998: 240–241). Centralized ordering does not reduce cycle stock, if the replacement principle is applied (Maister 1976: 132, Evers 1995: 2, 14f), unless minimum order and sales quantities have to be observed, as we show in section 5.3.3.2.

An optimal order policy should be followed, but inventory pooling is relatively cost-effective and often better than optimizing order policies (Alfaro and Corbett 2003: 13, 24).

An optimal order policy should be followed, but pooling (component commodity) is relatively robust to suboptimal policies and often better than optimizing order policies (Alfaro and Corbett 2003: 13, 24).

An optimal order policy should be followed, but pooling (postponement) is relatively robust to suboptimal policies and often better than optimizing order policies (Alfaro and Corbett 2003: 12, 24).

Not only risk pooling performance or outcomes can be distorted in a multi-level multi-retailer supply chain model by over-simplification of various parameters such as batch size, delivery frequency, and ordering cycle (Hwang et al. 2005). Although not theoretically ideal, implemented, form postponement in three companies improved responsiveness of manufacturing (Harrison and Skipworth 2008: 193).

An optimal order policy should be followed, but pooling (SKU rationalization) is relatively robust to suboptimal policies and often better than optimizing order policies (Alfaro and Corbett 2003: 12, 24).

Evers (1999: 127, 129, 132f) determines, by a simulation that the benefit of risk pooling through emergency transshipments and order splitting decreases with increasing reorder or safety stock size.

For high stockout costs per unit and lead time variability and low order quantity and safety stock levels emergency transshipments perform particularly well compared to splitting orders.

Evers (1999: 132). However, Kelle and Silver (1990a: 792, 1990b: 356) find order splitting can be valuable for medium to high lead time uncertainty and large order quantity compared to expected lead time demand to reduce the risk of stockouts before and after the shipment and delivery in case they are delayed.

In Wardle's (2003: 122) model a low safety factor favors inventory pooling, as it increases the coordination effect, although this variable is of low importance.

Evers (1999: 132). “When demand is uncertain, the cost of inventory pooling is high, and the cost of stockouts is low, the optimal policy is to order up to the base-stock level S and to order immediately after the demand is known.”

Wanke (2009: 123). When demand is uncertain, the cost of inventory pooling is high, and the cost of stockouts is low, the optimal policy is to order up to the base-stock level S and to order immediately after the demand is known.


Evers (1999: 132). The incremental ordering cost per split should be low (Thomas and Tywowski 2007: 172, 178, 188).

