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MANAGING RISK AT NEW VENTURES, ESTABLISHED FIRMS, AND IN THEIR SUPPLY CHAINS

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presented by

Ingmar Zanger

M.Eng., Cornell University
B.Sc., Technical University of Dresden

born on 25.08.1988 in Dresden
citizen of Germany

accepted on the recommendation of
Referee: **Prof. Dr. Stephan M. Wagner**
Co-Referee: **Prof. Dr. Roman Boutellier**

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... to my family.

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Ingmar Zanger
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Content

Abstract

Risk exposure is inherent within all businesses. Dealing with it is one of the major challenges in an increasingly complex and global economy. Managers of large firms devote most of their efforts to avoiding and mitigating risks to fulfil their targets. But also in newly started firms, entrepreneurs face multiple risks, resulting in high failure rates in their initial years.

Two out of four papers of this dissertation investigate internal risks of firms, which could contribute to complete failure of the firm. The first paper examines failure risks of established firms. In six data sets of important firm rankings and stock indices the paper observes truncated power-law distributions with similar parameters for firm survival times. The second paper builds on dynamic capability (DC) theory to shed light on how new venture firms develop and nurture supply chain (SC) capabilities to reduce their failure risk. More specifically, findings include upstream DCs for selecting suppliers, organizing procurement and outsourcing, but also downstream DCs for organizing distribution channels, transportation, and customer service.

The two other papers focus on external risks resulting from SC integration. Those risks must be considered as seriously as other business risks, since SCs are inherently vulnerable to risk. Recently, more severe SC incidents are reported both in the news and academic world. The number of negative events affecting SCs exceeds by far the memorable natural hazards like the Japanese tsunami in 2011 or hurricane Katrina in 2005 in the U.S. On the one hand, there is a lack of investigations concerning SC investment decisions when facing high levels of risk. Therefore, the third paper of this dissertation familiarizes the SC domain further to real option valuation as a methodology to quantify investment risks. On the other hand, materialized risks have a

negative impact on the operational performance of a SC (throughput, service level, lead times, etc.) and the SC risk literature is limited with regard to quantifying and modelling responses to SC risks. Thus the fourth paper answers recent calls for investigating the effectiveness of risk mitigation measures (redundant suppliers, increased inventory, etc.).

In sum, the dissertation arrived at three key messages for investigating and practicing risk management. First, risks are quantifiable by several methodologies: investment risks by real option valuation, failure risks by power-law distributions, and SC risks and their mitigation measures by adjacency matrices and clusters. Second, practice requires academia to adopt a holistic thinking in risk management, which has to offer frameworks linking and mitigating different kinds of risks, e.g., financial and operational risks. Third, two of the papers support the claim that the study of organizations requires a move from Gaussian to Paretian thinking (Paretian from Pareto distribution, which follows a power-law). Since especially risk managers care more about extreme values than average values, there is a need for a more accurate description of distribution tails than offered by stylized normal distributions.

Zusammenfassung

Die Gefährdung durch Risiken ist eine Gemeinsamkeit allen Wirtschaftens. Mit ihr in einer zunehmend komplexen und globalen Weltwirtschaft umzugehen, ist eine der grossen Herausforderungen für das Management. Manager grosser Firmen setzen bei der Realisierung ihrer Ziele die meiste Zeit für das Vermeiden und Abschwächen von Risiken ein. Doch auch in sehr jungen Unternehmen sehen sich deren Gründer hohen Risiken ausgesetzt, die schlussendlich zu geringen Überlebenswahrscheinlichkeiten in den Anfangsjahren führen.

Zwei der insgesamt vier in die Dissertation eingebundenen Paper untersuchen interne Risiken von Firmen, welche bis zum vollständigen Scheitern der Geschäftstätigkeit führen können. Das erste Paper bewertet das Ausfallrisiko grosser Firmen. In sechs Datensätzen basierend auf bedeutsamen Firmenrankings und Aktienmärkten konnten für das Ausfallrisiko von Firmen abgeschnittene Potenzfunktionen mit ähnlichen Parametern identifiziert und bestätigt werden. Das zweite Paper verdeutlicht mithilfe der Dynamic Capability (DC) Theorie, wie junge Firmen sich entwickeln und ihre Supply Chain (SC) Capabilities zum Überleben nutzen. Dabei konzentrieren sich die Ergebnisse Upstream auf DCs zur Auswahl von Zulieferern und der Organisation des Einkaufs und Outsourcings. Downstream werden DCs zur Organisation von Vertriebskanälen, des Transports und Kundenservices näher betrachtet.

Bei den zwei weiteren Paper stehen externe Risiken im Fokus, die sich aus der Integration von Firmen in SCs ergeben. Derartige Risiken müssen mindestens so ernst genommen werden wie andere Geschäftsrisiken, da SCs von Natur aus anfällig für Risiken sind. In letzter Zeit berichten sowohl Medien als auch wissenschaftliche

Untersuchungen über immer schwerwiegendere SC-Störungen. Die Anzahl an negativen Vorfällen, die SCs beeinträchtigen, übersteigt dabei bei weitem die in Erinnerung gebliebenen Naturgefährdungen wie z. B. den Tsunami 2011 in Japan oder den Hurrikan Katrina 2005 in den USA. Einerseits besteht ein Mangel an Untersuchungen über SC Investitionen bei hohem Risiko. Deshalb führt das dritte Paper der Dissertation die Real-Options-Bewertung als Methode der Risikoquantifizierung weiter in das SCM ein. Andererseits haben materialisierte Risiken negative Auswirkungen auf die operative Leistungsfähigkeit einer SC (Durchsatz, Servicelevel, Durchlaufzeiten etc.). Die Fachliteratur zeigt jedoch nur wenige Möglichkeiten zur Quantifizierung und Modellierung von risikoabschwächenden Massnahmen auf. Deshalb folgt das vierte Paper neuesten Aufrufen in der Literatur zur Untersuchung der Effektivität derartiger Gegenmassnahmen (redundante Zulieferer, erhöhter Lagerbestand etc.).

Insgesamt werden mit der Dissertation drei Kernergebnisse für die Untersuchung und praktische Ausübung eines Risikomanagements abgeleitet: Erstens sind Risiken mit Hilfe verschiedener Methoden quantifizierbar: Investitionsrisiken über Real-Options-Bewertung, Ausfallrisiken über Potenzfunktionen sowie SC-Risiken und deren Gegenmassnahmen über Adjazenzmatrizen und Cluster. Zweitens verlangt die Praxis von der Wissenschaft ein umfassendes Denken im Risikomanagement, welches verschiedene Risikoarten und deren Gegenmassnahmen verknüpfen kann, z. B. finanzielle und operative Risiken. Drittens unterstützen zwei der Paper die Forderung eines Wechsels von Gausscher Normalverteilungsbetrachtung auf die von Pareto vorgeschlagenen Potenzverteilungen. Da Manager im Risikobereich ihr Augenmerk mehr auf Extreme als auf Mittelwerte richten, werden Verteilungsfunktionen mit realistischerem Randverhalten als dem der idealisierten Normalverteilung benötigt.

Chapter I

Introduction

"A ship is always safe at the shore – but that is not what it is built for."
Albert Einstein

1.1. Motivation to investigate risk

Risk exposure is inherent within all businesses. Risk allows markets to work and profits to be made. One can imagine a risk-free world in which opportunities for profits would be exploited by all actors immediately and then disappear. In large firms, managers devote most of their efforts to avoiding and mitigating risks to fulfil their targets. In newly started firms, entrepreneurs face multiple risks, resulting in high failure rates in their initial years. To aid in understanding risks, several definitions have been developed within the literature. Building upon the well-recognized work of our research group on supply chain (SC) risk, *risk* is a negative consequence or loss that materializes with a certain probability (Wagner and Bode, 2006, 2008, 2009; Tang and Musa, 2011). The higher the loss and probability of a risk, the higher the negative impact on firm performance. A complete definition of risk considers the negative "downside" and positive "upside" consequences of risk (Michell, 1995). This two-sided risk definition, typically used for option pricing in the field of finance, will be adopted by only one of the papers included in this dissertation.

This dissertation investigates two major types of risks: first, SC risks, which are external to a focal firm spanning a SC, and second, internal risks of a focal firm. These internal risks could contribute to the complete failure of the focal firm. Thereby, *firm* *failure is* the disability to remain independent in a defined and tracked market (e.g., Mitchel, 1994; Baker and Kennedy, 2002; Sinha and Noble, 2008; Tsoukas, 2011). In two papers included in this dissertation the failure risks of established firms (paper A) and new ventures (paper B) are explored. The second risk type, external SC risks, must be considered by firms as seriously as other business risks (Elkins et al., 2005; Wagner and Bode, 2009). SCs are inherently vulnerable to risk. While SCs have become more complex and globalized during the past decades, more severe SC incidents are reported in the news and academic world. The number of negative events affecting SCs exceeds by far the memorable natural hazards like the Japanese tsunami or hurricane Katrina in the U.S. Several researchers have identified and discussed SC risks (e.g., Chopra and Sodhi, 2004; Wagner and Bode, 2008; Hopp, Iravani, and Liu, 2012). Chopra and Sodhi (2004), for example, characterized nine risk sources in SCs (disruptions, delays, systems, forecast, intellectual property, procurement, receivables, inventory, and capacity). Wagner and Bode (2008) divided sources of SC risk into five classes: (1) demand side; (2) supply side; (3) regulatory, legal and bureaucratic; (4) infrastructure; and (5) catastrophic.

Two main *impacts of SC risks* can be identified. First, Hendricks and Sighal (2005) confirmed a negative impact on *financial performance* observing stock prices after risk incidents. As Hult et al. (2010, p. 435) point out, there is still "a lack of investigations that center on SC investment decisions when facing high levels of risk." SC risks affect investment payoffs and need to be combined analytically for decision making. Therefore, paper C of the dissertation familiarizes the SC domain further to the real option valuation (ROV) as a methodology to quantify investment risks. Second, materialized risks have a negative *impact* on the *operational performance* of a SC (throughput, service level, lead times, etc.) (Wagner and Bode, 2008). SC risk literature is still limited with regard to quantifying and modelling responses to SC risks. Recently, Talluri et al. (2013) call for investigating the effectiveness of risk mitigation measures (redundant suppliers, increased inventory, etc.) (Chopra and Sodhi, 2004; Sodhi and Tang, 2012). Hence, paper D aims to quantify the impact of commonly practiced risk mitigation measures. All four papers provide empirical evidence to address several of the most current issues in the field of supply chain management (SCM) and strategic management in a multidisciplinary and multi-method research approach (Sanders and Wagner, 2011).

1.2. Research objectives

1.2.1. Failure risk of established firms

Exhaustive research efforts have been directed to address the failure of established firms and new ventures. Most researchers have confirmed factors that influence firm failure. We summarize those factors into four clusters: *firm-specific* (Carroll et al., 1996; Agarwal and Gort, 2002), *industry-specific* (Audretsch and Mahmood, 1995; Audretsch, Houweling, and Thurik, 2000), *financial* (Guariglia, 2008; Tsoukas, 2011), and *innovation-related* (Boutellier, Gassmann and Von Zedtwitz, 2008; Buddelmeyer et al., 2010; Wagner and Cockburn, 2010; Wang et al., 2013). First, *firm-specific* or *structural factors*, such as firm age, were found to have a positive influence, described as "liability of newness" by Stinchcombe (1965) and more recently confirmed by Agarwal and Gort (2002). Some researchers tried to capture a similar kind of structural starting bonus by using prior experience (Brüderl et al., 1992) or parent firm relationships as failure factors (Carroll et al., 1996). Second, *financial indicators* are included directly or as control variables in all studies on firm failure due to the quality and availability of reporting data. Proxies for the size of the firm range from revenue, profit, or headcount to more sophisticated ones like leverage, collateral, or initial endowment (e.g., Agarwal and Gort, 2002). Third, an active stream of research examines *innovation-related factors*. In general, high rates of innovation have been linked to higher survival rates. Due to the absence of explicit accounting standards for innovation, a variety of proxies have been used and proven significant. Early work focused on inputs of the innovation process as (accumulated) R&D expenditures (Segarra and Callejon, 2002) or quality and newness of applied manufacturing technologies (Colombo and Delmastro, 2000; Doms, Dunne, and Roberts, 1995), whereas later, a variety of outputs was used as proxies: patents, trademarks, registered designs, and grants (Wagner and Cockburn, 2010). The fourth group includes *industry-specific factors*, which have been largely studied since the fundamental work of Audretsch (1995): industry growth, concentration, firm-level heterogeneity, size disadvantage, and capital intensity in an industry relate already known structural (size) and financial factors (revenue, initial endowment) to a firm's competitive peer group. Innovation-related factors at the industry level are, for example, the technological regime of an industry (Audretsch, 1995).

These factors were empirically verified by a large number of studies using different types of multivariate regression analyses (e. g. Bothner et al., 2011). The heterogeneity of used data sets and methods does not allow for either the sorting of factors by importance or combining them into a manageable set that drives firm failure. This not yet consistent field of individually validated factors for firm failure prevents the derivation of explicit management strategies. This dissertation will contribute to this literature by deepening the understanding of the interplay of factors at the global scale, in large sample sizes, and across time spans of over a century.

