Deparment of Mathematics and Systems Analysis

Decision models for managing demand and supply uncertainties in supply networks

Anssi Käki

Aalto University

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Abstract

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Abstract

Companies can use mathematical models to improve their decisions under uncertainty. This Dissertation focuses on sourcing and supply management decisions under i) uncertain demand of products or components and ii) uncertain capability of suppliers to deliver high-quality materials and services. Modern planning systems help automatize and optimize decision making in these areas, but most these systems are not good at accounting for uncertainties. However, in many industries, the effective management of demand and supply uncertainties is an important source of competitive advantage. Thus, there is a need for decision models that help managers analyze the impacts of uncertainties.

The Dissertation develops methods based on stochastic optimization where both continuous and discrete (scenario-based) probability distributions are used to model demand and supply uncertainties. Particular attention is given to the qualitative characteristics of distributions and interdependencies between uncertainties. In addition, a static methodology for assessing disruption risks in complex supply networks is presented.

The Dissertation illustrates how the neglect of uncertainties can lead to sub-optimal decision recommendations, and, on the other hand, how a decision maker can better utilize decision models by modeling the relevant uncertainties appropriately. The theoretical part is complemented with experimental results which show that subjects have significant difficulties in making simple procurement decisions in the presence of demand and supply uncertainties, and that decision support tools can significantly improve their decision making in this area.

The careful modeling of uncertainties yields robust decision recommendations that perform well in most or all uncertainty scenarios. By using the methodologies presented in Dissertation, managers can better manage the uncertainties in customer demand and suppliers' performance and material availability. This increases the competitiveness and capability to manage risks in an uncertain business environment.

Keywords Stochastic optimization, Demand and supply uncertainties, Scenarios, Copula functions, Supply management, Newsvendor model, Risk management

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Tiivistelmä

Yritykset käyttävät matemaattisia päätösmalleja parantaakseen päätöksentekoa epävarmuuksien vallitessa. Tässä väitöskirjassa tarkastellaan toimittajasuhteiden johtamiseen ja hankintatoimeen liittyviä päätöksiä huomioiden epävarmuudet sekä tuotteiden ja palveluiden kysynnässä että tarjonnassa (esim. toimittajien toimitusvarmuudessa ja materiaalin laadussa). Hankintatoimen päätöksiä tehdään enenevissä määrin automaattisesti suunnittelujärjestelmissä optimointiin perustuen. Tällaiset järjestelmät eivät kuitenkaan huomioi epävarmuuksia kattavasti. Monella teollisuudenalalla kysynnän ja tarjonnan epävarmuuksien hallinta antaa kilpailuetua, mikä luo tarvetta epävarmuuksien analysointiin perustuville päätösmalleille.

Väitöskirjassa kehitetään menetelmiä, jotka perustuvat stokastiseen optimointiin. Kysynnän ja tarjonnan epävarmuudet on näissä menetelmissä mallinnettu joko jatkuvia tai diskreettejä (skenaariopohjaisia) todennäköisyysjakaumia käyttäen. Erityisesti mallinnuksessa on kiinnitetty huomioita jakaumien kvalitatiivisiin ominaisuuksiin sekä useamman epävarman muuttujan välisiin riippuvuuksiin. Lisäksi väitöskirjassa esitetään myös todennäköisyyspohjainen menetelmä riskienhallintaan monimutkaisissa toimittajaverkostoissa.

Tulokset osoittavat, että toisaalta epävarmuuksien huomiotta jättäminen johtaa osaoptimaalisiin päätössuosituksiin ja toisaalta, että epävarmuuksien huolellinen mallintaminen tarjoaa hyvät edellytykset päätösmallien käyttämiselle. Teoriaosuutta täydennetään myös tuloksilla kokeesta, jossa yksinkertaisien hankintatoimeen liittyvien päätöksien todetaan olevan vaikeita koehenkilöille erityisesti silloin, kun sekä kysynnässä että tarjonnassa esiintyy epävarmuutta. Koeasetelmassa havaitaan myös, että päätöksenteon tukivälineillä voidaan huomattavasti parantaa hankintatoimen päätöksentekoa.

Epävarmuuksen huomiointi päätöksentekomalleissa johtaa päätössuosituksiin, jotka ovat hyviä suuressa osassa tai kaikissa epävarmuuksiin liittyvissä skenaarioissa. Käyttämällä väitöskirjassa esitettyjä menetelmiä, organisaatiot voivat paremmin hallita epävarmuuksia sekä asiakaskysynnässä että toimittajien kyvykkyydessä ja materiaalin saatavuudessa. Tämä lisää epävarmassa liiketoimintaympäristössä toimivan organisaation kilpailu- ja riskienhallintakykyä.