Continuation of Table D.3

100 High inventory holding costs favor drop-shipping for the retailer (Randall et al. 2002: 55f; 2006: 57f; Netessine and Rudi 2006: 814).
101 Ögren and Silver (1987a: 224); Nooka and Evers (1998); Evers (1999: 201; 313); Jung et al. (2003); Hui et al. (2003); Wei and Dada (2005: 1519); Wong (2005). However, if the inventory holding or product cost is high compared to the backorder cost and the minimizes their expected costs, inventory sharing may increase the expected system backorders, because dealers share more inventories (reduce their rationing levels) to reduce their inventory carrying costs (Zhao et al. 2005: 545). Wanke and Salzberger (2009: 690) find regular transshipments compared to inventory centralization are rather adequate for low holding costs.
102 Expensive holding costs for inventory surplus make centralized ordering worthwhile (Eppen and Schrage 1981: 51; Schoenmeyer 2005: 5). However, the overall value of pooling risk over the outside-supplier lead time decreases with the pipeline inventory holding cost (Schwart 1989).
115 Duvall (2000).
116 Ghroravov and Chandra (2001), Kulkreja et al. (2001), Kulkreja and Schmidt (2005), Kutaqowu (2008: 341). However, if the product cost and thus inventory holding cost is high compared to the backorder cost and the dealers minimize their expected inventories, inventory sharing may increase the expected system backorders, because dealers share more inventories (reduce their rationing levels) to reduce their inventory carrying costs (Zhao et al. 2005: 545).
117 Order splitting "is worthwhile only when lead-time variability and unit values are unusually high in relation to industry norms" (Thomass and Tyworth 2007: 188, cf. 178).
118 A low common component cost relative to the product cost is conducive to component commonality (Thomass and Tyworth 2003: 319f).
120 A high salvage value for unsold stock at the end of the period may be beneficial for product substitution (Bassok et al. 1999: 632f).
121 If the manufacturer sets the wholesale price (endogenous wholesale price), he benefits and the retailers are often worse off under transshipment (Dong and Rudi 2004: 645, 654).
122 Randall et al. (2006: 567).
123 Bassok et al. (1999: 633).
124 A low profit margin (price to cost ratio) is conducive to substitution (Bassok et al. 1999, Liu and Lee 2007).
125 The value of substitution increases as the cost/price differential between the substitutes decreases (Bassok et al. 1999: 632, Chopra and Meindl 2007: 325f.)
126 Younger, small (in terms of revenues/sales) internet retailers with a high product variety, demand uncertainty, higher product weight/size, lower gross profit margin, high ratio of the number of retailers to wholesalers, higher observations risk, and high (weighted average) cost of capital sensibly do not own fulfillment capabilities and inventory, but have products drop-shipped from the wholesalers to the consumers. Companies that do not adhere to this tend to go bankrupt more often (Randall et al. 2006: 567, 576, 578). Although a high demand uncertainty and high ratio of the number of retailers to wholesalers theoretically are conducive to drop-shipping (Netessine and Rudi 2006, Randall et al. 2006: 569, Randall et al. (2006: 574f.) report mixed results on the statistical significance of this association. For the other italicized variables the association is not statistically significant (Randall et al. 2006: 574f.).
Appendix D

117 Pagh and Cooper (1998: 24) recommend manufacturing postponement and full specification for products with low monetary density (dollar value divided by product weight or volume). A product may have a low monetary density, if either its value is low or its weight or volume high. “Firms selling a product whose value is greatly reduced if shipped unassembled” may use assembly postponement (Zinn and Bowersox 1988: 133). If a “[g]ood’s cube and/or weight increases through customization/final manufacturing”, postponement may reduce transportation and inventory holding costs (Van Hoek et al. 1998: 38, Van Hoek 2001: 173). That means postponement may be suitable for large and heavy end-products.

118 Bucklin (1965: 30). Pagh and Cooper (1998: 24) recommend logistics and full postponement for products with high monetary density (dollar value divided by product weight or volume). A product may have a high monetary density, if either its value is high or its weight or volume low.


120 Although a high rate of product obsolescence theoretically favors drop-shipping, Randall et al. (2006: 567, 571, 578) find no association between it and inventory ownership, perhaps because they measured it imprecisely.


122 Theoretically, "relatively high demand rates" favor order splitting (Thomas and Tyworth 2007: 178, 180).


126 "[R]ecursive inventory management is more appropriate for low-volume items so that speculative movement downstream in the channel can be minimized" (Bowersox and Closs 1996: 302). Postponement allows the trigger a high turnover and high variety (Kotha 1995, Gilmore and Pine II 1997, Van Hoek et al. 1999a: 333). It may improve inventory turnover (Lin et al. 2001b: 77) and is especially suitable for low-volume products (Movrianto 2010). However, Zinn and Bowersox’s (1988: 131f.) simulation study, the demand level in units "is the least important variable" and only supports, i.e., has a statistically significant positive discriminant weight for, packaging (0.25) and manufacturing postponement (0.46). Lägensch (2004: 78) finds a high turnover reduced transportation costs due to higher utilization, which favored postponement.


130 “[W]hen neither the product nor the process is modular, a firm can effectively manage product variety by product standardization” (Swaminathan 2001: 132), i.e., the company stocks only a few of the items it offers and uses downward substitution in case of a stockout (Swaminathan 2001: 130). Product substitution can also be applied, if the product and/or the process are modular, but then modules could be added or removed to produce the desired product in case of a stockout. The company would not have to sell a substitute, but this might be more expensive than product substitution.