Obviously, the identification of influential factors alone cannot explain the complex phenomenon of firm turnover at an aggregated level. Whereas management literature focused on single firm's success and the interplay within small groups, there is little research regarding how multiple firms affect each other's survival. Our research focuses on very prestigious firm samples with clear status order, entry, and exit criteria. Therefore, we derived data sets from three firm rankings (*Fortune 500, Forbes Global 2000, Financial Times Global 500*) and three stock indices (*Dow Jones Industrial Average 30, NIKKEI 225, S&P 500*) as an empirical basis. In line with several authors' definitions, we recognize *firm failure* as the disability to remain independent in a defined and tracked market (e.g., Baker and Kennedy, 2002; Mitchel, 1994; Sinha and Noble, 2008; Tsoukas, 2011). Since *status* arises from a hierarchical order among actors

(Podolny, 2005), we use the position in firm rankings and the exclusiveness of being listed on a stock index as proxies for *firm status* (Bothner et al., 2011; Bothner et al., 2014; Merton, 1968).

As a starting point, we tested whether there were status effects in the data. This would indicate advantages for already successful firms or the preservation of existing differences. The earlier-mentioned high firm turnover rates can be a possible outcome of such status effects. In the first part, we aimed to identify statistical properties for such a biased survival behavior. In the second part, we extended the analysis toward growth dynamics. Longitudinal ranking data allowed for differentiation between successful firms moving up in firm rankings and those squeezed out across the years. Deriving distributions for these movements could improve understanding of up- and downward mobility in competitive markets. Considering the above-mentioned aspects, **paper A** examines the following **three research questions**:

- Does high firm status decrease the likelihood of firm failure?
- Which distributions describe the failure behavior of firms in stock indices and firm rankings?
- Which distributions describe firms' growth dynamics?

1.2.2. SC risks of new ventures

New and fast-growing ventures are a key factor in job creation, market innovation, and economic growth in many industrialized countries (Hisrich, Langan-Fox, and Grant, 2007), despite their high probability of failure (Shepherd et al., 2000; Tatikonda et al., 2013). Little is known about how successful entrepreneurs manage to start from a point without any operations, suppliers, or routines to deliver innovative and competitively priced products a few years later. What is known is that SCM is a strategic core competence creating competitive advantage in established firms (e.g., Hsu et al., 2011). Therefore, this paper will aim to answer the call for research at the nexus of SCM and entrepreneurship to investigate the external operations of new ventures (Arend and Wisner, 2005; Goodale et al., 2011; Kickul et al., 2011; Linderman and Chandrasekaran, 2010; Tatikonda et al., 2013). This is based on the efforts scholars put into exploring why new ventures evolve (e.g., Gartner, 1985), how they grow (e.g., Greiner, 1998; McKelvie and Wiklund, 2010), how best to allocate resources in different stages (e.g., Levesque, Joglekar and Davies, 2012; Tatikonda et al., 2013), and numerous identified success factors (e.g., Duchesnau and Gartner, 1990; Song et al., 2008). Thereby, a new venture is a firm active in the creation of goods or services that still suffers from a liability of smallness and newness (generally younger than 6 to 8 years) that either was founded by an individual or by a company as long as the new firm is not given key resources by a mother company (Robinson, 1999; Tatikonda et al., 2013; Zahra, Ireland, and Hitt, 2000).

A rich stream of literature on dynamic capabilities (DC) holds promising answers regarding how new ventures successfully expand, change, and reconfigure their initial resource base into an established firm (Zahra et al., 2006). Both the development of DCs and DCs in general require more empirical evidence after a long theoretical discourse initiated by the seminal paper of Teece, Pisano, and Shuen, (1997) (e.g., Helfat and Peteraf, 2009; Schilke, 2014). Our work contributes to a consolidation of the literature by capitalizing on previous research; the main dimensions of DCs are reviewed from the literature and explored in real-world case studies. This should help to clear the observed “proliferation of concepts and relationships” in DC research (Barreto, 2010, p. 277; Stadler et al., 2013). The majority of DC research focuses on established firms, ignoring the stark differences of new ventures regarding survival, legitimacy, and capitalization of innovations (Sapienza et al., 2006; Zahara, Sapienza, and Davidsson, 2006). Moreover, new ventures are ideal for understanding the role of DCs, since small firms are less complex and allow their managers or founders a more detailed overview. Recently, Tatikonda et al. (2013) empirically confirmed the positive influence of DCs on new venture survival probabilities based on the archival data of 812 manufacturing firms. Tatikonda et al. (2013, p. 1412) point toward promising questions regarding the evolving SCs of new ventures by asking, "How does a new firm initiate supply and distribution networks? How best can new ventures leverage SC partners' resources and capabilities […] at different points in the firm's evolution?" This research should include inter-organizational partnerships (Terjesen et al., 2012) as well as links to research institutions for acquiring expert knowledge. Moreover, resource scarcity per se should force new ventures to get access to external resources of partners by outsourcing, purchasing, and leveraging distribution channels (Zahra et al., 2006). Therefore, **paper B** studies DCs in the field of entrepreneurship with the following **two research questions**:

- Which dimensions of DCs allow new ventures to build up their external operations (upstream, downstream)?
- How does the development of DCs itself take place?

Thereby, external operations include on the upstream-side make-or-buy decisions, supplier selection, and procurement, and on the downstream-side transportation or physical delivery of the products, exploration of sales channels, and customer service (Mentzer, Stank, and Esper, 2008; Tatikonda et al., 2013).

1.2.3. Risks of SC projects

Recent literature has made real option valuation (ROV) the most popular solution for strategic decision making and projects characterized by high levels of uncertainty (e.g., Driouchi and Bennett, 2011; Liang, Wang, and Gao, 2012; Wallace and Choi, 2011). Projects are often multi-staged decisions, which makes them, according to modern financial theory, "options – 'real' options, as opposed to financial options – in which managers have the right but not the obligation to invest" (Copeland and Tufano, 2004, p. 90). This flexibility can be used to model managerial decision flexibility to defer, abandon, expand, stage, or contract capital investments. Hult et al. (2010, p. 435) have recommended ROV as "an appealing theoretical lens" for SC risk uncertainty. Investigating SC investment decisions with the help of real options would fit into a promising stream of literature on successful applications of ROV in the field of SCM (Dobson, Lederer, and Robinson, 2012; Kodukula and Papudesu, 2006; Su et al., 2009; Tiwana, Keil, and Fichman, 2006; Tiwana et al., 2007). In addition to the application of ROV, this paper proposes a solution that considers the resource constraints that each firm faces when improving its SC. Therefore, **paper C** focuses on two **research questions**:

- How can SC projects be evaluated as real options with their cost, time structure, and related risks?
- How can a portfolio of SC projects be selected and scheduled with considerations of the risk, time, cost, and criticality of all projects subject to the constraints of the firm?

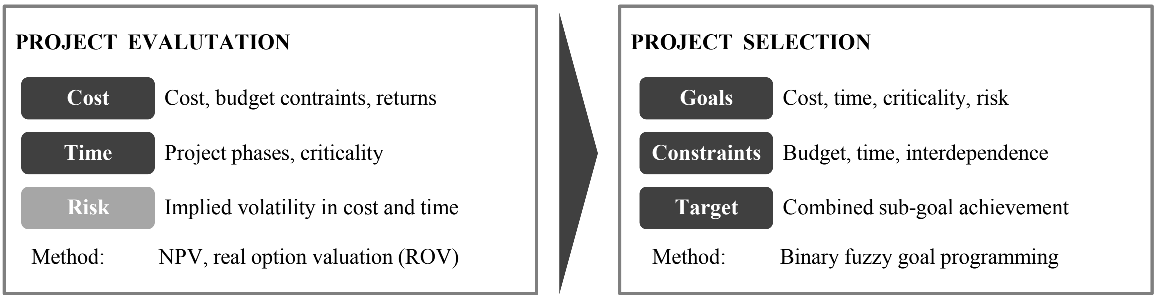

Figure 1: Introducing Real Option Valuation (ROV) in SCM

1.2.4. Mitigation of SC risks

Interconnected SCs evolve and firms' non-core operations are traded for lower costs and greater responsiveness as offered by external suppliers, contract manufacturers, and third-party logistics providers (Zsidisin, Ragatz, and Melnyk, 2005). These strategies increase the complexity mainly due to a manifold separation of production processes and an increased number of supplier interfaces (Tang and Musa, 2011; Wagner and Bode, 2009). Furthermore, advancements in information technology and a nearly ubiquitous transportation infrastructure enable firms to source pre-products from low-cost countries. Such global extension and adding of even more nodes in the supply network have increased the complexity of SCs (Hendricks and Singhal, 2005). In combination with the significant influence of procurement on firm performance, firms are exposed to more severe risks.

Several different kinds of risks have been identified and classified in a mature stream of literature on SC risk (e.g., Pettit, Croxton, and Fiksel, 2013; Wagner and Bode, 2006). In their review, Tang and Musa (2011) take three main categories to classify risks: material, information, and financial flow risks. They provide a picture of how specific SC risks have been investigated qualitatively and quantitatively and reveal that only a small fraction of studies is quantitative. Similarly, Rao and Goldsby (2009) and Sodhi, Son, and Tang (2012) found that most of the articles are considered to be either qualitative or conceptual. For quantitative descriptions of SC risks, one can find the following methodological approaches: optimization, multivariate analysis, stochastic programming, simulation, and real options (Tang and Musa, 2011). Since risks are heterogeneous, many specific models exist. This presents a certain difficulty to find a uniform or standardized method for describing SC risks.

Starting points for linking risks along the SC can be found in the work on risk correlations (Han, and Huang 2007; Wallace, Keil, and Rai 2004) or copula functions (Babich, Burnetas, and Ritchken 2007; Wagner, Bode, and Koziol 2009). A SC model integrating all risks and their connectivity would allow one to build more realistic risk models of SCs and investigate their dynamic behavior. Therefore, the first research questions of **paper D** focuses on:

- How much are SC risks interconnected (risk connectivity)?

Moreover, this paper aims to quantify the impact of commonly practiced risk mitigation measures (e.g., redundant suppliers, increased inventory) on frequently occurring SC risks. SC risk literature is still limited with regard to modelling responses to SC risks. Recently, Talluri et al. (2013) called for investigating especially the effectiveness of risk mitigation measures. Therefore, the paper's second research questions focuses on:

- How does risk connectivity determine the success of risk mitigation in a SC?

1.3. Structure of the dissertation

The doctoral thesis consists of four papers (A-D). Each paper addresses specific gaps in the SC literature with regard to content or methodology, as outlined above. The first two papers have a more strict focus on the failure and growth of OEMs spanning a SC. Whereas paper A uses large archival data sets (quantitative), while paper B analyzes almost 20 case study firms intensely (qualitative). The other two papers (C-D) try to capture risk in the entire SC. Paper C is more quantitative in nature, trying to find an optimal scheduling solution for projects with the help of real options. Paper D models risk clusters and risk reduction in manufacturing SCs. Figure 2 links the four papers to a typical SC setup.

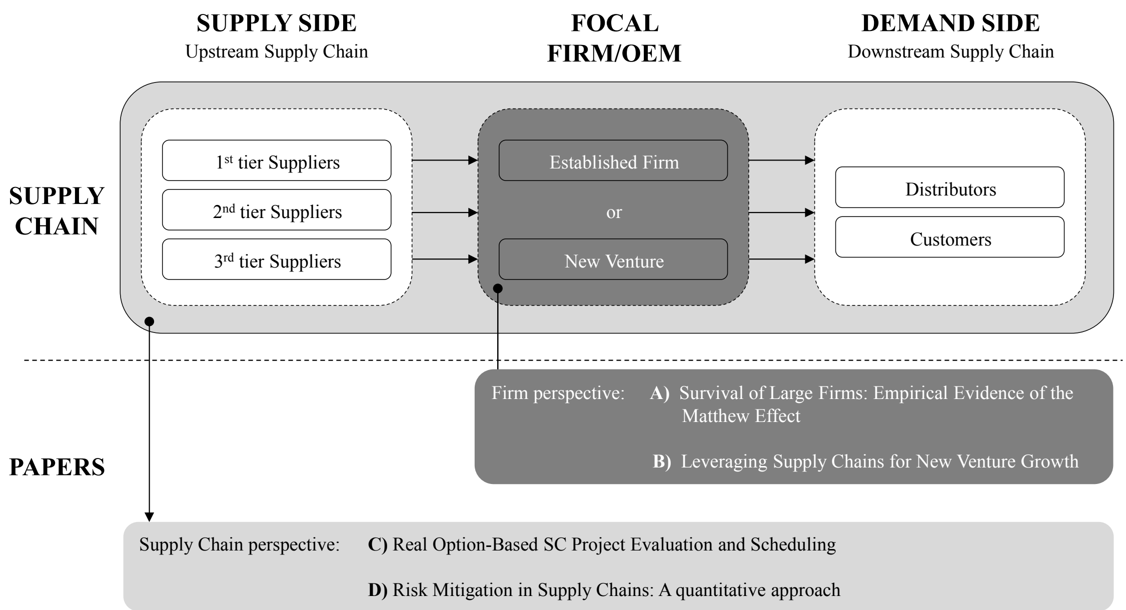

Figure 2: Allocation of papers in the SC

Table 1 comprises the meta-level characteristics of all four papers of the dissertation project. Each of them addresses a specific gap in the literature, applies a unique methodology following a multi-method approach (Sanders and Wagner, 2011), and draws on a different data set.