Avainsanat Stokastinen optimointi, kysyntä- ja toimitusepävarmuudet, skenaarioiden käyttö, copula-funktiot, toimitusten hallinta, newsvendor-malli, riskien hallinta

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[III] Käki, A., Salo, A. and Talluri, S. (2014). Scenario-Based Modeling of Interdependent Demand and Supply Uncertainties. *IEEE Transactions on Engineering Management*, 61(1): 101–113.

[IV] Käki, A., Salo, A. and Talluri, S. (2013). Disruptions in Supply Networks: a Probabilistic Risk Assessment Approach. *Manuscript*, 36 pages.

Contributions of the author

Käki proposed the research topic of Paper [I]. He developed the decision models and produced results on the value of information. As its primary author, Käki wrote this paper under the guidance of Salo and Talluri.

Käki proposed the research topic of Paper [II]. Analytical results were established jointly by Käki and Liesiö who made equal contributions. The experiment was designed by Käki and Liesiö. Käki ran the experiment and analyzed its results. Käki is the primary author of this paper. He incorporated the suggestions made by Liesiö, Salo and Talluri.

Käki proposed the research topic of Paper [III]. He developed the scenario generation algorithm, implemented stochastic optimization models, and analyzed the results of these models. He is the primary author of the paper. Salo and Talluri provided comments and helped Käki finalize the paper.

Käki proposed the research topic of Paper [IV] and is the originator of its main methodological contributions. He implemented the Bayesian network models and analyzed them. Käki is the primary author of the paper. Salo and Talluri provided comments.

Preface

Finishing a challenging project is rewarding and this Thesis makes no exception. In addition to the actual research topics, I have a learnt a great deal about scientific writing, research, and sharing results via academic publications and conferences. I wish to thank several people who have contributed to this project.

I want to thank Professor Ahti Salo for supervising this Thesis and providing crucial support throughout the process. Ahti has been positive and constructive from the start to the end, and I appreciate his ability to take on a research topic outside the key focus areas of our research group. Professor Sri Talluri has contributed to all papers in the Thesis, and our co-operation has been both efficient and fun. I would also like to thank Professors Hartmut Stadtler and Martin Grunow who provided thorough and supportive pre-examination reports of the Thesis. In addition, I would like to acknowledge the financial support provided by KAUTE and Emil Aaltonen foundations.

I have had great colleagues during my few years at the Systems Analysis Laboratory. Juuso Liesiö is a co-author of a paper which I personally find the best in this Thesis, and he has been supportive and helpful throughout my time at the laboratory. Antti Punkka and Eeva Vilkkumaa have provided invaluable support in both research and non-research related topics. It has been a great pleasure to work with you! I would also like to thank Raimo Hämäläinen and the other professors for running the laboratory and the (former) graduate school, Minna Westerlund for all administrative support, and Antti T., Eero, Heikki, Ilkka, Jirka, Jouni, Jussi, Kimmo, Matteo, Mikko H. & V., Paavo, Pekka, Simo, Tuomas, Ville, and others for making such a nice work environment.

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Helsinki, March 12, 2014,

Anssi Käki

Contents

1 Introduction

Companies operate in business environments that are increasingly volatile, which is one of the reasons why managing demand and supply uncertainties has become a key objective for operations (Fisher et al. 1994; Simchi-Levi 2010). Demand uncertainty relates to product characteristics (Fisher 1997): for example, the demand of a new product is less predictable than that of an improved version of an existing product, and an innovative high-technology consumer product is less predictable than a functional product such as basic food or energy. Supply uncertainty, on the other hand, is linked to the supply process (Lee 2002): when the manufacturing process and technology are mature, the supply process is typically stable, but if technology is novel and the supply base is limited in size and experience, the supply process evolves in more uncertain ways. In addition to these operational factors, various low-probability high-impact events, such as natural catastrophes can cause unexpected drops in demand or shortages in supply (Kleindorfer and Saad 2005).