131 Products are common to two or more locations (Kukreja et al. 2001: 1371, Kukreja and Schindl 2005: 2039).


133 Capacity pooling may be based on commonalities (Mayne et al. 2008).

134 Substitute goods are goods that satisfy the same or similar needs and therefore are seen as an alternative or replacement by consumers. The reason for this replacement relationship is the functional replaceability between two goods, if they correspond in price, quality, and utility so that they are able to meet the consumer’s need (Wildemann 2008: 72).


138 The benefit of inventory sharing/transshipments increases as the system utilization (arrival rate of customer demands divided by the production or replenishment rate) increases (Zhao et al. 2005) and demand is high relative to storage capacity (Arachibald et al. 1997).

139 Capacity pooling is valuable for approximately equal total capacity and expected demand (Jordan and Graves 1995: 583, Chapon and Terviesch 2009: 348).

140 The savings from lateral transshipments increase with increasing system congestion in multi-echelon repairable item inventory systems with finite repair capacity (Jung et al. 2003).
Appendix D

Continuation of Table D.3
The benefit of product substitution increases with the number of products involved (Eynan and Fouque 2003: 712), the fraction of customers switching to a substitute (Eynan and Fouque 2003: 205: 96), and the degree of substitution (Ganesh et al. 2008: 1124). However, "most of the potential improvement is achieved with a relatively small portion of customers switching products" (Eynan and Fouque 2005: 96; cf. Eynan and Fouque 2003: 707).

Randall et al. (2002: 57, 2006: 567, 569): However, the association between the internet retailer's size/revenue and drop-shipping is not statistically significant (Randall et al. 2006: 575).


ICT may enable postponement (Bowersox et al. 1992, Dörge et al. 1995, Van Hoek 1998a, 2001: 177, Van Hoek et al. 1998: 51, Özdemir 2003, Yang et al. 2004). External application of ICT is positively, the internal surprisingly negatively correlated to the implementation of postponement (Van Hoek 1998a). Advance demand information, where customers with positive demand lead times place orders in advance of their needs, can be a substitute for production and shipment lead times and inventory and enhance the outcome of delayed differentiation or postponement (Özdemir 2003: 269, Pashchenkov 2008, Pashchenkov and Richter 2009).

Strategic effects of competition can make delayed differentiation unattractive for a company. For the consumer postponement is attractive with or without competition (Amand and Girotra 2007). Production and/or delivery postponement in a symmetric duopoly with uncertain demand increase profits and reduce profit variability, capacity utilization, and the range of prices charged. Monopolists are more likely to be flexible, i.e., able to use postponement, than duopolists (Amupindi and Jiang 2008). In a decentralized newsvendor model with multiplicative and price-dependent demand the expected value of perfect information about demand for price and order postponement may be negative for the channel and even for both members (the manufacturer and the retailer) because of vertical competition (Granot and Yin 2008: 121). However, in case of "[price competition]; postponement leads to "lower cost levels" (Van Hoek et al. 1998: 38, Van Hoek 2001: 173). Pagh and Cooper (1998: 24) recommend postponement for a cost (competition) strategy.

The use of manufacturing flexibility is associated with a high number of flexible competitors in the North American automotive industry (Goyal et al. 2006: 221). If a lot of competitors apply manufacturing flexibility others (have to) follow to keep up with them. However, "following the herd" in terms of investment in flexibility may actually have an unfavorable impact on productivity" (Goyal et al. 2006: 23). "Flexible technology is not a panacea for all ills — there are conditions under which dedicated technology emerges in equilibrium, and flexibility is not a universal best response to competition" (Goyal and Netessine 2006: 23). Goyal and Netessine (2006: 1, 23) hypothesize flexibility ought to be favored for low total market size (total mean demands for two markets with price-dependent and uncertain demand, in which two companies compete) and market size differential. Manufacturing flexibility may also be a competitive advantage in a market with few flexible competitors, as Mayne (2008) describes for Honda.