Table 1: Overview and status of the paper projects

	Paper A (Chapter II)	**Paper B (Chapter III)**	**Paper C (Chapter IV)**	**Paper D (Chapter V)**
Title	Survival of Large Firms: Empirical Evidence of the Matthew Effect	Leveraging Supply Chains for New Venture Growth	Real Option-Based SC Project Evaluation and Scheduling	Risk Mitigation in Supply Chains: A Quantitative Approach
Authors	Zanger, Ingmar; Wagner, Stephan; Padhi, Sidhartha	Zanger, Ingmar; Wagner, Stephan	Wagner, Stephan; Padhi, Sidhartha; Zanger, Ingmar	Padhi, Sidhartha; Zanger, Ingmar; Wagner, Stephan
Core of investigation	Probability distributions for large OEM failure	Dimensions of dynamic capabilities used in setting up new ventures' SC	Impact of (SC) risk dimension in project scheduling	Impact of risk mitigation measures on a stylized SC model
Theoretical foundation	Matthew effect	Dynamic capabilities, new venture growth	Real option valuation (ROV), SC risk, project scheduling	SC risk
Methodo-logical approach	Quantitative: power-laws, Poisson	Qualitative: case studies	Real options, fuzzy goal programming	Adjacency matrix, clustering, power-law, simulation
Data/ Research context	Six archival data sets (e.g., Fortune 500, Dow Jones, S&P500)	18 new ventures from Switzerland and China, interviews, archival data	21 SC projects from Indian case study firm	12 Swiss purchasing expert interviews, simulation
Episte-mological stage	Existing theory is tested on novel setups and data	Theory development and testing	Two existing methods are combined into the new framework; theory testing	Existing theories and statistical methods are used for theory development
Major contributions	Truncated power-law distributions with similar parameters for survival times in all six data sets. This confirms the Matthew effect generally observed in social systems.	Four dimensions of DCs are evident in new venture growth (Sense, Integrate, Develop, Reconfigure). Detailed characterization of DCs relevant from an SCM perspective.	Introduction of ROV to SC project scheduling as a flexible method to quantify risks. Scheduling performance improved in comparison to methods ignoring risk.	Simulation of the impact of mitigation measures in the procurement area on risks. Results show how varying connectivity of risks leads to bottlenecks for risk reduction.
Status publication	Under review	Working paper, ready for submission	Published in International Journal of Production Research Vol. 52 (2014), No. 12, pp. 3725-3743	Under review

1.4. Selected research findings of the dissertation

1.4.1. Paper A Survival of Large Firms: Empirical Evidence of the Matthew Effect

Authors: Zanger, Ingmar; Wagner, Stephan M.; Padhi, Sidhartha S.

Even large firms face high turnover. For example, 90% of the 500 largest US firms disappeared due to marginalization, merger and acquisition (M&A), or bankruptcy from 1955 to 2011. This study aims to identify a pattern characterizing firm survival times and to provide a stochastic model to explain the pattern. Therefore, we derived data sets from three important firm rankings (Fortune 500, Forbes Global 2000, Financial Times Global 500) and three stock indices (Dow Jones Industrial Average 30, NIKKEI 225, S&P 500). We observed truncated power-law distributions with similar parameters for survival times in all six data sets. This is in line with existing work (Cook and Ormerod, 2003; Fujiwara, 2004; Hong et al., 2007; Podobnik et al., 2010), and we provide empirical evidence that both firm survival times and growth dynamics fall into power-law cumulative distribution functions (CDFs) and interpret the related power-law coefficients. Similar findings in the econophysics literature have shown that firm size *cdfs* in several countries follow power-laws (Axtell, 2001; Luttmer, 2007, 2011; Sutton, 1997). These and numerous discovered power-laws in the behavior of other man-made phenomena could not yet be explained by a uniform theory or generative mechanism (Andriani and McKelvey, 2009; Stumpf and Porter, 2012). Following the current research (Bothner et al., 2011; Bothner et al., 2014), we tested the status to explain firm survival and failure, which answers calls in the literature for more empirical evidence on the role of status on success (Azoulay, Stuart, and Wang, 2014), and yields a better understanding of interaction and influence among firms. We applied the concepts of step-wise, self-fueling growth and random hazards used in the field of status research (Azoulay et al., 2014; Bothner et al., 2011; Petersen et al., 2011) to a stochastic Poisson model to predict the observed behavior. Our proof of power-law distributions in firm survival times confirmed the Matthew or rich-get-richer effect generally observed in social systems.

From a managerial policy perspective, the shift from Gaussian to power-law distributions means a focus on rare events, which affect most managers more than averages (Andriani and McKelvey, 2009). In particular, our results can help to better quantify firms' dropout risks. This is in the interest of both investors and the public. If firms reach for the top measured, for example, by revenue, their exposure to failure remains unexpectedly high: Turnover rates are of large single-digit percentages, which is in line with other empirical research findings of firm survival times. Typical firm survival and failure is characterized by lots of firms having short life spans and very few having extraordinarily long life spans. Positive effects are opportunities to enter the existing and growing markets. On the negative side, even the largest firms of their time tend to systematically fade away or, in the best case, disappear by M&A. Finally, in addition to these managerial implications, our work develops future alleys of research in the field of firm failure and power-laws.

1.4.2. Paper Project B Leveraging Supply Chains for New Venture Growth

Authors: Zanger, Ingmar; Wagner, Stephan M.

Fast-growing new ventures are a key factor for job creation and innovation but are little understood from a SCM perspective. Since entrepreneurs operate under permanent resource scarcity, capitalizing on a powerful SC to source and sell across several countries is crucial for success. Addressing this research gap with dynamic capability (DC) theory, we shed light on how DCs are developed and add to the lack of empirical evidence in the field of DCs. Therefore, we conducted case studies with 18 manufacturing new ventures from Switzerland and China. The main results contain four dimensions of DCs evident in new venture growth (Sense, Integrate, Develop, Reconfigure). The provided typology of DC dimensions encourages a consolidation of research fronts and might be applicable to established firms as well.

Furthermore, we derived propositions for future research concerning the development and path dependence of DCs. From a practitioner perspective, the case studies offer directly applicable best practices of highly successful firms, which help in prioritizing and benchmarking own operations. More specifically, findings include upstream DCs for selecting suppliers, organizing procurement, and outsourcing. Downstream DCs organize distribution channels, transportation, and customer service.

The results presented in this research impact the SCM/OM field in two ways. First, the scope for investigating DCs is further broadened to new ventures instead of only established firms. New ventures' high rate of change in the initial years and the path dependence of learning experiences further the understanding of the development of DCs much more effectively than studying merely the outcome at established firms, especially since learning results from intuitive actions and outcomes, thus subsequently forming routines and capabilities (Zahra et al., 2006). Second, DCs are not just crucial for the transition from resource scarcity to an established resource base, but with increasing firm age, the majority of resource-based changes result from DCs. We found a higher relevance of the development and reconfiguration of DCs in later life phases of new ventures, indicating that internal efforts like improvement, innovation, and change management are most important for upgrading the resource base of established firms compared to external efforts (e.g., R&D-partners, suppliers, distributors).

Besides giving a starting point for theory building to explain operations of new ventures, our results are beneficial for founders of new ventures and managers of corporate ventures in at least two ways. First, the case studies offer patterns of directly applicable DCs, which are best-practice capabilities of highly successful manufacturing-based ventures from Switzerland and China. As firm environments and starting positions are manifold, these patterns mainly help to prioritize professionalization efforts and benchmark the own development against competitors and across industries. Second, it provides a systematic approach for explaining and communicating the build-up of operations. For example, life phases help to structure the rapid expansion and shift foci to most likely upcoming operational issues like product derivatives, supplier contract renegotiation, or ERP-system preparation in a later life phase of a new venture. In contrast, new ventures with a low level of outsourcing should evaluate steps to free internal resources, like working capital or employees, by integrating external resources of R&D partners, suppliers, and distributors.

1.4.3. Paper Project C Real Option-Based SC Project Evaluation and Scheduling

Authors: Wagner, Stephan M.; Padhi, Sidhartha S.; Zanger, Ingmar

SC departments spend their time managing numerous projects that will improve and maintain their SC. Recent literature has most frequently described the content of these projects and their scheduling but neglected to include risk and uncertainty in the expected cost, profits, and time durations of these projects. In this article, we have introduced real option valuation (ROV) to SC project scheduling as a flexible method to quantify those risks. Our proposed two-step framework links ROV to all relevant constraints of a multi-project setup by binary fuzzy goal programming. We applied the framework to real-life case study data of 21 projects facing numerous risks and resource constraints. The results show how scheduling performance improved in comparison to methods ignoring risk and uncertainty (e.g., net present value-based scheduling (NPV)).

Combining ROV with a binary fuzzy goal programming algorithm contributes to the literature by linking two concepts that have been intensively discussed in finance and operations management within the field of SCM. Hence, we present another case in which a multi-disciplinary and multi-method approach is better suited to meet the contemporary challenges in SC practice (Sanders and Wagner, 2011). For validation, we conducted hypothesis tests and sensitivity analysis.

On a more practical level, we reveal a complexity reduction of decision making by introducing a step-wise method for scheduling SC projects. The method captures the managerial flexibility and uncertainty for each project and lifts optimization to the level of the entire SC project program by making each project analytically comparable across the four dimensions of risk, time, cost, and criticality (Boutellier and Gassmann, 2001). With the case study data, we demonstrate how a large set of project decisions in a SC is derived by following the method proposed.

1.4.4. Paper Project D Risk Mitigation in Supply Chains: A Quantitative Approach

Authors: Padhi, Sidhartha S.; Zanger, Ingmar; Wagner, Stephan M.

Financially distressed suppliers are more likely to cause stock-outs and deliver bad quality. From similar observations, we know that SC risks are connected. Quantifying the direction and magnitude of risk connectivity can help in reducing the impact of failures and hence improve the overall performance of the SC operations. Therefore, the paper studies a simple model for the evolution of risk in SCs. As a first step, all relevant risks are captured by Adjacency Matrices (AM) for 12 manufacturing SCs. In the second step, we simulate the impact of mitigation measures in the procurement area on these risks. The results show how varying the connectivity of risks leads to bottlenecks for risk reduction. Based on the developed model, reducing the connectivity of potential risks in a SC at the initial design and redesign would decrease risk most effectively. From a statistical perspective, we found that the rates of risk reduction follow power-law functions, also known as learning curves or progress functions. The approach can be used for modelling risk and evaluating mitigation measures in corporate practice.

We developed a model for the evolution of risk in SCs. The simulation analysis makes a unique contribution by linking literature on risk and risk measures into one numerical model. In contrast to previous work, we also quantified connectivity among risks. If risk measures are used on a trial-and-error basis, one can observe risk reduction curves following a power-law behavior with exponent $\alpha = 1/(\gamma[d, d^*])$, where d and d^* are fixed, and variable connectivity and γ describe the effort of reducing risk. The applied tools, adjacency matrix for procurement risks and the risk-measure interaction matrix, answer calls for simple methods and decision-making techniques for corporate practice (Ivanov, Sokolov, and Pavlov, 2013).

From a practitioner's perspective, current risk management literature creates huge potential for developing applicable models for decision making. Since risks in practice are rather manifold, simultaneously hard to assess, and hidden along the entire SC, it is almost impossible to fit them into specific risk models. Managers face multiple risks depending on their viewpoint: A financially distressed supplier holds the financial risk of getting bankrupt, but at the same time, it is also likely to cause stock-outs or deliver bad quality. Similarly, natural disasters can affect the operations of a firm itself, but also its suppliers and third-party logistics providers. In the second case, the impact and required recovery time will be much higher than forecasted for the firm itself. Both examples reveal the need for models to take the connectivity of risks into account. Such a perspective has to go beyond adding losses, delays, or similar performance indicators for each risk.

1.5. Future research directions

Since each of the four papers addresses a specific gap in the literature, the discovered alleys of future research vary strongly. Therefore, it makes to present them separately in the following:

Paper A: Future research might analyze the group of survivors in each of the data sets for commonalities. These firms, about 50 in the Fortune 500, hold the chance of recognizing managerial patterns of success due to a change in the level of analysis. Furthermore, a sophisticated model that incorporates endogenous termination factors (e.g., termination due to a sudden decrease in revenue below a given cutoff value for appearing in a ranking) is more difficult to model, which we leave as an open problem.

Paper B: In addition to characterizing the nature of DCs, more insights are required regarding how to improve and actively manage them in practice, especially since antecedents and factors influencing the development of DCs are hardly known yet. Although our research hints at the founders as the location of such factors, future studies could explicitly target the origin of DCs. Finally, service-based new ventures and their operations are promising fields for research on DCs (Tatikonda et al., 2013).

Paper C: The research could be extended by investigating issues related to the scheduling of multiple SC projects under a multiple sourcing environment, which is a NP hard problem and could be solved through genetic algorithm (GA) methods. Another area of research could include increasing the dimensions of the problem to more SC projects, and this could be addressed using GA methods as well.

Paper D: Whereas our study focused on the risk of the upstream part of SCs, an implementation of the framework should include the downstream SC as well (Ivanov, Sokolov, and Pavlov, 2013). Another extension lies in the specification of sub-risk factors and related sub-measures that detail the identified ones in the literature survey and experts' study. Such specialized risks and measures may be necessary for different industries, business units, and even products (Pettit, Croxton, and Fiksel, 2013).

1.6. Conclusions

In sum, the dissertation arrived at three key messages for investigating and practicing risk management. First, risks are quantifiable by several methodologies: investment risks by real option valuation, failure risks by power-law distributions, and SC risks and their mitigation measures by adjacency matrices and clusters. This proves the taken multi-method approach as fruitful in the field of SCM. Second, practice requires academia to adopt a holistic thinking in risk management, which offers frameworks linking and mitigating of different kinds of risks; e.g., financial and operational risks. Mere identification of risk factors is too far away from implementation from a managerial perspective. Third, two of the papers support the claim by Andriani and McKelvey (2009, p. 1053) that the study of organizations requires a move "from Gaussian to Paretian thinking" (Paretian from Pareto distribution, which follows a power-law). In short, to managers extremes matter more than averages. In organization science, researchers are currently leaving their linear models to investigate scalable ones to be able to describe non-linear organizational behaviors. This has consequences for the purely normal distribution-driven assumptions and models we apply in our research. In the case of much fatter and longer distribution tails of power-law distributions compared to normal distributions, for example, confidence intervals are no longer normally distributed but in most cases are calculated as such, leading to false conclusions and limited advice to practitioners.