Important decisions that are critical for managing demand and supply include designing the supply chain or network, determining the long term production capacity, and making sourcing decisions for critical materials and services (Kouvelis and Milner 2002). The impact of uncertainties on these decision problems varies from negligible to critical: planning daily operations when workforce and other resources are fixed is a largely deterministic problem, but the problem of designing a supply network for a new consumer product involves significant uncertainty. Even though the importance of uncertainties is recognized by most decision makers, they are not very well dealt with in practice. Sheffi (2005) lists various cases where demand and supply mismatches have had serious consequences: for example, in 1998, Marks&Spencer gambled on gray being the fashion color of the coming sales season for clothes and lost £150 million in sales failures and clearing excess stock; in 2000, IBM launched new ThinkPad models and seriously under-forecasted their demand, which lead to severe shortages, customer dissatisfaction and substantial amount of lost sales;

and in 2003, Wyeth prepared 4 million flu vaccine doses but was able to sell less than 400 000 of them. Yet, there are success stories, too, such as the video rental giant Blockbusters, which increased its US market share from 24% to 40% between 1997 and 2002 largely due to the introduction of a new revenue sharing contract for demand risk management (Cachon and Lariviere 2005); and Hewlett-Packard, who introduced a new procurement risk management strategy that generated over $400 million in cumulative cost savings between 2001 and 2007 (Nagali et al. 2008).

Demand uncertainty is a critical driver for modern supply chain planning practices and in industries such as fashion retail, demand forecast accuracy has a major impact on company's financial performance (Fisher and Raman 1996). In general, the higher upstream in the supply chain a company is, the more forecast-driven (as opposed to demand-driven) the operations, and thus, the higher the impact of demand uncertainty (Christopher 2000). This is illustrated by *the bullwhip effect* (Lee et al. 1997), which describes the amplification of order quantities and inventories when moving upstream in a supply chain. This fluctuation is partly caused by the poor visibility of the end customer demand, which results in "information distortion" in demand forecasting. In practice, however, systemic approaches to demand uncertainty are rare: a typical demand planning process is based on a point forecast over the planning horizon (Kilger and Wagner 2008; Van Mieghem 2004). At best, forecast deviation is estimated from historical performance and buffers such as safety stocks are adjusted based on the estimated deviation.

Supply uncertainty is as critical as demand uncertainty for supply chain strategy (Lee 2002). It has received increasing attention lately, and two separate trends can be identified (Kleindorfer and Saad 2005): i) intense competition, pressure to cut costs, and rapid pace of technological development have lead to operational supply uncertainties caused by, for example, constrained capacity, or quality problems; and ii) various high-impact disruptions such as natural catastrophes and financial turmoils have induced disruptive supply risks that have had serious consequences. Compared to demand, the impacts of supply uncertainties on supply chain decisions are not yet as well understood.

Lee (2002) and Simchi-Levi (2010) point out that demand and supply uncertainties should be accounted for jointly when supply chain strategy is devised. These uncertainties are not always independent of each other: unexpected changes in demand and supply can happen due to a common cause. For example, an economical boom can increase the demand for consumer electronics, but if suppliers of, say, semiconductors have been conservative in their investments, global capacity of semiconductor chips can become constrained. This can lead to unexpected demand peaks with an attendant drop in suppliers' capability to deliver components. Even though empirical evidence of these kinds of interdependencies has not been collected, it seems reasonable that such interdependencies exist, and that they can have a big impact on operations.

1.1 Objectives and scope

This Dissertation develops decision models which help in the design of resilient supply chains, the planning of production capacity, and the sourcing of critical raw materials under demand and supply uncertainties. This objective has been promoted in the literature (e.g., Christopher and Peck 2004; Simchi-Levi 2010) and it was also motivated by real business challenges brought up in interviews of supply chain practitioners in the beginning of the Dissertation process. To address these challenges, the Dissertation develops models which i) account for various types of uncertainties and ii) give recommendations that perform satisfactorily under most or all possible realizations of uncertainties. Such models can be adjusted based on attitude towards uncertainties, for example, by making a statement of how much risk the decision maker is willing to take. In the literature, such models are sometimes (and sometimes not) referred to as risk management models.

In practice, a typical way to analyze the robustness or riskiness of a decision is to conduct a "what-if" analysis by changing the model inputs and calculating the outcome with the same decision. For example, it can be tested how a 10% cost increase or 20% sales decrease would impact the outcome of a given strategy. This is illustrated with the top decision process in Figure 1. In the bottom process of the Figure, on the other hand, the what-if part is done *before* the decision. This approach also results in single decision recommendation, but the recommendation is robust in the sense that uncertainties have already been accounted for. This reduces the need for further sensitivity (what-if) analyses.

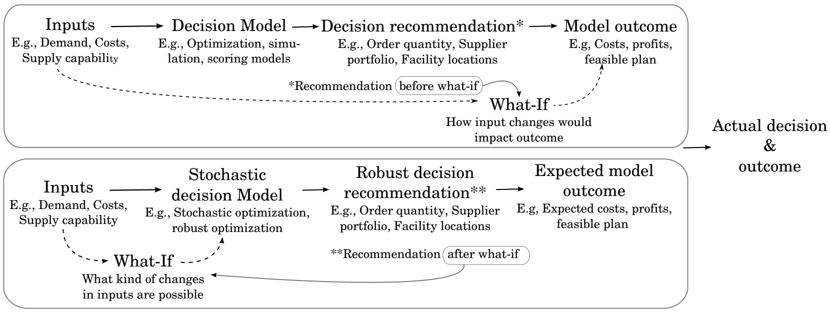

Figure 1. Approaches to the use of decision models under uncertainty.