Competitive relative to centralized inventory management might undervalue some of the substitutable products (Netessine and Rudi 2003: 329).

Transshipments between non-competing locations might become more attractive with external competition, because they might constitute a competitive advantage (Guglielmo 1999, Kroll 2006, Alvarez 2007) as our Paperco example in section 5.3.2.2 shows as well. Transshipments between competing retailers become less attractive as competition increases or retailer differentiation decreases (Zhao and Atkins 2009: 665).
### Table D.4 The Risk Pooling Methods' Advantages, Disadvantages, Performance, and Trade-Offs

<table>
<thead>
<tr>
<th>Possible Advantages</th>
<th>Risk Pooling</th>
<th>Virtual Pooling</th>
<th>Central Ordering</th>
<th>Group Sourcing</th>
<th>Co-located Inventory Pooling</th>
<th>Excess Product Substitution</th>
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<td>Reduce demand variability or uncertainty Reduce service, product availability, and possibly profit or reduce shortage cost maintaining the same service product availability, short-</td>
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<tr>
<td>Pairwise Performance Comparison</td>
<td>Inventory Pooling</td>
<td>Virtual Pooling</td>
<td>Transshipment</td>
<td>Central Ordering</td>
<td>Order Splitting</td>
<td>Component Commonality</td>
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<td>Inventory pooling ITO inventory availability</td>
<td>&gt; inventory pooling ITO inventory availability</td>
<td>Consolidated distribution &lt; location pooling ITO inventory reduction, but keeps inventory near customers</td>
<td>For endogenous lead times and high utilization: capacity pooling &gt; inventory pooling</td>
<td>Demand reshaping &gt; component commonality ITO efficiency and costs</td>
<td>&gt; inventory pooling ITO location accessibility and lost sales</td>
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<td>(approximately equal to) inventory pooling in terms of (ITO) inventory savings</td>
<td>&gt; (performs better than or preferred to) inventory pooling ITO larger flexibility through local inventories &amp; costs of centralized inventory such as double handling, higher transport charges and possibly longer total pipelines</td>
<td>&gt; order splitting ITO reductions in stockout inventory availability &amp; order placements</td>
<td>&gt; order splitting ITO reductions in in-transit inventories &amp; avoiding premium transportation costs of stock transfers</td>
<td>&gt; order splitting ITO reductions in on-hand inventory levels</td>
<td>&gt; cross-functional postponement ITO faster &amp; less expensive implementation</td>
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</table>

| Basic Trade-off (inventory) costs versus customer service level | Inventory (turnover) is traded off against (vs.) transportation cost, delivery time, product availability, sales | Large product assortment, inventory vs. transaction (IT), transportation cost, service level | Inventory, transshipment (cost for transportation, transaction, reordering of transhipped SKU, increased stockout probability at sending location (SL)) vs. cost of holding a unit in inventory until later at not SL, stockout cost at not receiving location | Economies of scale, inventory, (decreased lead time) vs. transaction, DC operating cost, responsiveness, local knowledge, sales | Decreased lead time (variability), savings in (inventory) holding & shortage costs vs. incremental ordering, shipping, transaction cost, no order discounts, more stockout possibilities |
| Trade-off (inventory) costs versus customer service level | | | | | | | | | | |

| Appendix D | Continuation of Table D.4 |
Continuation of Table D.4

1. Corbett and Rajaram (2006), Cachon and Terwiesch (2009: 334), location pooling (Cachon and Terwiesch 2009: 321ff.), centralization (e.g. Eppen 1979), selective stockkeeping (e.g. Pfahl 2004a: 118ff.).


5. Demand is aggregated so that higher-than-average demand may balance lower-than-average demand (Evers 1997: 55, Chen and Chen 2003).


7. If a wholesaler provides product to multiple retailers, demand across the retailers is pooled, which smooths demand fluctuations (risk pooling) (Randall et al. 2002: 56).