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Chapter II

Survival of Large Firms: Empirical Evidence of the Matthew Effect

Abstract

This study aims to identify a pattern characterizing firm survival times and to provide a stochastic model to explain the pattern. In six data sets of three important firm rankings and three stock indices. We observed truncated power-law distributions with similar parameters for survival times. These matched the predictions of a stochastic Poisson model, which we adapted to predict the influence of an existing status order on the future success of competing firms. Our proof confirmed the Matthew or the rich-get-richer effect generally observed in social systems. The shift from Gaussian to power-law distributions means a focus on rare events, which affect most managers more than averages. In particular, our results help to better quantify firms' dropout risks.

Keywords: Firm survival; Power-law; Stochastic modeling; Matthew effect; Status

2.1. Introduction

Due to the rapid and dramatic changes in the global landscape of firms in the last decades of the 20th century (DiMaggio, 2001), and the further acceleration of change at the beginning of the 21st century, it seems easier for the largest, leading firms to defend their top positions against smaller competitors than vice versa. Their higher status will attract the attention of investors and future employees and facilitate growth activities like mergers and acquisitions (M&As) (Shen et al., 2014). This argument of stronger growth for holders of higher status was introduced by Merton (1968) in the sociology of science. Initial status differences of researchers result in a cumulative advantage for the already successful ones. In an economic context, status differences are seen as a promising concept to explain inequalities among firms (Azoulay, Stuart and Wang, 2014; Bothner et al., 2014).

The annually published Fortune 500 ranking lists the largest U.S. firms (Fortune 500, 2013). A turnover rate of 90 percent within these firms from 1955 to 2011 shows that being at the top is no guarantee of future success. On closer examination, firms within the ranking achieved an average annual revenue growth of 8.1 percent. In the same time period, the U.S. gross domestic product (GDP) grew by 6.6 percent per year from US$415 billion in 1955 to US$15,075 billion in 2011 (U.S. GDP, 2013). How could leading U.S. firms, despite a generally growing U.S. market and growing revenues, be almost completely replaced? Of course, most firms at the top deal with the survival of their achieved status rather than immediate bankruptcy. Apparently, turnover rates in the U.S. top firm segment show a gap between prevailing management strategies and challenges in firms' markets. Similarly, existing management principles were challenged when top firms have been barely able to manage the economic downturn during the financial crisis of 2009. More than ever, calls for deeper insight into competition and survival strategies were raised (e.g., Geroski et al., 2010).

Exhaustive research efforts have been directed to the survival of established firms and new ventures. Most researchers have confirmed various factors influencing firm survival. We summarized those factors into four clusters: *firm-specific* (Agarwal and Gort, 2002; Carroll et al., 1996), *industry-specific* (Audretsch, 1995; Audretsch et al., 2000), *financial* (Cattani et al. 2008; Guariglia, 2008;), and *innovation-related* (Buddelmeyer et al., 2010; Wagner and Cockburn, 2010; Wang et al., 2013). Obviously, the identification of influential factors alone cannot explain the complex phenomenon of firm turnover at an aggregated level. Whereas the management literature has focused on explaining a single firm's success and the interplay within small groups, there is little research into how multiple firms affect each other's survival. Our research focuses on very prestigious firm samples with clear status order, entry and exit criteria. Therefore, we derived data sets from three firm rankings (*Fortune 500, Forbes Global 2000, Financial Times Global 500*) and three stock indices (*Dow Jones Industrial Average 30, NIKKEI 225, S&P 500*) serving as an empirical basis. In line with several authors' definitions of firm survival, we recognize *firm survival* as the ability to remain independent in a defined and tracked market (e.g., Baker and Kennedy, 2002; Mitchell, 1994; Sinha and Noble, 2008; Tsoukas, 2011). Since *status* arises from a hierarchical order among actors (Podolny, 2005), we use the position in firm rankings and the exclusiveness of being listed on a stock index as proxies for *firm status* (Bothner et al., 2011, 2014; Merton, 1968).

As a starting point, we tested whether there were status effects in the data. This could mean advantages for already successful firms or the preservation of existing differences. The earlier mentioned high firm turnover rates can be a possible outcome of such status effects. In the first part, we aimed to identify statistical properties for such a biased survival behavior. In the second part, we extended the analysis toward growth dynamics. Longitudinal ranking data allowed for differentiation between successful firms moving up in firm rankings and those squeezed out across the years. Deriving distributions for these movements could improve understanding of up- and downward mobility in competitive markets. Considering the above mentioned aspects, we examined three research questions:

1. Does high firm status increase the likelihood of firm survival?
2. Which distributions describe the survival behavior of firms in stock indices and firm rankings?
3. Which distributions describe the growth dynamics of firms in firm rankings?

In line with existing work (Cook and Ormerod, 2003; Fujiwara, 2004; Hong et al., 2007; Podobnik et al., 2010), we provide empirical evidence that both firm survival times and growth dynamics fall into power-law cumulative distribution functions (cdfs) and interpret the related power-law coefficients. Therefore, we examined relevant U.S., Japanese, and global data sets across time spans of up to 100 years. Similar findings in the econophysics literature have shown that firm size cdfs in several countries follow power-laws (Axtell, 2001; Luttmer, 2007, 2011; Sutton, 1997). These and numerous discovered power-laws in the behavior of other man-made phenomena could not yet be explained by a uniform theory or generative mechanism (Andriani and McKelvey, 2009; Stumpf and Porter, 2012). Following current research (Bothner et al., 2011, 2014), we tested status to explain firm survival, which answers calls in the literature for more empirical evidence on the role of status on success (Azoulay et al., 2014), and yields a better understanding of interaction and influence among firms. In the methodology section, we apply the concepts of step-wise, self-fueling growth and random hazards used in the field of status research (Azoulay et al., 2014; Bothner et al., 2011; Petersen et al., 2011) to a stochastic Poisson model to make the observed behavior predictable. Finally, in addition to managerial implications, our work develops future alleys of research in the field of firm survival and power-laws.

2.2. Literature review

2.2.1. Power-law distributions for firm size and related evidence

To understand the survival behavior of firms, we looked at how complex systems' behavior has been described by stochastic models. Research on firm populations and other social systems suggests the need to especially consider power-laws and similar fat-tailed distributions. Across many scientific disciplines, power-law distributions ($P(x) \sim x^{-\alpha}$) describe natural and man-made phenomena. For example, power-laws can be found in the heights of people (Newman, 2005), basketball and baseball in sports (Petersen et al., 2011), received citations of scientific papers and researchers (Petersen et al., 2011), website hits (Adamic and Huberman, 2000), family names in the U.S. (Newman, 2005), city sizes (Zipf, 1949), wealth of people (Pareto, 1964), and customer demand (Brabazon and MacCarthy, 2012), as well as firm size (Axtell, 2001; Luttmer, 2007, 2011; Sutton, 1997).

The stream of literature focusing on power-laws for firm size distributions can serve as a starting point for investigating firm survival. A significant amount of effort has been put into empirically identifying power-laws. Following the pioneering work of Simon and Bonini (1958), Steindl (1965), Luttmer (2011) demonstrated power-law distributions of firms' income in competitive industries (e.g., construction, wholesale) in Japan. Using large U.S. census-based data, Axtell (2001) described firm size distributions for more than 5 million firms across 10 consecutive years (from 1988 to 1997) by power-laws with a similar exponent α. A stable pattern of firm size results in almost constant ratios in the sizes of the largest firms in relation to their followers across different industries, countries, and time. Additionally, firm size ratios are independent of the scale of measurement, which means the absolute amount of a market or currency. Since power-law functions are the only distributions that are scale-free (for a proof, see Newman (2005)), this property predestines power-laws to describe complex systems behavior across multiple orders of magnitude, as seen from the numerous examples above.

Analytical models for generating stochastic distributions of firm size and growth have attracted a variety of researchers, especially economists and physicists. Starting with Gibrat (1931), who postulated that growth of cities and growth of firms are independent of their size (Gibrat's law); random growth, firm entries, and firm exits are the components used. Different theories have been applied to provide the reasoning for the underlying mechanisms of competition in markets: Rossi-Hansberg and Wright (2005) modeled fixed costs per period for Cobb-Douglas technologies with decreasing returns in an economy of identical firms. Klette and Kortum (2002) used research and development choices as the basis for growth. As in many other models, they linked random processes to geometric Brownian motion. Gabaix (1999) showed that geometric Brownian motion with a reflecting barrier creates power-laws. He explained under which circumstances power-laws are created. Their creation requires a kind of "return process" from a lower barrier under which firms exit and a return above that barrier. Luttmer (2007) implemented productivity improvements and aggregation, imitation by entrants, and selection as main principles to explain firm size in U.S. census data, similar to Axtell (2001). In a more recent paper, Luttmer (2011) combined organization capital theory and productivity shocks to explain employment growth of firms. Each firm has several blueprints of products that guarantee a competitive advantage but also depreciate over time through imitation of entrants. As a result, Luttmer (2011) was able to derive age and size distributions that matched the U.S. census data of 2008.

Firm failures seem to be directly linked to growth and competition observable from firm size distributions. Firm failure includes not only bankruptcies but also M&A activities that let firms disappear from the market as well as marginalization, which means firm size shrinks to an unimportant size or even below a minimum efficient size to operate properly (Sornette, 2006). Empirical evidence of firm failure rates reviewed on an aggregated level by Sornette (2006) showed Italy with on average a 5.7 percent failure rate per year, 55 percent with a four-year failure rate among all newly started U.S. companies in 1990, and 49 percent to 55 percent with a five-year failure rate for all newly started firms in Germany from 1983-1992. In past studies, Cox (1972, 1975) and Audretsch (1995) used linear hazard functions and piece-wise constant hazard functions (Buddelmeyer et al., 2010) to measure firm survival. Podobnik et al. (2010) combined power-law findings in firm size and default risk. Based on U.S. company bankruptcy data from the New Generation Research, Inc. database, the New York Stock Exchange (NYSE), and Nasdaq, they identified “a single risk factor — the debt-to-asset ratio R — in order to study the stability of the Zipf distribution of R over time.” (Podobnik et al., 2010, p. 18325) Power-laws described firm size, debt, and assets, as well as the debt-to-asset ratios R of 462 U.S. firms. Gabaix (2009) offered a general review of power-laws in finance and economics, including “income and wealth, the size of cities and firms, stock market returns, trading volume, international trade, and executive pay.” (Gabaix 2009, p. 255) This is based on the pioneering work in Gabaix et al. (2003) where a summary of power-laws applied to “histograms of relevant financial fluctuations, such as fluctuations in stock price, trading volume and the number of trades” (Gabaix et al., 2003, p. 267) can be found. Across various market sizes, types, trends, and countries, comparable power-law exponents have been identified, which indicate a general underlying mechanism in finance (Gabaix et al., 2003) and organizational theory (Andriani and McKelvey, 2009).

2.2.2. The Matthew effect and the allocation of rewards

An intersecting stream of status research has focused on fat-tailed distributions to explain the allocation of rewards. A preexisting status order is assumed to shape future success as an external factor. Status of a firm is an attribute resulting from its relative positioning toward competitors and other points of references (Podolny, 2005). Since the foundational work of Granovetter (1985) and its concept of embeddedness, both individuals and firms have been recognized as embedded in a pattern of social relations and interactions. Out of this theoretical background, the field of economic sociology introduced concepts from sociology like status to explain markets and economic behavior (e.g., Bothner et al., 2011; Jayaraman et al., 2000; Podolny, 1993; Sornette, 2006). The majority of these studies uses status as a lens to focus on influences of hierarchy on decision making and performance under market competition. The social and scientific literature has distilled analytical concepts of self-fueling growth and statistical distributions from the competitive arenas of scientists (Merton, 1968), athletes (Petersen et al., 2011), and other professions. Merton received high recognition after labeling this phenomenon “the Matthew effect” based on his research on Nobel laureates’ disproportionate recognition in their scientific communities (Merton, 1968). Interestingly, a shortage of resources such as research facilities, talented assistants, grants, and prizes is used to explain the cumulative advantage of a few high-status scientists. Depending on the context, various proxies have been used to capture status, for example, number of first prizes in contests like car races (Rao, 1994), Nobel prizes or number of publications in academia (Merton, 1968), education, prestigious social club memberships or number of boards appointments for status in corporate elites (Park and Westphal, 2013), or influence power via shares in a venture capital context (Bothner et al., 2014). In this stream, the allocation of success to scientists has been given the most attention. Therefore, a variety of models for the distribution of journal paper citations to scientists has been developed and empirically validated. More recently, adjustments for journal, scientific field, time, or number of authors, among others, have been made (Petersen et al., 2011). We also examined the influence of status orders on future success, but the context is complementary to past studies. By looking into stock indices and firm rankings, we aimed to quantify the effect status has on firm survival, or more generally how the status hierarchy is linked to market mechanisms and helps to explain their outcomes.

2.3. Methodology

2.3.1. Mechanisms to create power-laws

Mathematically, a quantity y follows a power-law probability density function (*pdf*) if $p(r) \propto r^{-\alpha}$, where α is the scaling parameter. An overview of 15 alternative mechanisms for generating power-laws can be found in Andriani and McKelvey (2009). These power-law-generating mechanisms can be classified into two principles: *orientation,* a direction-driven system (self-fueling growth, rich-get-richer, random external process), and *adjustment,* an optimization-driven system (least effort, highest optimized tolerance, self-organized criticality, random group formation). The most often used preferential attachment mechanism is a hybrid of the two (Andriani and McKelvey, 2009; Newman, 2005; Stumpf et al., 2012).