Methodologically, the main approach adopted in this Dissertation is stochastic modeling of demand and supply. The analyses focus on the impact of these uncertainties on decision recommendations from processes that follow the schematics of the bottom one in Figure 1. In this setting, the Dissertation seeks to answer the following research questions, which are linked to Papers [I]–[IV] as shown in Table 1:

RQ1: What is the impact of demand distribution shape on decisions that consider supply chain design, capacity, or sourcing?

RQ2: What is the impact of operational supply uncertainties, for example, quality problems, on the costs and risks of sourcing?

RQ3: How to assess the risks caused by disruptional supply uncertainties, for example, supplier bankruptcy, or labor strike at a critical supplier?

RQ4: How can interdependent demand and supply uncertainties be modeled, and what are the implications on sourcing decisions?

Table 1. Scope of Papers [I]–[IV]. The parentheses indicate that the uncertainties are explicitly modeled, but they are not in focus of analysis.

Uncertainty	[I]	[II]	[III]	[IV]
Demand (RQ1)	X	(X)	(X)	
Supply (RQ2)		X	(X)	
Supply disruptions (RQ3)				X
Demand and supply (RQ4)		X	X	

1.2 Research methods and dissertation structure

Mathematical decision models are central in supply chain planning (Simchi-Levi et al. 2003; Stadtler 2005) and, methodologically, the Dissertation consists of models that can be classified as analytic (Papers [I] and [II]) or scenario-based (Paper [III]) stochastic optimization models, or probabilistic risk analysis (Paper [IV]). Sourcing applications of stochastic optimization models and their scenario-based approximations have been proposed already by Dantzig (1955), and there are stochastic formulations for a variety of planning problems (Shapiro et al. 2009). Among these models, the analytical approach requires the use of continuous probability distributions, as exemplified by papers [I] and [II]. When discrete distributions are employed, scenarios can be used to model uncertainties in the spirit of Paper [III]. In complex systems such as supply networks, special structures for representing the joint distribution of uncertain variables may be needed: in Paper [IV] one such structure called a Bayesian network (Darwiche 2009) is utilized.

The rest of this summary article is structured as follows. Section 2 discusses the theoretical foundations of the main topics in this Dissertation. Section 3 presents the key results of Papers [I]-[IV]. Section 4 summarizes the implications of results and suggests some future research topics.

2 Theoretical foundation

2.1 Supply management and sourcing under uncertainty

Planning is a fundamental management component in supply chain management (Cooper et al. 1997; Stadtler 2005). According to Meyr et al. (2008), there are various planning processes under the umbrella of supply chain planning. Within these, this Dissertation focuses on supply chain design, capacity, and sourcing decisions. Examples of supply chain planning applications that consider uncertainties in these areas, respectively, include long-term supply network planning of a package manufacturer (Santoso et al. 2005), mid-term demand planning of a fashion product manufacturer (Fisher and Raman 1996), and short-term inventory optimization at an electronics manufacturer (Cohen et al. 1990).

Tang (2006) reviews quantitative models under the rubric supply chain risk management. While a clear definition for supply chain risk management has not been established yet (Sodhi et al. 2012), risk management clearly has a different meaning in the context of operations from what it means in the risk analysis of technical systems, for instance. As an example, in operations management, a model that minimizes expected costs can be considered as a risk management model, even though it would not have explicit risk objectives or constraints. Tang (2006) divides supply chain risks into operational and disruptional: the former refers to risks caused by uncertainties in customer demand, material and labor costs, or supplier lead times; and the latter to major disruptions caused by natural and man-made disasters. Further, Tang and Tomlin (2008) categorize supply chain risks based on their underlying cause as supply risks (upstream partners); process risks (inherent to all supply chain partners); and demand risks (downstream partners, e.g., customers).

In operational models for inventory management and sourcing with the focus on demand risks, the Newsvendor model (e.g., Qin et al. 2011) is arguably one of the most influential. It is a single period model that characterizes situations where a costly commitment (e.g., a procurement order, a production order, or a capacity plan) must be made before a realization of unknown demand occurs, and both excess commitments and shortages carry a cost. The model is particularly applicable to situations in which products are perishable, fashionable, or for some other reason have short life cycles. It has a simple analytic solution (Porteus 1990), it has been extended for many different purposes (Khouja 1999), and, despite of its simple structure, experiments have shown that humans are not good at making optimal newsvendor decisions (Schweitzer and Cachon 2000; Bolton and Katok 2008).