15. A “late-arriving order at one location may be offset by an early-arriving order at another…’; consequently, inventory availability improves” (Evers 1999: 122).


17. Consolidated distribution may decrease (Dills 2005: 43) or increase (Cachon and Terwiesch 2009: 359) lead time.


20. “Postponement permits firms to be more responsive and other advantages that are often mentioned are risk-pooling and lead-time uncertainty reduction” (Caux et al. 2006: 3243). It allows to reduce (manufacturing) lead time (Yang et al. 2004: 1054).

21. Virtual pooling permits to be more “adaptable to an abrupt change in product demand” (Fung et al. 2005) and flexible (Christopher 1998: 135).


23. The allocation of orders to the retailers or stores is postponed to a later date and made according to more recent demand information (Pishchulov 2008: 22).

24. Component commonality decreases manufacturing lead time and improves material availability (Maskell 1991, Sheu and Wacker 1997) and time to market (Zhou and Grubbström 2004).


26. Controlling inventories centrally but locating it strategically closer to customers or plants using information technologies (virtual or electronic inventory) can lead to the same inventory savings as centralization, while maintaining larger flexibility through local inventories and reducing the costs of centralized inventory such as “double handling, higher transport charges and possibly longer total pipelines” (Christopher 1998: 135).


29. Randall et al. (2002: 55ff.).

Continuation of Table D.4

35. Virtual inventories allow to widen the product selection without the purchasing and administrative costs (Guglielmo 1999).
36. Transshipment may save fixed and variable replenishment costs (Herer and Rassli 1999: 525, Herer and Tjur 2003: 419), if e.g. one location makes a larger replenishment order to transship some of it to other locations (Herer and Tjur 2003: 419).
38. Multiple "suppliers may ensure competitive pricing and other favorable terms" (Evers 1999: 123).
38. Product pooling may lead to economies of scale in production and procurement of a single universal component relative to small quantities of several components and lower labor costs (Cachon and Terwiesch 2009: 355, Hamstra 2009, Ryan 2009, Thayer 2009: 23).
42. Virtual inventories reduce investment in inventory and fulfillment capabilities and handling and warehousing costs due to economies of scale (Randall et al. 2002: 55f.).
43. The per unit holding cost is lower at the DC than at the stores or regional warehouses (Cachon and Terwiesch 2009: 339).
44. Splitting an order into multiple deliveries by one supplier (scheduled release) leads to lower operating costs and average stock (Hill 1996, Mishra and Tadikamalla 2006).
45. Component commonality may save costs in warehousing and manufacturing operations (Mohabadi and Choobineh 2005: 473).
49. Inventory pooling may allow to include slow movers in a product line economically (Cachon and Terwiesch 2009: 329).
50. Virtual pooling may permit to offer a higher product selection (Guglielmo 1999: 37, Randall et al. 2002: 56), which may constitute a marketing advantage (Kroll 2006, Alvaraz 2007).
Transshipments might increase daily average inventories (Reyes and Meade 2006). Not all supply chain members may benefit from transshipments: They can increase overall or retailer inventories and harm the distributor or individual retailers in a supply chain, in which a manufacturer supplies integrated or autonomous retailers with a one-for-one inventory policy via a central depot (Graehavc and Chakravarty 2001). Order splitting does not decrease the sum of in-transit and cycle stock in the system, but only systemwide safety stock (Thomas and Tyworth 2006, 2007). Total safety stock (of common and specialized components) drops after pooling, but total stock of product-specific components may increase (Baker et al. 1986, Gerchak and Henig 1986: 157, Gerchak et al. 1988, Gerchak and Henig 1989: 61, Van Mieghem 2004: 423) depending on the used service-level measure (Gerchak et al. 1988). Time-based postponement at the company level can increase supply chain inventory, as other members of the supply chain may be forced to use more speculation, i.e., hold more inventories (García-Dastugue and Lambert 2007).

If demands are of different variability, pooling production capacities may increase inventory costs for the low-demand-variability facility (Iyer and Jain 2004) or total cost (Jain 2007).