We describe a discrete power-law distribution by a *pdf* $p(r)$ such that $p(r) = \Pr(R = r) = Cr^{-\alpha}$ where r can take any discrete value. We chose a lower bound $r_{min} > 0$ and, calculating the normalizing constant, we obtained $(r) = \frac{r^{-\alpha}}{\zeta(\alpha,\ r_{min})}$, where $\zeta(\alpha, r_{min}) = \sum_{n=0}^{\infty}(n + r_{min})^{-\alpha}$ is the *Hurwitz zeta function*. The cumulative distribution function (cdf) of the power-law distribution is $(r) = \frac{\zeta(\alpha,r)}{\zeta(\alpha,\ r)}$. For both discrete and continuous power-laws, the scaling parameter α can be estimated by following the maximum likelihood estimation (MLE) approach outlined in Newman (2005):

$$\hat{\alpha} = 1 + n\left[\sum_{i=1}^{n} ln\frac{r_i}{r_{min}}\right]^{-1} \text{where } r_i \geq r_{min}, for\ all\ i = 1, 2, \ldots, n. \qquad (1)$$

A related stream of literature, especially in statistics and physics, has concentrated on developing robust methods to identify and distinguish power-law distributions from other distribution types. For instance, log-normal distributions are hard to distinguish from power-laws due to large fluctuations in the distributions' tails and high similarity across multiple orders of magnitude. Clauset et al. (2009) and Virkar and Clauset (2014) offered rigorous recipes to identify power-laws.

2.3.2. Framework of firm survival

Why performance differences exist among firms is one of the core questions in strategic management. For instance, in the case of a startup firm under monopoly, its resources start to grow from starting position $x_0 \equiv 1$ and move forward randomly through time to position x ≥ 1. However, in the presence of a competitor, this growth of resources (or revenue) is limited by the competitor's success rate. Although both firms grow in terms of resources, as illustrated in Figure 1, when they are ranked based on factors like revenue, profit, or market capital, one differs from the other. This acquisition of new opportunities can be seen as a standard positive feedback mechanism providing greater success to already successful firms (Petersen et al., 2011).

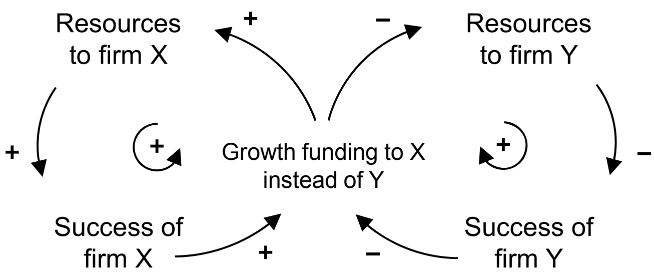

Figure 1: Firm growth in the case of competition

In theory, every firm starts with approximately zero standing and establishes itself through growth over time. We hypothesize that the stochastic process governing firm growth is analogous to a Poisson process, where growth is made at any given period of time with some approximate probability or rate. When ranking all firms of a specific market or scope, there is for all firms at each ranking position r an opportunity for growth as well as the possibility for no growth (analogous to a Poisson process). A new opportunity, corresponding to the advancement to rank position $(r + 1)$ from rank position r, can refer to any revenue growth opportunity. For each particular firm, the change in rank position Δr has an associated time frame Δt. Optimally, a firm yields revenue by growing at a constant rate over time t ($\Delta r \equiv \Delta t$).

Each step forward in firm rank position contributes to the firm's status and reputation. Hence, we refined the process to a dynamic Poisson process, where the probability of progress $g(r)$ depends explicitly on the firm's rank position r within a ranking. In this model, the growth rate $g(r)$ is defined as $g(r) = \sum_{i=1}^{n} x_i$, where i represents a set of factors like asset, sales, market value, and profit, which determines a firm's rank position r in a ranking. Apparently, the criterion for applying the Matthew effect is that the growth rate is monotonically increasing with rank position (Petersen et al., 2011), so that $g(r + 1) > g(r)$. Thus, firms' life spans are then defined as the final rank position $r \equiv r_T$ along the growth path over the considered time period T.

Let $P(r|T)$ be the conditional probability that at time T a firm is at the ranking position r_T. For simplicity, we assume that the growth rate $g(r)$ depends only on r. As a result, $P(r|T)$ assumes the familiar Poisson form, but with the addition of $g(r)$ as the rate parameter,

$$P(r \mid T) = \frac{e^{-g(r)T}[g(r)T]^{r-1}}{(r-1)!}. \tag{2}$$

Due to the Matthew effect, it becomes easier for a firm to excel with increasing success and reputation. Hence, the choice of *g(r)* should reflect the fact that newcomers — lacking the reputation of their competitors — have a tougher time moving forward, whereas experienced old-timers often have an easier time moving forward. For this reason, the progress rate g(r) can be represented as a functional form,

$$g(r) \equiv 1 - exp[-(r/r_c)^{\alpha}]. \tag{3}$$

Equation (3) allows a firm's rank to increase from almost zero to unity during period r_c. Furthermore, $g(r) \sim r^{\alpha}$ for small $r \ll r_c$. In Figure 2, we have plotted $g(r)$ for several values of α (alp), with fixed $r = 1{,}000$ (in random units), where the parameter α is the power-law exponent of the *cdf* $P(r)$, that is, the firm survival time (Petersen et al., 2011). The yearly progress can be modeled as random waiting times, with on average:

$$\langle \tau(r) \rangle = 1/g(r). \tag{4}$$

Considering that not every firm's revenue growth is of the same magnitude, nearly every firm is faced with the constant vulnerability of losing its revenue growth or prominence, possibly as the result of downturns in its market. Survival in a ranking requires that the firm maintain its performance level with respect to all possible downturns. In general, firm survival times are influenced by many competing random processes that contribute to the random dropping time *T* of a firm from a ranking. The *pdf* $P(r|T)$ calculated in Equation (2) is the conditional probability that a firm has achieved a rank position *r* by its given dropping time *T*. Hence, to obtain a joint *pdf* of firm survival time $P(r)$, we average over the *pdf* $r(T)$ of random dropping times *T*,

$$P(r) = \int_0^\infty P(r \mid T) r(T) dT. \tag{5}$$

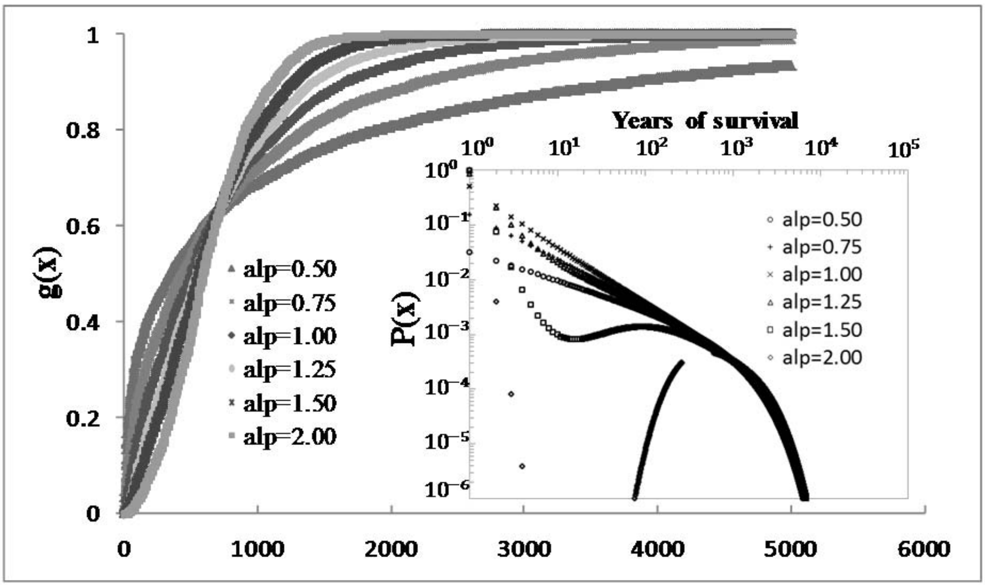

Figure 2: Firm position and survival time

Then we make the defined $r(T)$ the hazard rate, $H(T)$, the probability that dropping occurs at time $T + \delta T$, if not before *T*. This is written as:

$$H(T) = r(T) / S(T) = -\tfrac{\partial}{\partial T} \ln S(T), \tag{6}$$

where $S(T) \equiv 1 - \int_0^T r(t)dt$ is the probability of a firm surviving until time period *T*. The exponential *pdf* of dropping times,

$$r(T) = r_c^{-1} \exp[-(T / r_c],\tag{7}$$

has a constant hazard rate $H(T) = \frac{1}{r_c}$ and thus assumes that exogenous hazards are uniformly distributed over time. Substituting Equation (7) into Equation (5) and computing the integral, we obtain the following:

$$P(r) = \frac{g(r)^{r-1}}{r_c\left[\frac{1}{r_c} + g(r)\right]^x} \approx \frac{1}{g(r)r_c} e^{\frac{r}{g(r)r_c}}.\tag{8}$$

Depending on the functional form of *g*(*r*), the theoretical prediction given by Equation (8) is much different than the model in which there is no Matthew effect, corresponding to a constant growth rate $g(r) \equiv \lambda$ for each firm (for details, see Petersen et al., 2011). For the case of $\alpha < 1$, we get a truncated power-law, resulting in a *P*(*r*) that can be approximated by two regimes,

$$P(r) \propto \begin{cases} r^{-\alpha} & r \lessapprox r_c \\ \exp[-r / r_c] & r \gtrapprox r_c \end{cases}\tag{9}$$

From the theoretical plot in Figure 2, one can observe a special boundary value for *P*(*r*), between *P*(*r*) for ($\alpha > 1$) increasing and for ($\alpha < 1$) monotonically decreasing. This boundary is due to the small *r* behavior of the growth rate for $r < r_c$, which serves as a barrier that a new firm must overcome to earn status. The magnitude r_b of the *potential barrier* is represented by $g(r_b) = {}^1/_{r_c}$, which can be scaled by ${}^{r_b}/_{r_c} \approx r_c^{-1/\alpha}$. Thus, the value $\alpha_c = 1$ separates convex growth ($\alpha > 1$) from concave growth ($\alpha < 1$) in early growth of a firm.

In the case $\alpha > 1$, a group of firms is stunted by the barrier, whereas the other group of firms excels, resulting in a bimodal $P(r)$. In the case of $\alpha < 1$, it is relatively easier to achieve growth in a firm's initial phases. This framework predicts a significant statistical orderliness that bridges the gap between very short and very long firm survival times (and rank movement) as a result of the concavity of $g(r)$ in early firm growth and visibility. However, in the case of a constant progress rate $g(r) \equiv \lambda$, the *cdf* (and *pdf*) *P(r)* would be exponential with a characteristic firm survival time of $l_c = \lambda r_c$.

2.4. Data

The derived dynamic-stochastic model for survival in competitive environments is based on two mechanisms, stepwise random upward improvements and random hazardous termination events. Obvious parallels to firms, which are ranked quarterly or at least yearly — on the basis of annual reports and market prices, among other factors — and face unforeseeable setbacks, offer a chance to test the model and explain firm survival in competitive environments. Analyzing firm rankings and stock indices allows for capturing high-status arenas and different facets. Yearly rankings include a large number of firms that provide additional information of movers and shakers of firm ranks as indicators of firm survival or failure. Stock indices often include a narrower set of firms, but therefore firms with highest investor attention and status.

2.4.1. Data sets

The research is based on two types of data sets, firm rankings and stock indices. Over the last decades, various publications like Fortune, Forbes, and the Financial Times have published firm rankings on a yearly or quarterly basis. They use key financial performance indicators to rank a substantial number of firms. Moreover, variables like country and industry type are tracked in these data sets. Although success measures vary greatly among such rankings, each itself ranks firms consistently and allows for measuring the fitness of a focal firm by tracking its appearance in a single ranking over time. Staying in the ranking is seen as survival. This is similar to Mitchell (1994) and Sinha and Noble (2008) defining firm failure as the inability to stay in a market. This incorporates bankruptcies, M&As, and marginalization due to low revenues or market capitalization into the definition of firm failure. The three corporate rankings — Fortune 500, Forbes Global 2000, and Financial Times Global 500 — were selected for data analysis as they satisfy our above mentioned criteria, are popular and international, and have data that are readily available. While Fortune 500 spans more than half a century of U.S.-firm history (1955-2011) and ranks based on revenue only, Forbes and Financial Times provide a global picture using four financial performance dimensions (sales, profits, assets, and market value, or just market value) during shorter periods: 2006-2012 and 1997-2011. Sample sizes of at least 500 firms and valid sources (Interactive Data, Thomson Reuters Fundamentals, Worldscope databases, and Bloomberg) justify our empirical research.

As a second type of data set, we used established stock indices. These are institutionalized arenas with higher barriers to entry compared to firm rankings. Similarly, they include stories of success and destruction resulting from bankruptcies, M&As, or marginalization, evidenced by departure from a certain stock index. Success can again be defined by the period a stock has been listed in that index. To include national versus international firms, large sample sizes, and long time horizons, and to guarantee the validity of data, the following three indices were chosen: Dow Jones Industrial Average 30, which includes 30 U.S. industrial firms and spans more than a century (1903-2011), NIKKEI 225 from Japan, which includes 225 mainly Japanese firms and spans a 12-year period (2000-2012), and S&P 500, which has global coverage and spans a 22-year period (1990-2012). Table 1 provides details of the data sets used in this research.