While the Newsvendor model helps managing frequent operational risks caused by uncertain customer demand, the management of disruptional risks accounts for high-impact events that occur with low frequency. As noted by Snyder et al. (2012), due to the vast scale of modern supply chains and wide array of possible events, there is a high likelihood that a disruption will strike a given supply chain in a given year; thus there is a need to manage disruptional risks systematically. Tomlin (2006) lists possible tactics for managing disruptions: in addition to risk mitigation with, e.g., insurance or inventories, he also promotes responsive strategies such as switching to alternative suppliers. These mitigation strategies can be studied with stochastic optimization models.

2.2 Stochastic optimization

Complex planning problems have traditionally been solved through mathematical optimization, formulated as deterministic linear or mixed integer linear programs. The significance of uncertainties in problem parameters has given rise to stochastic optimization, where at least one of the parameters is uncertain (Santoso et al. 2005; Shapiro et al. 2009). A classification can be made between stochastic optimization and dynamic optimization: many supply chain planning problems contain multiple time steps, and can require even tens of consecutive (e.g., weekly) decisions; these kinds of problems are best approached with dynamic optimization techniques. In contrast, stochastic optimization tends to focus more on uncertainties and less on dynamics, and the solving techniques are also different (see, e.g., Rockafellar 2001).

The focus of this Dissertation is on one- and two-stage stochastic optimization models that are either continuous (Papers [I] and [II]) or discrete (Paper [III]) models. In continuous models, stochastic variables are modeled with continuous probability distributions whereas discrete models employ discrete distributions, or scenarios (Rockafellar and Wets 1991). The choice of modeling approach matters: continuous models can be used to derive generalizable insights about a specific problem such as the Newsvendor problem and, thus, they are particularly valuable in theory development. For actual problem solving, the discrete approach can be more suitable because the use of sampling techniques makes it possible to recast stochastic problems as deterministic ones (Shapiro et al. 2009). This means that complex, industrial size problems can be solved effectively with computers (Santoso et al. 2005). There are also differences in the estimation of uncertain variables: probability distributions can often be estimated from data or expert judgments (Keeney and Von Winterfeldt 1991) but, on the other hand, there are effective ways to generate multivariate, multistage scenarios which can be more readily understood by managers (Høyland and Wallace 2001).

The discrete approach is particularly useful for problems that involve many uncertainties, because of complex multivariate distribution functions. This makes it challenging to analytically determine the global optimum of, for example, expected profit function that contains such a distribution function. Multivariate distributions are complex especially when there are dependencies among the uncertainties. However, sampling multivariate distributions and generating scenarios with dependencies is quite straightforward (see Dupačová et al. 2000; Høyland and Wallace 2001, and references therein). This approach is increasingly used in financial risk management, in which dependencies need to be modeled especially when solving portfolio problems. For example recently, more attention has been paid to the structure of dependencies, and modeling with copula functions has gained popularity (Embrechts et al. 1999; Embrechts et al. 2005). Copulas are used to model, for example, non-linear dependencies.

Stochastic optimization approaches to the modeling and management of uncertainties can be used to solve a variety of planning problems. The optimal solutions, however, are sensitive to assumptions about the uncertainties, as will be illustrated in this Dissertation. It should be noted that optimization under uncertainty does not require such assumptions: robust optimization (Bertsimas and Sim 2004) is a distribution-free stochastic optimization approach that has been applied to the Newsvendor problem (Gallego and Moon 1993; Perakis and Roels 2008) and inventory planning problems (Bertsimas and Thiele 2006), for example. Especially in cases where optimal solutions are sought but few assumptions of the probability distributions can be made, robust optimization can provide better solutions than traditional stochastic optimization. But then again, decision recommendations of robust optimization models can also be overly conservative (e.g., order zero items because that implies no risk) and thus non-practical.

2.3 Probabilistic risk analysis

Jüttner et al. (2003) call for the adoption of a network perspective in supply chain risk management, and Sheffi (2005) describes various cases where disruptions at a company originate from disruptions in the supply base. But companies can have very complex supply bases (Choi and Krause 2006), which restricts the efficient use of optimization based approaches. Instead, Deleris and Erhun (2011) apply Probabilistic Risk Assessment (PRA; also referred to as quantitative risk analysis, QRA; and probabilistic safety analysis, PSA) to supply chains. PRA is a generic methodology for analyzing the risks of complex systems, and it has been successfully utilized in various technical applications (Paté-Cornell 1996; Bedford and Cooke 2001; Stamatelatos et al. 2011).