Chopra and Meindl (2007: 321f.).


McGavin et al. (1993: 1094). Consolidated distribution incurs additional transportation costs from the DC to the retailers (Cachon and Terwiesch 2009: 341).


Companies can experience longer delays with capacity pooling (Yu et al. 2008).


The drop-shipping wholesaler might not deliver the same quality service as the retailer (Randall et al. 2002: 56).

Transshipments may decrease customer service, if they increase the number of receipts per order and/or order cycle times (Jönsson and Silver 1987a: 115, 224, Diks and de Kok 1996: 378, Evers 1996: 111, 1997: 56, 1999: 122, Burton and Banerjee 2005: 169).

Centralized ordering may decrease responsiveness and sales due to decreased local knowledge (Ganesan et al. 2007: 341).

Order splitting increases the number of receipts per order and/or order cycle/response times (Evers 1996: 111, 1997: 56, 1999: 122f.).


Customers might be dissatisfied, because they did not obtain their desired product, but a substitute (Swaminathan 2001: 131).

With increasing size there are no gains from rationalization anymore, but increasing transaction and coordination costs and thus increasing warehouse unit costs in big warehouse systems (Pfohl 1994: 143, Delfmann 1999: 194).

Chopra and Meindl (2007: 321f.).
Appendix D

Continuation of Table D.4

81 Transshipments increase transaction (transportation, shipment documentation, receiving, handling, and administration) costs (Evers 1999: 122, 2001: 312f.) and the sending location's cost of reordering the transshipped product from the supplier and its probability of a stockout (Evers 2001: 312f.).

82 McGavin et al. (1993: 1094).

83 Order splitting may increase ordering, shipping (Gupta and Kini 1995, Thomas and Tyworth 2006: 246), receiving (Chiang 2001: 70), inspection, handling (Gupta and Kini 1995), and administrative costs, but EDI might mitigate it (Evers 1999: 122f.).

84 Although component commonality reduces the average work load, it increases work load variability and work-in-process inventory variability (Guererro 1985: 409, Valkarhia et al. 1996: 3, Ma et al. 2002). It may increase production cost (Thonemann and Brandeau 2000, Simpson et al. 2001), especially if the extent of commonality is too narrow (Simpson et al. 2001).


86 Pooling manufacturing capacity can increase handling efforts (Cachon and Terwiesch 2009: 347f.). Pooling server capacity can increase labor costs, because the service personnel have to have more skills. It might make additional setups necessary and increase the service process's variability, if different customer classes are pooled (Cachon and Terwiesch 2009: 151).

87 Demand reshape entails efforts to make a customer buy a substitute (Eynan and Fouque 2003: 705, 2005: 91).

88 Physical inventory pooling by warehouse centralization is difficult to change or undo at least in the short or medium run (Domschke and Drexel 1996: 1, Evers 1999: 122f., Klose and Stählby 2000: 434, Klose 2001: 3), expensive, and has long-term economical, social, and ecological effects (Klose and Stählby 2000: 434).

89 Herer et al. (2002: 201).

90 Sometimes, it is necessary to redesign products and/or processes to achieve commonality (Bagchi and Gutierrez 1992: 817, Swaminathan 2001: 129, 131, Ma et al. 2002: 536, Ians et al. 2008: 801, Simchi-Levi et al. 2008: 345, 348), which may result in a smaller and more economical set of components though (Whybark 1989).


92 It is expensive to have manufacturing flexibility (Jordan and Graves 1995, Mayne et al. 2008, Cachon and Terwiesch 2009: 349).


94 The universal design may be more expensive, because its components or quality of components targeted to many different uses might not be necessary to some consumers (Cachon and Terwiesch 2009: 335).

95 Postponement may decrease product integrity or quality (Graman and Magazine 2006: 1076ff.).

96 Product pooling might not provide the desired product functionality to consumers (Cachon and Terwiesch 2009: 335).

97 Consolidated distribution might incur extra costs of operating the distribution center (Cachon and Terwiesch 2009: 341). The same applies to “between-replenishment risk-pooling” (McGavin et al. 1993: 1094).