Table 1: Data sets

	Type	Time horizon	Size per year	Size total[a]	Ranking/ entry criteria	Region
Fortune 500	Ranking	1955-2011	500	2,098	Revenue	US
Forbes Global 2000	Ranking	2006-2012	2,000	3,468	Sales, profit, assets, and market value	Global
FT Global 500	Ranking	1997-2011	500	1,064	Market value	Global
Dow Jones IA 30	Stock Index	1903-2012	30	118	Market value	US
NIKKEI 225	Stock Index	2000-2012	225	297	Market value	Japan
S&P 500	Stock Index	1990-2012	500	1,067	Market value	Global

[a] Total number of firms ranked/listed during the time horizon

2.4.2. Data processing

We defined survival of firms as the sum of the time periods a firm has been part of an elite arena (e.g., ranking or stock index). Due to yearly published ranking data, we analyzed composition of stock indices yearly as well (first traded weekday of the year). The following steps were performed to process the data for further analysis for each data set:

Step 1: Arrange a matrix $\boldsymbol{M}_{i,j}$ which contains the rank $r \in [1; R]$ in a ranking or just 1 if being listed in a stock index, else 0; for all firms $i \in [1; I]$, which appear in a specific year $j \in [1; J]$ after the initial year $j = 1$.

Step 2: Create a vector f_l including a list of all unique firms $l \in [1; L]$ which appeared across all years $j \in [1; J]$.

Step 3: Create a matrix $\boldsymbol{R}_{l,j}$ including the rank or appearance for all unique firms $l \in [1; L]$ across all years $j \in [1; J]$.

2.5. Results

2.5.1. Initial analysis of firm size and variability in Fortune 500 firm rankings

Insights from the Fortune 500 firm rankings serve as a starting point to examine competition among large firms. The yearly published Fortune 500 list allows insights into growth and trends within the business world of the U.S. Tracking revenues in these lists across decades offers surprising regularities: Figure 3 shows revenue-to-rank distributions for selected years (1955, 1975, 2005, 2011). The shape of the yearly distributions is highly similar. At the top, revenue figures are far apart and defined by a few superior firms. Although data are drawn from slightly different firm populations (1955 to 1994, i.e., before the introduction of financial firms, and 1995 onwards), revenues follow straight lines in a double log-plot indicating power-laws. The characteristic ratio of revenues within the ranking of 500 firms remains constant. Parallelism could indicate similar parameters in the exponents α of possible power-laws. The horizontal shift shows the change in absolute revenues in millions of US dollars due to inflation and overall market growth. Furthermore, the mean skewness of all 56 Fortune 500 distributions from 1955 to 2011 is positive (0.786). This indicates the presence of a large number of firms with low revenues at the bottom of the yearly rankings. This upfront analysis of revenue distributions confirms earlier findings about firm size distributions in the U.S. and other countries (Axtell, 2001; Luttmer, 2007, 2011; Sutton, 1997). Based on U.S. census data, Axtell (2001) described firm size distributions for more than five million firms across 10 consecutive years (from 1988 to 1997) by power-laws with similar exponents α. Including such a large number of firms allowed for identification of power-laws in firm-size frequency plots, whereas our analysis just takes the top of the U.S. firm population to show a power-law-driven decline in revenues. Both analyses show a surprisingly strong pattern emerging from seemingly independent firm growth over time. This provides validity for using the Fortune 500 list and similar rankings as a data basis for our analysis.

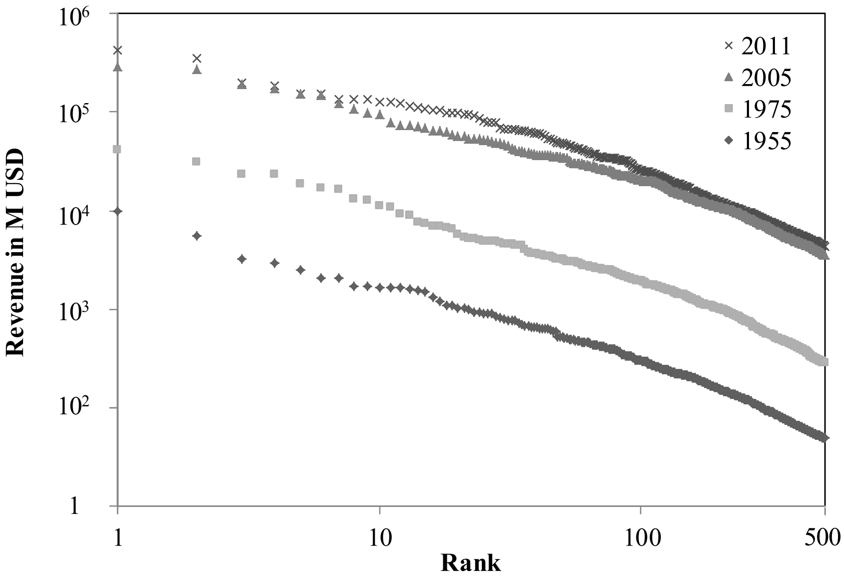

Figure 3: Revenues in the Fortune 500

A second upfront analysis examined the variability of the firm composition in the Fortune 500 ranking to understand the dynamics at the very top of the U.S. economy. Across the second half of the 20th century, these dynamics generated and renewed the characteristic revenue distribution shown in the first analysis. A suitable measure of variability in rankings is the well-known Spearman rank correlation coefficients ρ. Figure 4 depicts yearly ρ for the Fortune 500 ranking. The inclusion of financial companies in 1995 caused a ρ of 0.161, which was substituted by the three-year average of 0.883. Major phases of economic booms and recessions are indicated to link the variability of the firm composition to the growth of the U.S. economy. These phases are derived from the U.S. annual percentage growth rate of GDP at market prices based on constant US dollars in the year 2000. There are three main observations. First, from the 1960s, variability in the ranking order of top U.S. companies increased (1960-1970:

ρ=0.911; 2001-2011: ρ=0.865). In addition to larger rank changes, a lower ρ implies more companies leaving the ranking and new companies joining (1960-1970: survival rate 94.5 percent; 2001-2011: survival rate 91.3 percent), which could be due to bankruptcy, M&A, or revenues below the cutoff value at rank 500. This leads to only 54 of 500 companies being able to survive in the index from 1955 to 2011. Common strategies and characteristics among them could be a fruitful focus for further research. Second, variation of ρ increased starting in 1975, as seen in the larger fluctuations between peaks of stabilization (high ρ) and valleys of high changes in the ranking (low ρ). Staying in the elite group of the U.S. economy became more difficult due to this increase in dynamics. Third, ρ shows a correlation with the annual U.S. GDP from 1961 to 2011 (Spearman correlation of 0.310, $p < 0.05$). All major boom and recession periods of the U.S. economy led to peaks and valleys of ρ, indicating that booms stabilize current firm order whereas recessions lead to increased competition with lots of existing "giants" losing importance and new companies entering the Fortune 500. In summary, although the U.S. economy has an impact on the composition of the top 500 U.S. firms, the revenue distribution stays nearly constant. The following main analyses will investigate the effects of these regularities on firm survival times and the movement of firms within rankings.

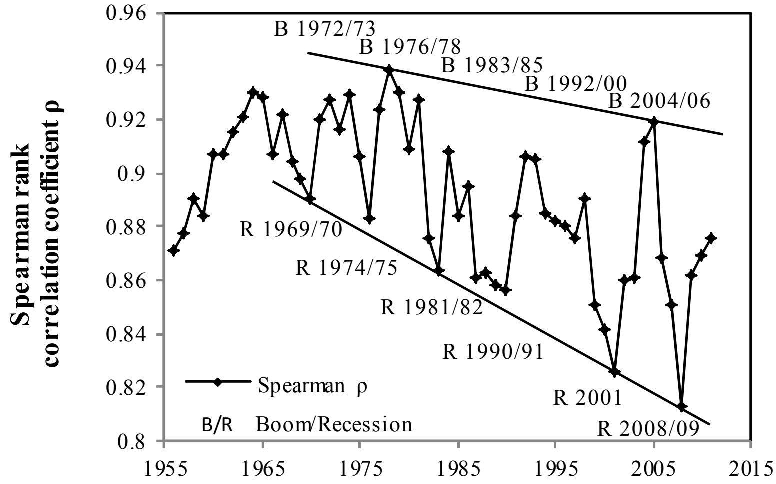

Figure 4: Spearman rank correlation coefficient ρ in the Fortune 500

2.5.2. Power-laws in firm survival times

Before testing the survival probability model, a look into average firm survival rates in the Fortune 500 ranking confirms the cumulative advantage logic of the model. Separated by quartiles, Table 2 captures how higher ranked firms are able to stay longer in the ranking measured by absolute and normalized averages. This provides clear evidence of the Matthew effect, which states how rich and established actors are given even more and others lose and can never catch up.

Table 2: Average survival times in Fortune 500 ranking

	Absolute			Normalized[b]			Average
	1955[a]	1975[a]	1990[a]	1955[a]	1975[a]	1990[a]	normalized
Top 75%-100%	39.0	25.5	16.3	1.000	1.000	1.000	1.000
50%-75%	30.8	20.9	11.7	0.789	0.821	0.717	0.776
25%-50%	20.9	15.0	6.70	0.536	0.586	0.412	0.511
Lowest 0%-25%	14.4	12.4	4.70	0.370	0.485	0.288	0.381
Total	26.3	18.4	9.90	0.674	0.723	0.604	0.667

[a] Average survival times of base year's firm composition tracked up to 2011
[b] Normalized on basis of top 75%-100%

The following two steps derive *pdfs* of firm survival times:

Step 1: Create a vector $\boldsymbol{s}_l$ that contains the sum of years survived for all unique firms $l \in [1; L]$:

$$\boldsymbol{s}_l = \sum_{l=1}^{L} \sum_{j=1}^{J} 1 \quad if\ l \in \boldsymbol{R}_{l,j} \quad else\ 0$$

Step 2: A probability density function (*pdf*) of the survival times in years $j \in [1; J]$ can be found by the survival matrix $\boldsymbol{S}_j$:

$$\boldsymbol{S}_j = \frac{\sum_{j=1}^{J} \sum_{l=1}^{L} 1\ if\ \boldsymbol{s}_l = j \quad else\ 0}{L}$$

Based on these steps, it is possible to derive *pdfs* of firm survival times of three major rankings and three stock indices, which are shown as cumulative distribution functions (*cdfs*) in Figure 5. All *cdfs* have a similar right-skewed and possibly power-law behavior on a log-log scale. For better visualization, data sets were vertically shifted. Therefore, we multiplied each data set by a constant in accordance with logarithm rules: Financial Times by 4, Forbes by 0.25, NIKKEI by 6, and S&P by 0.17. All six curves show more or less two regimes, a straight line section and a curved tail. Power-law behavior in the beginning years is due to the Matthew effect. The straight line sections are parallel to a certain extent, which can be tested by comparing the exponent parameters α of possible power-laws. Then there is a curved tail at the end of the analyzed time periods, which results from a censoring effect of the empirical data sets: There are not enough old firms in the tail since the data are based on time intervals that cannot cover all firm life spans totally. This cutting of the longer life spans causes a bias towards short life spans.

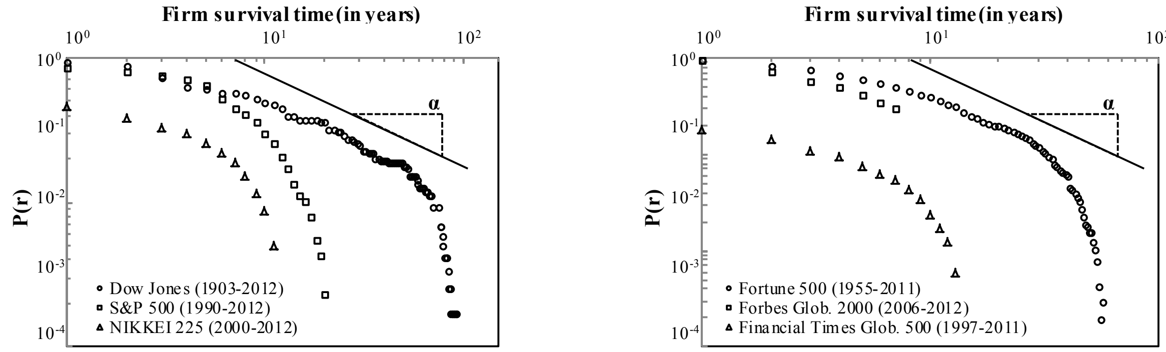

Figure 5: Cumulative distribution functions (*cdfs*) of firm survival time

The main target is to identify and validate a statistical distribution that fits all six data sets. We have shown that fat-tailed distributions, and in particular power-laws, seem to be most promising. Power-laws can be derived according to Eq. (1). Two parameters have to be estimated: A lower bound r_{min} divides the probability distribution of each data set into an initial part ($r < r_{min}$) and power-law regime ($r \geq r_{min}$). Estimates of r_{min} and α are derived from numerical iterations of r_{min} and least squared regression in Eq. (1). Starting values for $r_{min} = 0$ can be taken based on the change of slope in the *cdfs*. Values for α mainly fall in an interval of 2 < α < 3, which is consistent with most power-law behavior of natural and man-made systems. We derived standard deviations for all estimated α, which imply stable parameter estimates within this interval. First, we measured the goodness-of-fit for power-laws. Table 3 summarizes parameters and test statistics for all six data sets.