PRA provides a quantitative estimate of a system's risk, where a system refers to a complex entity such as nuclear power plant and its risk is related to an undesired event, such as nuclear core melt. When combined with optimization, PRA also helps set priorities among risk mitigation actions for given resource constraints and, in addition, it can be used to explore alternative system designs from the risk perspective (Deleris and Erhun 2011). PRA consists of several methods such as fault models, event trees, and statistical analysis (Bedford and Cooke 2001; Høyland and Rausand 2009). In a typical PRA process, the system is divided into basic events or components, and their failure probabilities are estimated. Then, a causal analysis is performed to link these basic events to a top event (system failure or an accident, for example) using tools such as fault trees. Finally, the top events are linked to consequences (to humans, environment, production) using, for example, event trees. The use of probabilistic data and system modeling make it possible to analyze the aggregated risk quantitatively, and to assess the impact of individual events or components on the system risk.

Where optimization models give specific decision recommendations, PRA is a generic methodology that aims to increase risk-awareness in an organization (Deleris and Erhun 2011). Indeed, Apostolakis (2004) promotes the term risk-informed decision making (as opposed to risk-based), meaning that the results of PRA should not be used as the sole basis for decision making. While this reflects the author's experiences in the nuclear power industry where risk assessment is critical for safety and mandated by regulations, the principle of risk-informed decision making seems relevant to business problems as well. In business operations, disruptions can be hazardous and threaten the safety of, e.g., employees in operations management context, too, but in most cases the focus of operational disruption management is on the financial consequences (which can be severe; see, e.g., Sheffi 2005; Hendricks and Singhal 2005). Thus, the role of PRA in operations management is to provide information for cost-risk tradeoff analyses and inputs to further decision models.

3 Results

Table 1 summarizes the contributions of Papers [I]-[IV]. Paper [I] examines widely used supply chain planning models and discusses their out-

Table 2. Contributions of Papers [I]-[IV]

Paper	Research objectives	Methodology / Approach	Results
[I]	Evaluate the impact of demand distribution shape on planning models	Analytical study and numerical sensitivity analysis of three models	Insights on the impact of demand shape in inventory management, sourcing, and facility location
[II]	Study how supply uncertainty affects Newsvendor decision making	Theoretical development of the Newsvendor model; experimental study with on-line Newsvendor game	Newsvendor solution for interdependent demand and supply; analysis of subject behavior under supply uncertainty
[III]	Assess the impact of interdependency between demand and supply uncertainties on sourcing strategies	Scenario generation with copulas; stochastic programming model to sourcing with capacity reservation option	Insights on how interdependent uncertainties can impact both costs and risks of sourcing
[IV]	Develop a methodology for supply disruption risk assessment	Modeling supply networks with Bayesian networks; analysis based on risk importance measures; conceptual examples and simulation	Generic methodology for high-level risk analysis; insight on the relationship between network structure and disruption risk

come in the light of different types of demands. Papers [II] and [III] present extensions for the Newsvendor model. In addition, Paper [II] describes a Newsvendor experiment with results related to the impact of supply uncertainty. Paper [III] focuses on more complex sourcing setups than the Newsvendor; these are modeled as scenario-based stochastic optimization problems. Paper [IV] develops a methodology for supply risk assessment in large supply networks.

Specifically, Paper [I] discusses three typical decision models in supply chain planning: i) Inventory management with safety stock (Silver et al. 1998); ii) Procurement with capacity reservation options (Cachon and Lariviere 2005); and iii) Facility location and capacity acquisition (Dasci and Laporte 2005). The basic formulation of these models assumes that there is a single demand uncertainty (of component, product or market area), and the paper presents sensitivity analysis of these models with respect to the shape of the demand distribution. The key result is that the distribution shape has a major impact on decision recommendations of the three models (RQ1). In the analysis, the first two moments (expected value, variance) of distributions were held constant, but the shape had a significant impact on optimal strategies and their outcomes. For example, in the procurement model, there were two suppliers available: a cheapless costly supplier who required fixed order quantities, and a more costly but flexible supplier that offered capacity reservation options. With identical expected demand and variance, the optimal share of capacity options in the total order quantity under normal demand was 83% and under positively skewed demand 29%. Results of similar scale were obtained for all models.

Papers [II] and [III] both contribute to the Newsvendor literature and provide insights on sourcing in buyer-supplier relationships. Paper [II] focuses solely on the Newsvendor model and its analytical contribution relates to modeling uncertain supply with the stochastic yield model and, moreover, considering interdependent demand and supply uncertainties in the Newsvendor setting. It is shown that under the assumption of independent, uniformly distributed demand and supply yield, the Newsvendor solution changes in a non-trivial manner (RQ2). For example, if the expected yield, i.e., the share of received goods of the ordered quantity, is 50%, it is not optimal to order twice the optimal order under perfect supply yield.