98 Centralization (decreasing the number of warehouses) may lead to diseconomies of scale mostly in organization (Chandler 1990: 25, Scherer and Ross 1990: 103f., Bohr 1996: 385ff.). With increasing size there are no gains from rationalization anymore, but increasing transaction and coordination costs and thus increasing warehouse unit costs in big warehouse systems (Pfohl 1994: 143, Delfmann 1999: 194).


102 Virtual pooling may cause loss of control and possibly business to the drop-shipping party (Randall et al. 2002: 56ff.).
Continuation of Table D.4

Dong and Rudi (2002, 2004) find that if the wholesale price is endogenous, a single manufacturer benefits from its retailers' transshipments, the more, the larger the risk pooling effect. The identical (except in their normal demands) retailers in many situations are worse off under transshipment due to a higher wholesale price, especially if the risk pooling effect is large. Zhang (2005) extends Dong and Rudi's (2004) results under normal demand to general demand distributions.

Centralized ordering may decrease responsiveness and sales due to decreased local knowledge (Ganesan et al. 2007: 341).


Product pooling might not achieve the same total demand as a set of focused designs, may eliminate some brand-price segmentation opportunities (Cachon and Terwiesch 2009: 335), and reduce market share or profits (Kim and Benjaafar 2002: 16).

Revenue might suffer, if customers are dissatisfied with the substitute (Swaminathan 2001: 131) or if the substitute has a lower selling price than the originally desired product (Eynan and Fouque 2003: 707).


Evers (1997: 72, 1999: 125f.).

Herer et al. (2002: 201).


The relative benefit of inventory pooling decreases with utilization (arrival rate divided by service rate) in contrast to multisourcing (Benjaafar et al. 2004a: 1441f.). Counter-intuitively, if demand (order arrival) variability is high, demand splitting among several facilities is preferred to inventory (demand) pooling, since it reduces the arrival variability of orders to the production facilities (demand variability effect) (Benjaafar et al. 2004a: 1446).

Benjaafar et al. (2005: 563) find that in systems with symmetric costs where supply lead times are endogenously generated by a finite-capacity production system 'the effect of capacity pooling is more significant than that of inventory pooling'. "[W]hile the relative benefit of capacity pooling tends to increase with utilization, [...] capacity pooling alone achieves nearly the same relative benefit as the joint pooling of capacity and inventory" (Benjaafar et al. 2005: 550).

Eynan and Fouque (2005: 96f.).


Ganesan et al. (2007: 341).


Cachon and Terwiesch (2009: 344, 346, 348f.).
Appendix E: Subadditivity Proof for the Order Quantity Function (5.1)

The total system-wide order quantity in the centralized system is no greater than the one in the decentralized system, because the order quantity function (5.1) is subadditive:

\[ q_c = s \cdot \max \left\{ \left\lceil \frac{d_1}{s} \right\rceil, \left\lceil \frac{m_1}{s} \right\rceil \right\} \leq q_d = \sum_{i=1}^{m} s \cdot \max \left\{ \left\lceil \frac{d_i}{s} \right\rceil, \left\lceil \frac{m_i}{s} \right\rceil \right\}. \quad (5.4) \]

In order to prove this, we first resort to two warehouses with forecast demand minus available inventory (net demand) \( d_1 \) and \( d_2 \) and seek to prove:

\[ s \cdot \max \left\{ \left\lceil \frac{d_1 + d_2}{s} \right\rceil, \left\lceil \frac{m}{s} \right\rceil \right\} \leq s \cdot \max \left\{ \left\lceil \frac{d_1}{s} \right\rceil, \left\lceil \frac{m}{s} \right\rceil \right\} + s \cdot \max \left\{ \left\lceil \frac{d_2}{s} \right\rceil, \left\lceil \frac{m}{s} \right\rceil \right\}. \quad (E1) \]

The order quantity function (5.1) is a compound function \( F \) consisting of an outer maximum function and an inner ceiling function, which we henceforth denote by \( f \) and \( g \), respectively. The ceiling expression \( \left\lceil \frac{m}{s} \right\rceil = c \) is a constant.