Table 3: Goodness-of-fit for power-law cdfs

	Parameters			**Test statistics**	
	r_{min}	α	σ_α	MSE	KS
Fortune 500	4	1.93	0.02	0.0008	0.103
Forbes Global 2000	1	**1.65**	0.06	0.0044	0.127
FT Global 500	2	2.76	0.03	0.0237	0.184
Dow Jones IA 30	3	2.34	0.05	0.0007	0.126
NIKKEI 225	2	**3.35**	0.14	0.0097	**0.071**
S&P 500	5	3.04	0.07	0.0071	0.158

Mean square errors (MSE) of the derived power-law functions are low and the same or better than for the three alternative distributions summarized in Table 4. The largest deviations for all distributions appear for small r around r_{min}, which does not affect the prediction of the tail of the distributions. Rare events (e.g., very long firm life spans) are located there. Judgment was further improved by a Kolmogorov–Smirnov test (KS test), as suggested by Clauset et al. (2009).

After quantifying the goodness-of-fit for power-laws, promising fat-tailed distributions were selected and tested as alternatives. Exponentials are similar to power-laws and are often hard to distinguish from them. Again, least squared regression was used to derive best-fit estimates. The error matrices of MSE and KS-test are higher for the exponential fits than the power-law fits. Similar steps were taken for lognormal and beta distributions. The results are shown in Table 4. Lognormal distributions in particular proved to be less accurate than the initially tested power-laws, but were a good alternative.

Table 4: Goodness-of-fit for alternative distributions

	Exponential			**Lognormal**			**Beta**		
	MSE	KS	p	MSE	KS	p	MSE	KS	p
Fortune 500	0.0351	0.148	>0.15	0.0153	**0.075**	>0.15	0.0202	0.208	0.02
Forbes Global 2000	0.1521	0.303	>0.15	0.0495	0.201	>0.15	0.1028	0.302	>0.15
FT Global 500	0.0953	0.315	0.15	**0.0111**	**0.141**	>0.15	0.0531	0.239	>0.15
Dow Jones IA 30	0.0165	0.321	<0.01	0.0025	0.217	0.03	0.0404	0.592	<0.01
NIKKEI 225	0.1383	0.349	0.11	0.0144	0.165	>0.15	0.0411	0.171	>0.15
S&P 500	0.0175	0.218	>0.15	**0.0036**	0.123	>0.15	0.0140	0.163	>0.15

Recent work on power-law statistics (Clauset et al., 2009; Vikar and Clauset, 2014) has suggested the likelihood-ratio test (LR-test) and its p-values as another measure of goodness-of-fit. We performed LR-tests, favoring power-law only against a linear regression (LR 2.05, p = 0.04). Against the above distributions, LR-tests were indifferent due to data scarcity. Sample sizes of more than 1,000 observations just in the tails of *cdfs* ($r > r_C$) are seen as necessary to statistically rule out alternative distributions by LR-test and the framework presented in Clauset et al. (2009).

2.5.3. Power-laws in rank movements of firms

Whereas firm survival times are a summarizing measure, one must look further into the yearly changes in rankings to understand the underlying mechanism. Such changes can be seen as rank movements of a firm, either up or down, when comparing two consecutive ranking lists. Interestingly, we found statistical evidence for power-laws as well, which means success and failure follow a certain behavior. This is a new insight into firm growth at the market level. Evidence is based on the Fortune 500 ranking for the U.S. and on the Financial Times Global 500 ranking for the global scale. Thus, a large sample of firms (2,098 for Fortune and 1,067 for Financial Times) across long time intervals was considered (56 years for Fortune and 14 years for Financial Times). For each rank $r \in [1; R]$ in a ranking of R ranks during a time interval $j \in [1; J]$ there exists a matrix $\boldsymbol{RM}_{i,j}$ of *rank movements* for all uniquely appearing firms $l \in [1; L]$:

$$\boldsymbol{RM}_{l,j} = \boldsymbol{R}_{l,j-1} - \boldsymbol{R}_{l,j} \; if \; \boldsymbol{R}_{l,j} \; and \; \boldsymbol{R}_{l,j-1} \in [1; R] \; else \; 0$$

where positive $\boldsymbol{RM}_{l,j}$ indicates rank success of firm l in year j and negative $\boldsymbol{RM}_{l,j}$ a loss in rank, respectively. A *pdf* of absolute rank movements m in a range of $k \in [-K; K]$ can be derived from:

$$m_k = \frac{\sum_{l=1}^{L} \sum_{j=1}^{J} \sum_{k=-K}^{K} 1 \; if \; \boldsymbol{RM}_{l,j} = k}{\sum_{l=1}^{L} \sum_{j=1}^{J} 1 \; if \; \left|\boldsymbol{RM}_{l,j}\right| > 0} \; else \; 0$$

Figure 6 shows *pdfs* of rank movements in the Financial Times Global 500 (1997-2011) and Fortune 500 (1955-2011). Probabilities for Financial Times are multiplied by 8 to separate them from Fortune figures. One must consider the discrete nature of the observations.

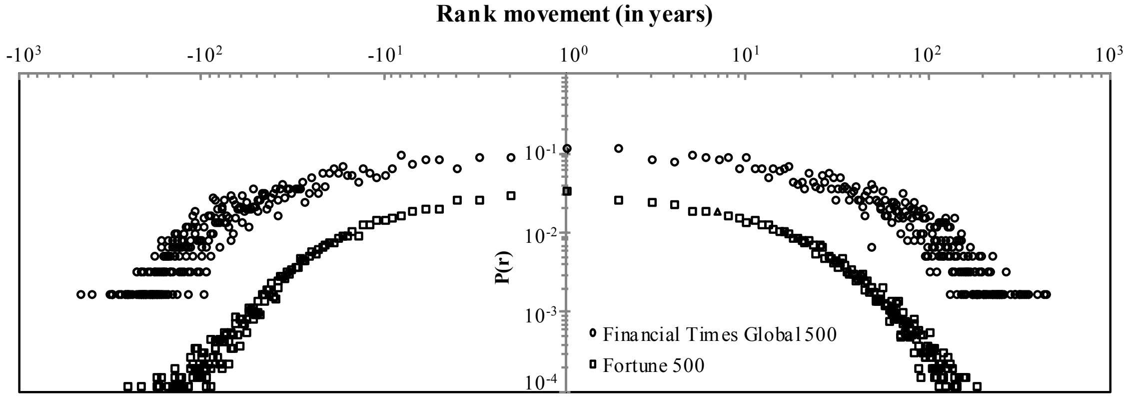

Figure 6: Probability density functions (*pdfs*) of yearly rank movements

Least-square best-fits according to Eq. (1) result in α of 1.57 and $r_{min} = 7$ for the Financial Times Global 500 and in α of 1.74 and $r_{min} = 4$ for the Fortune 500. Standard deviations for α are pretty low with $\sigma_\alpha = 0.010$ for the Financial Times and $\sigma_\alpha = 0.007$. So, both survival of firms and the dynamic change of their ranking are driven by fat-tailed distributions and most likely also by power-laws. Aggregated behavior of such a large group of firms tends to show similar characteristics across countries (U.S., Japan, globally).

In Figure 7, we link firms' dropout to market growth at an aggregated level. The market growth rate is measured by the cutoff value of the last ranked firm in a specific ranking, which can be seen as an indicator of total growth of the market in which the firms compete. We analyzed the Fortune 500 ranking data over 56 years from 1955 to 2011 to plot the revenue cutoff values against the cumulative phase-out of the initial group of 500 firms in 1955. Thus, we found negative correlations, especially when correcting the huge steps in 1995 of both data sets, which were caused by then allowing financial firms in the ranking. From 1956 to 2011, gradually almost 90 percent of the firms dropped from the ranking, whereas the revenue of the last firm in the ranking grew from US$50 million to US$4,385 million.

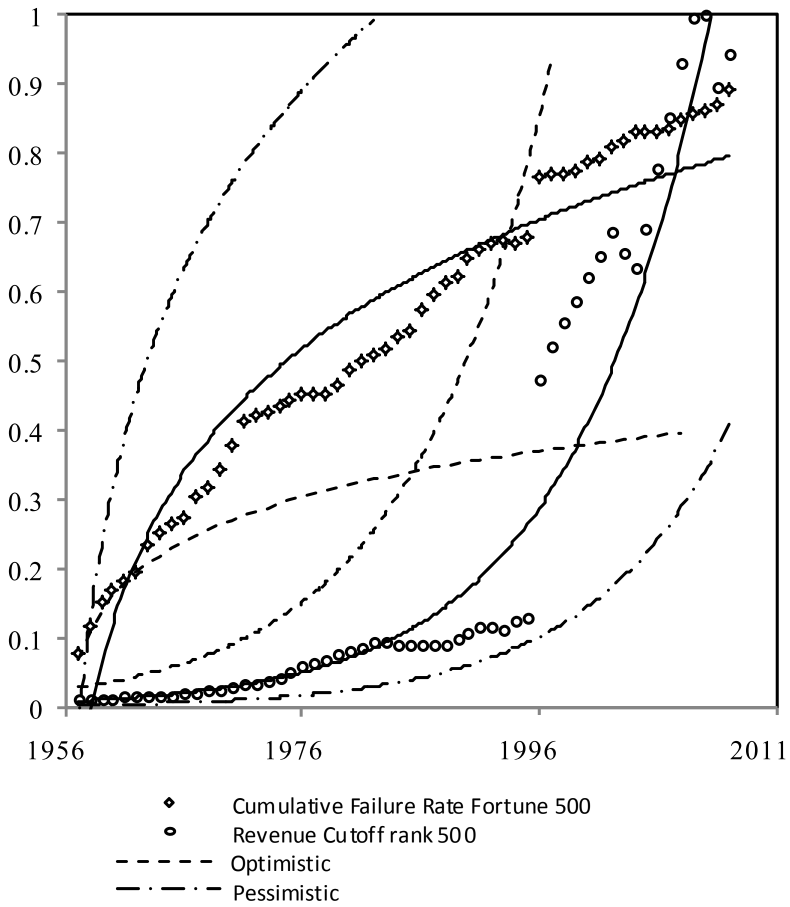

Figure 7: Normalized revenue cutoff and cumulative failure rate of the 1955 group of the Fortune 500

Two scenarios can be derived from the empirical case data of the Fortune 500 (optimistic, pessimistic). In an optimistic scenario, GDP of the economy grows much faster and therefore the slope of the revenue cutoff curve becomes steeper. A much lower failure rate will be the consequence. This means economic growth will stabilize the existing composition of firms in the ranking, which is similar to the findings in Figure 4. On the other hand, in a pessimistic scenario, lower GDP growth will flatten the slope of the revenue cutoff curve. As a consequence, one could expect the failure rate to rise much more quickly. In reality, recessions have been the times of highest firm turnover in the ranking according to Figure 4. The crossing point for optimistic, observed, and pessimistic data of market growth and firm dropouts shows an earlier, average, and later occurrence of the Matthew effect for firms with $\alpha >> 1, \alpha > 1$, and $\alpha \leq 1$.

2.6. Discussion

The empirical approach followed in this paper is supported by secondary data sets obtained from resources of significant importance. Without ambiguity, the underlying firms are the most relevant of their time due to the stock indices and rankings employed. Empirical data cover different countries and varying time horizons and include more than 8,000 firms and 64,000 firm-year observations. The six data sets used for empirical validation answer calls in the literature for longitudinal data covering more firms, longer time horizons, and a global scale and the data sets are publicly available.

Our empirical evidence extends earlier findings of power-law distributions of firm dropout in certain markets or industries (Fujiwara, 2004; Luttmer, 2007; Podobnik et al., 2010) by investigating the top firms in the U.S., Japanese, and global market (answering research question 2). First, we confirm the observation of power-laws in the distribution of firm sizes (Axtell, 2001) with Fortune 500 data. Second, based on average survival times, we confirm that high firm status increases the likelihood of survival (answering research question 1). This provides an additional view on the same phenomena: A large number of firms follows power-law-driven behavior (e.g., in their size, growth, and survival times). This is far away from randomness, but instead a result of how firms strive for individual success and influence one another on an aggregated level. Our findings are supported by comparisons of MSE and KS-tests, which yield a clear preference for power-law distributions over log-normal, exponential, and beta distributions (Tables 3 and 4).

In rankings, we identified an empirical pattern in terms of year-wise relative growth of firms (answering research question 3). We called such growth "rank movements" and found such movements following similar distributions for the firms listed in the Financial Times Global 500 and Fortune 500 across several decades. An underlying mechanism seems to govern relative growth of firms in competitive markets. Success and failure are both hard to reach: Huge steps are therefore rare, but short steps and change in general are just the nature of market behavior. Very recently, Ibragimov (2014) developed a quantitative model to predict firm growth under heavy-tailed consumer responses.

The proof of power-law distributions in firm survival matches stochastic results known from the sociological Matthew effect (Merton, 1968; Petersen et al., 2011; Rao, 1994). By this, similar mathematical concepts from economics and sociology are linked. Based on our findings, striving for status involves high-risk exposure resulting in large phase-outs. Elite arenas are a basket of survivors, which outshine in their present success endless firms joining and leaving those paths of success. Status can be a further lens offering insights into the mechanics of such striving. Seeing firms embedded in a social environment (Granovetter, 1985) could allow for understanding patterns at an aggregated level, similar to examples of ant colonies where behavior arises not just from an understanding of single elements, but from a larger scale understanding. Additionally, the paper introduces comprehensive data sets of status arenas into economic sociology to further validate the concepts of status (Podolny, 2005) and the Matthew effect, among others. Based on our results, firms' success and failure are not only linked to their competitors, but also appear with their power-law *cdfs* as a result of interplay forces at the macro level. Statistical regularities observed in this paper for firm survival times at the aggregated level are counter-intuitive to complexity and diversity at the single-firm level (Dosi et al., 1995). In a last step, we linked firm survival times to management strategies and future research questions.