Paper [II] also discusses interdependency between demand and supply: in the paper, the interdependent case is modeled with a copula structure that exhibits only moderate dependency (corresponds to correlation coefficient of $\pm\frac{1}{3}$), but the differences in optimal order quantity and expected profit due to interdependency are still substantial (RQ4). In particular, positive dependency both increases the expected profit and lowers the risk level measured with Conditional-Value-at-Risk.

The experimental results of Paper [II] shed light on how human decision makers react in the face of supply uncertainty in Newsvendor decisions. The main result is that supply uncertainty makes it more difficult to reach the optimal decision, but this also depends on the subjects (RQ2). The control group (standard Newsvendor setting with perfect supply yield) and the primary test group (additional stochastic supply yield) consisted of bachelor and master level engineering students. They faced two kinds of products: one with high profit margin and one with low profit margin. The ordering decisions were severely non-optimal: in the case of high profit margin, the average order by the student group was 44% short of the optimal order quantity. For a product that has a low profit margin, the optimal order should have been 39% lower than what was observed on average. Both results exhibit the so-called pull-to-center effect where orders are adjusted towards the average demand. But, in addition, a group of supply chain consultants participated the experiment. These consultants made only 18% smaller orders than the optimum under the high profit margin; this substantially closer-to-optimal strategy also lead to over 20% improvement in the average profit when compared to the student group.

While Paper [II] focuses on theoretical and experimental investigation of the Newsvendor setting, Paper [III] focuses on more complex sourcing situations. First, the decision maker can order from two alternative suppliers: in addition to an unreliable low-cost supplier, also a perfectly reliable but more costly supplier is available. Moreover, this supplier offers a capacity reservation option which is used to share demand risk in a buyer-supplier relationship. Second, the uncertainties are modeled with scenarios that can be generated with little assumptions. For example, these scenarios can be generated from expert knowledge, such as percentile estimates of demand and supply yield for the planning period in question. In particular, with this scenario approach, various structures of dependency can be used to construct the joint distribution for demand and supply. In the paper, linear and tail-dependent dependency structures are compared. The scenarios are used in conjunction with a stochastic optimization model for procurement cost minimization. The model is also extended to two products with two components, which makes it possible to evaluate how the use of common components helps mitigate risks.

The model in Paper [III] shows that the capacity reservation option is an effective tool for risk mitigation: in the examples of the paper, the Conditional-Value-at-Risk (of the procurement cost) at 95% level is almost 10% smaller compared to the case where the option was not available; also expected costs are decreased by more than 10% due to the option. The value of the option, however, varies depending on the dependency strength between demand and supply (RQ4). In particular when demand and supply are negatively correlated, i.e., high (low) demand tends to occur at the same with low (high) supply capability, capacity reservation is preferred to (cheaper) fixed orders. This is due to the fact that under negative dependency, high demands are particularly difficult to fulfill because of expectedly lower supply yields at the unreliable supplier. Thus, having a reliable supply source pays off, even though the order cost is higher. Paper [III] also shows that tail-dependent demand and supply can increase the worst-case costs of procurement compared to linear dependency; this result is pertinent to industries in which there are no clear dependencies between demand and supply under normal conditions, but during, e.g., sudden demand peak the suppliers' capacity might not be sufficient and supply yields drop.

Paper [IV] presents a methodology for supply risk assessment, but instead of operational supply uncertainty discussed in Papers [II] and [III], it focuses on disruptional uncertainties where supplier capacity is 0% or 100%. Unlike the other papers in this Dissertation, Paper [IV] does not focus on a specific decision model, but the methodology supports as-is analysis for risk-informed decision making. Thus, the key result is the methodology and the insights based on analytical and numerical examples of using the methodology. In particular, these insights relate to i) how supply network design relates to disruption risk, and ii) how suppliers can be prioritized for, e.g., risk mitigation actions.

A key result of Paper [IV] is that disruption risk assessment in complex supply networks should not be based on simple rules or assumptions: for example, whether using single or multiple suppliers involves greater risks depends on the specific case at hand (RQ3). Another result is that even though complex supply networks are inherently less reliable than less complex networks, they are more resilient to disruptions (at least in relative terms) when complexity is high. The paper discusses the use of risk importance measures, and points out that different measures are suitable for different purposes: when planning supply network design (how many nodes and arcs), a different measure should be used compared to a situation, where targets for improvement actions in the existing network are sought.