Recall that a function \( f(x) \) is called subadditive, if it obeys the inequality

\[ f(x_1 + x_2) \leq f(x_1) + f(x_2) \quad \text{for any } x_1, x_2 \text{ from the function's domain.} \tag{E2} \]

We first show that \( g(\cdot) = \left\lfloor \frac{\cdot}{s} \right\rfloor \) is subadditive, i.e. that the following holds for any \( d_1, d_2, s \):

\[ \left\lfloor \frac{d_1 + d_2}{s} \right\rfloor \leq \left\lfloor \frac{d_1}{s} \right\rfloor + \left\lfloor \frac{d_2}{s} \right\rfloor. \quad (E3) \]

This can be verified by a case differentiation:

For \( \neg(s \mid d_1) \), \( \neg(s \mid d_2) \) \( \Rightarrow \left\lfloor \frac{d_1 + d_2}{s} \right\rfloor < \left\lfloor \frac{d_1}{s} \right\rfloor + \left\lfloor \frac{d_2}{s} \right\rfloor \), \( (E4) \)

\[ \begin{align*}
\text{for } & \neg(s \mid d_1), s \mid d_2 \\
& \Rightarrow \left\lfloor \frac{d_1 + d_2}{s} \right\rfloor = \left\lfloor \frac{d_1}{s} \right\rfloor + \left\lfloor \frac{d_2}{s} \right\rfloor,
\end{align*} \tag{E5} \]

where notation \( a \mid b \) stands for „\( a \) divides \( b \)“ or, equivalently, “\( b \) is a multiple of \( a \)” and \( \neg \) designates negation.

We now prove that \( f(\cdot) = \max\{\cdot, c\} \) is subadditive as well, i.e. that the following holds for any \( g_1, g_2 \):

\[ \max\{g_1 + g_2, c\} \leq \max\{g_1, c\} + \max\{g_2, c\}. \tag{E6} \]

\[ \begin{align*}
g_1 < c, g_2 < c & \Rightarrow \max\{g_1 + g_2, c\} < \max\{g_1, c\} + \max\{g_2, c\}. \tag{E7} \\
g_1 < c, g_2 \geq c & \Rightarrow \max\{g_1 + g_2, c\} < \max\{g_1, c\} + \max\{g_2, c\}. \tag{E8} \\
g_1 \geq c, g_2 < c & \Rightarrow \max\{g_1 + g_2, c\} = \max\{g_1, c\} + \max\{g_2, c\}. \tag{E9}
\end{align*} \]
Then for the compound function $F(d) = f(g(d))$ holds:

$$F(d_1 + d_2) \leq F(d_1) + F(d_2),$$ \hspace{1cm} (E9)

since

$$F(d_1 + d_2) = f(g(d_1 + d_2)) \leq f(g(d_1) + g(d_2)) \leq f(g(d_1)) + f(g(d_2)) = F(d_1) + F(d_2),$$ \hspace{1cm} (E10)

where the first inequality is due to subadditivity of $g$ and non-decreasing behavior of $f$ and the second inequality is due to subadditivity of $f$.

It is now straightforward to generalize (E9) to any number of summands. Given $F(d_1 + d_2) \leq F(d_1) + F(d_2)$, we by induction on $n$ have:

$$F(d_1 + \cdots + d_{n-1} + d_n) \leq F(d_1 + \cdots + d_{n-1}) + F(d_n) \leq F(d_1) + \cdots + F(d_{n-1}) + F(d_n),$$ \hspace{1cm} (E11)

which hence gives

$$F(\sum d_i) \leq \sum F(d_i)$$ \hspace{1cm} (E12)

and proves (5.4) to hold.
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