4 Discussion

4.1 Theoretical and practical implications

Uncertainties, in general, and demand and supply uncertainties, in particular, are critical inputs to stochastic decision models for sourcing. While the value of information about these uncertainties in such models has been discussed in the literature (e.g., Perakis and Roels 2008), most studies have a simple uncertainty model (e.g., a particular probability distribution) because of theoretical tractability. This Dissertation suggests that especially when moving to more concrete applications, uncertainties should be modeled with due care. Inventory management, for example, is largely dependent on the shape of the demand: for products with normally distributed demand, the optimal safety stock can differ from that of products with bimodal demand, which occurs if demand consists of many small orders and few large orders.

Decisions related to matching demand and supply are particulary difficult when there are multiple uncertainties. Paper [III] develops a scenario generation method that can be used to model multiple uncertainties subject to a broad range of different assumptions. Modeling multiple uncertainties and, in particular, their interdependencies, is rare in the literature (but not exceptional, see Tomlin and Wang 2005). Still, it is realistic to assume that multiple uncertainties should be accounted for: on the supply side, risk management or capacity requirements lead to use of multiple suppliers, and on the demand side, the increase in product variety on the one hand, and the increase in product modularity and use of common components, on the other, makes component demands more intertwined than before. These can further depend on each other so that it is desirable to account for interdependencies in the decision models, too. Linear dependency models have been considered before (Tomlin and Wang 2005; Fu et al. 2010), but the non-linear models introduced in this Dissertation are novel.

Most planning systems for supply chain management are essentially deterministic (Van Landeghem and Vanmaele 2002). Yet, stochastic models such as those presented in this Dissertation have considerable potential for practical use. For example, Sodhi (2005) develops a stochastic model for tactical demand-supply planning process of a consumer electronics manufacturer to illustrate the benefits of risk-informed decision making. Also Paper [II] shows that in simple procurement settings, the optima under demand and supply uncertainties can be flat and that the risk levels can be decreased significantly by ordering either more or less than the optimum with the expense of losing only little of the optimal expected profit. This kind of profit-risk tradeoff analysis can be valuable in risk-informed decision making.

Many managerial decisions are ultimately based on intuition or experience, even if decision models and tools are available. Paper [II] shows how operational decision making under supply uncertainty is difficult even in simple cases such as ordering of one product for one sales period, i.e., in the Newsvendor setting. The situation can, however, be improved: the experiment showed that subjects can learn while playing the Newsvendor "game". Also other studies (Bolton and Katok 2008; Bostian et al. 2008; Bolton et al. 2012) have found that experience and task training can improve decisions. Moreover, the experimental results suggest that use of decision support systems such as spreadsheet simulation tools can significantly improve decision making.

4.2 Avenues for future research

The Dissertation opens up several research avenues related to supply management and risk assessment under demand and supply uncertainties. First, analytical models that consider multiple uncertainties can be developed further. While the Dissertation sheds some light on how, e.g., interdependent demand and supply uncertainties can impact procurement strategies, more research is needed for building a comprehensive picture of the impact of facing multiple, possibly interdependent uncertainties. In particular, cost uncertainties are relevant for many environments and they are likely to be linked to both demand and supply. Copula-functions seem especially useful for modeling multiple uncertainties and only few copula structures were employed in this Dissertation.

Second, empirical studies of multiple uncertainties would be valuable. Both market information and company specific data can be collected to answer questions such as: Are unexpected demands and sudden supply problems inter-related? How have unexpected, negative high-impact events impacted a particular supply chain? In addition to mapping the central phenomena with empirical data, also case studies that implement methodologies such as those presented in this Dissertation would be important for validating the potential benefits. In this respect, the elicitation of probabilities related to uncertain demand, supplier capability, and disruptional events is not easy in practice and would merit further research, too.

Third, behavioral aspects in supply management decisions provide a fertile ground for research. As an example, in the experiment of Paper [II], the subjects' behavior appears heterogeneous. A more structured study could help identify different types of behavior, instead of focusing on the average behavior. This would deepen the understanding of why different decision biases occur. Also some potential prescriptive research topics exist. First, it was observed in Paper [II] that the use of decision support systems can improve decisions; in-depth analysis in this area would be particularly valuable for practitioners. Second, key performance indicators (KPIs) are increasingly used to evaluate and reward employees based on their performance. Behavioral experiments would provide an excellent approach to the study of how exactly KPIs impact human behavior in different situations. Finally, it should be noted that mass experiments and statistical analyses are not the only approach experimental research. Gavirneni and Isen (2010) use verbal protocol analysis which is based on a dialogue between the experimenter and the subject, and can thus suggest findings that cannot be discovered from numerical mass experiment data.

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