2.7. Conclusions

To study top firm survival in competitive markets, we employed a stochastic modeling approach using six data sets. As the data sets inherit the concepts of step-wise, self-fueling growth and random hazards for firm survival time in terms of rank and index, this is analogous to a Poisson process. Furthermore, we refined the process to a dynamic Poisson process, considering the firm's growth in rank position or indices over years (i.e., monotonically increasing). We observed significant empirical evidence for the Matthew effect and its power-law distribution in firm survival in two global and one U.S. firm ranking and in one stock index of global, U.S., and Japanese coverage. This proved that firms as single market elements influence each other systematically and, moreover, force each other into specific stochastic properties instead of an idiosyncratic path.

To the best of our knowledge, no research has identified these macro-level influences of top firms. Additionally, for yearly firm movements in rankings we found similar power-law-driven *cdfs* as proposed by our model. Validation was conducted using sample sizes of 10,000 rank movements within U.S. and global firm rankings. Our results point toward defined *cdfs* governing firm survival in competitive markets instead of random distributions resulting from individual strategic and operational decisions. When we looked into market growth in the Fortune 500 ranking over the last 56 years, it was possible to show that market growth at all levels in the ranking is of the same nature. At the top, we found proof for the Matthew effect, which predicts future success for already successful firms (Merton, 1968).

From a managerial policy perspective, the shift from Gaussian to power-law distributions means a focus on rare events, which affect most managers more than averages (Andriani and McKelvey, 2009). In particular, our results can help to better quantify firms' dropout risks. This is in the interest of both investors and the public. If firms reach for the top – measured, for example, by revenue — their exposure to failure remains unexpectedly high: Turnover rates are of large single-digit percentages, which is in line with other empirical research findings of firm survival times. Typical firm survival is characterized by lots of firms having short life spans and very few having extraordinarily long life spans. Positive effects are opportunities to enter existing and growing markets. On the negative side, even the largest firms of their time tend to systematically fade away or, in the best case, disappear by M&A.

This research has some limitations; for example, results from 60 years of data are compared to results of 10 years to show similar patterns. For more analytical rigor, censored data are recommended for use. However, due to unavailability of data, we keep this as our future research agenda. Our findings hold true for very large firms since entry criteria are often revenue based. Hence, one can reduce the revenue cutoffs in rankings to investigate a larger number of firms. Our framework can be applied as long as there is competition. Future research might analyze the group of survivors in each of the data sets for commonalities. These firms, about 50 in the Fortune 500, hold the chance of recognizing managerial patterns of success due to a change in the level of analysis. Furthermore, a more sophisticated model that incorporates endogenous termination factors (e.g., termination due to sudden decrease in revenue below a given cutoff value for appearing in a ranking) is more difficult to model analytically, which we leave as an open problem.

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Chapter III

Leveraging Supply Chains for New Venture Growth

Abstract

Since new ventures operate under permanent resource scarcity, powerful supply chains are crucial to obtain needed resources from suppliers and business partners and sell products to customers. Surprisingly, new ventures are not well understood from a SCM perspective. Therefore, we build on dynamic capability (DC) theory to shed light on how new venture firms develop and nurture supply chain (SC) capabilities. From case studies with 18 manufacturing new ventures from Switzerland and China we derive capabilities in new venture growth related to the four dimensions of DCs evident (Sense, Integrate, Develop, Reconfigure). More specifically, findings include upstream DCs for selecting suppliers, organizing procurement and outsourcing. Downstream DCs organize distribution channels, transportation, and customer service. Further, we present propositions related to the DCs and the path dependence of these DCs. For practitioners our research can serve as a best-practice benchmarking of highly successful firms.

Keywords: Supply chain management; New venture; Growth; Dynamic capabilities; Case study

3.1. Introduction

New and fast growing ventures are a key factor for job creation, market innovation, and economic growth in many industrialized countries (Hisrich et al., 2007) – despite their high probability of failure (Shepherd et al., 2000; Tatikonda et al., 2013). Little is known on how successful entrepreneurs manage to start from a point without any operations, suppliers or routines to deliver innovative and competitively priced products a few years later. What is known, is that supply chain management (SCM) is a strategic core competence creating competitive advantage in established firms (e.g., Hsu et al., 2011). Therefore, this paper aims at answering calls for research at the nexus of SCM and entrepreneurship to investigate external operations of new ventures (Arend and Wisner, 2005; Goodale et al., 2011; Kickul et al., 2011; Linderman and Chandrasekaran, 2010; Tatikonda et al., 2013). This can be based on the efforts scholars put into exploring why new ventures evolve (e.g., Gartner 1985), how they grow (e.g., Greiner, 1998; McKelvie and Wiklund, 2010), best allocate resources in different stages (e.g., Levesque, Joglekar and Davies, 2012; Tatikonda et al., 2013), and numerous identified success factors (e.g., Duchesnau and Gartner, 1990; Song et al., 2008). Thereby, a new venture is a firm active in the creation of goods or services that still suffers from a liability of smallness and newness (generally younger than 6 to 8 years) that either was founded by an individual or by a company as long as the new firm is not given key resources by a mother company (Robinson, 1999; Tatikonda et al., 2013; Zahra, Ireland, and Hitt, 2000).

A rich stream of literature on dynamic capabilities (DC) holds promising answers how new ventures successfully expand, change, and reconfigure their initial resource base into an established firm (Zahra et al., 2006). Both the development of DCs and DCs in general require more empirical evidence after a long theoretical discourse initiated by the seminal paper of Teece et al. (1997) (e.g., Helfat and Peteraf, 2009; Schilke, 2014). Our work contributes to a consolidation of the literature by capitalizing on previous research: main dimensions of DCs are reviewed from the literature and explored in real-world settings with the help of case studies. This should help clearing the observed “proliferation of concepts and relationships” in DC research (Barreto, 2010, p. 277; Stadler et al., 2013). Moreover, new ventures are ideal for understanding the role of DCs, since small firms are less complex and allow their managers or founders a more detailed overview. Similarly, entrepreneurship is seen as a key to renew and manage innovation in large firms.

Most recent work by Tatikonda et al. (2013, p. 1412) points toward promising questions regarding evolving supply chains (SC) of new ventures by asking "How does a new firm initiate supply and distribution networks? How best can new ventures leverage supply chain partner's resources and capabilities […] at different points in the firm's evolution?" This research should include inter-organizational partnerships (Terjesen et al., 2012), as well as links to research institutions for acquiring expert knowledge. These external partners are presumably an effective source for new venture growth under initial resources scarcity and limited initial funding. Therefore, the paper studies DCs in the field of entrepreneurship with the following two main research questions:

- Which dimensions of DCs allow new ventures to build up their external operations (upstream, downstream)?
- How does the development of DCs itself takes place?

Thereby, external operations include on the upstream-side *make-or-buy decisions*, *supplier selection*, and *procurement*, and on the downstream-side *transportation* or physical delivery of the products, exploration of *sales channels*, and *customer service* (Mentzer et al., 2008; Tatikonda et al., 2013). For answering these questions, we first review DC literature to derive four distinct DC dimensions and form a conceptual framework used in the multi-case-study approach as an initial structure. Then these four DC dimensions are empirically characterized from our field-notes of 18 Swiss and Chinese new ventures. The proposed DCs and their development provide a sound basis for conducting large firm studies and navigating entrepreneurs through startup life.

3.2. Theoretical background and conceptual framework

3.2.1. Dynamic capabilities

The DC perspective builds on evolutionary theory of the firm (Nelson and Winter, 1982) by assuming amongst others path-dependent organizational learning of routines (Zahra et al., 2006). Further, it extends the resource-based view (RBV), which primarily focuses on *existing* resources of the firm, by addressing the *extension* and *change* of these resources (Helfat and Peteraf, 2003; Schilke, 2014). DCs received not much attention before the seminal paper by Teece et al. (1997, p. 516), which generated a plethora of strategic management literature. In this initial paper DCs are defined as “the firm’s ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments.“ Recently, Baretto (2010, p. 271) aimed at bringing together numerous definitions by suggesting DCs as “the firm’s potential to systematically solve problems, formed by its propensity to sense opportunities and threats, to make timely and market-oriented decisions, and to change its resource base.” More broadly, Helfat and Winter (2011, p. 1244) see a DC as “one that enables a firm to alter how it currently makes its living”, and assign each DC a very specific purpose addressing specific activities.

There is a wide agreement on the distinction between *dynamic* and *operational capabilities*. Firms find standardized solutions, *routines*, for solving their recurring problems. The pattern of routines represents the operational capabilities of a firm. These routines evolve over time and require updates when the environment of the firm changes or growth takes place. Changing existing routines is done by higher-order routines, so-called dynamic capabilities (Zahra et al., 2006). Recent contributions by Helfat and Winter (2011) and Stadtler, Helfat, and Verona (2013) stress there is no bright line between these two forms of capabilities, but significant systematic change of existing resources and routines can be understood as the result of DCs.

Latest research addresses the need for empirical verification and clarification of theory. One aspect of interest are dimensions of DCs. The literature introduced a variety of synonymously used notations, which can be summarized into four distinct dimensions: *Sense* covers all DCs aiming at the exploration of external resources including their identification and assessment. The firm analyzes external resource bases to find potential complements to the own existing resource base. *Integrate* includes all activities that bring external resources — including knowledge — into the boundaries of the firm. This could be from the resource bases of external partners like suppliers, R&D institutions, or distributors. The third dimension, *Develop*, can be seen as the hearth of DCs since it contains the internal creation of the firm’s resource base. In other words, it comprises the setup of new routines, knowledge and also products by own capabilities. *Reconfigure* covers all transformations of existing resources for a better match with the environment, which include updates of existing routines and assets. Table 1 links these four dimensions to their alternative notations and selected references.

Table 1: Main dimensions of dynamic capabilities

Dimensions	Alternative notations	Descriptions	Selected references
Sense	Sensing and Identification, extend, assessment	Exploration, identification and assessment of opportunities, resources, partners, knowledge in the environment of the firm.	Baretto (2010), Nelson and Winter (2003), Stadtler et al. (2013), Teece et al. (2007)
Integrate	Seizing, extend, aquire	Integration of outside resources and knowledge into the firm.	Makkonen et al. (2014), Nelson and Winter (2003), Schilke (2014), Teece et al. (2007)
Develop	Transforming, create, build	Development of new knowledge, routines, and also new products within the firm.	Nelson and Winter (2003), Schilke (2014), Teece et al. (2007)
Reconfigure	Transforming, modify, change, renew	Update and change of the existing resource base for a better match with the environment.	Baretto (2010), Helfat and Winter (2011), Makkonen et al. (2014), Nelson and Winter (2003), Stadtler et al. (2013), Teece et al. (2007)

The majority of DC research focuses on established firms ignoring the stark differences of new ventures regarding survival, legitimacy, and capitalization of innovations (Sapienza et al., 2006; Zahara, Sapienza, and Davidsson, 2006). However, numerous studies on DCs form a solid theoretical and empirical basis for research on new ventures. Recently, Tatikonda et al. (2013) empirically confirmed the positive influence of DCs on new venture survival probabilities based on archival data of 812 manufacturing firms. But what makes DCs relevant for new ventures? When environmental dynamism is medium and low, well researched DCs like new product development loose importance since firms can sell their already developed products (Schilke, 2014). Then expanding upstream and downstream operations effectively becomes key to gain competitive advantage. Moreover, resource scarcity per se should force new ventures to get access to external resources of partners by outsourcing, purchasing, and leveraging distribution channels (Zahra et al., 2006).

3.2.2. New Venture growth and external operations

The following prepares a conceptual framework shaping the initial research design of the case study questions and analysis (Bourgeois and Eisenhardt, 1988; McCutcheon and Meredith, 1993; Voss, Tsikriktsis, and Frohlich, 2002). Many scholars have investigated the growth of technology based new ventures (Gilbert et al., 2006; Greiner, 1998; Kazanjian and Drazin, 1989) and identified life phases. Consistent with earlier work and recently Tatikonda et al. (2013), we assume mainly three life-phases between incorporation and being an established firm: an initial *start-up* phase, a *growth* phase, and a *stability* phase. These three phases, although fuzzy in their delimitation, are characterized by different organizational structures and operational challenges, for example finding first suppliers vs. roll-outs in foreign markets vs. launching product derivatives. Besides this time dimension, a consistent understanding of external operations and the here synonymously used SCM is required to systematically capture all relevant DCs. However, the interdisciplinary nature of SCM creates a diffuse picture of it in the academia and practice. Depending on the department, which is responsible of the research or management, the view, definition and key aspects vary considerable (Mentzer, Stank, and Esper, 2008). Commonly, both upstream (supply) and downstream (demand) operations, which cross organizational boundaries, are considered external operations (Mentzer et al., 2008; Tatikonda et al., 2013). This includes on the upstream side purchasing, outsourcing, R&D partners, and on the downstream side distribution channels, related logistics, and customer service.

3.3. Methods

The paper attempts to answer the described research questions by exploratory, qualitative case studies, which are most suitable to investigate subtle and less defined phenomena (Denzin and Lincoln, 1994; Yin, 2003). This contextually rich case data from bounded real-world settings (Barratt et al., 2011; Dubé and Paré, 2003) is intended to delineate the exercise of DCs at new ventures to guide future quantitative research.

3.3.1. Sampling and data collection

Considering the variety of new ventures in practice, the interviewed firms were chosen for theoretical reasons. First, we focused on new ventures with a manufacturing background, thus only firms engaging in production of physical products were considered. Thereby, we sampled from different industry sectors such as consumer devices, machinery, electronics, materials, and medical, since different supply chain strategies and developments in different industries were expected. Second, as Choi and Hong (2002) and Fisher (2007) suggest we used leading and most successful entrepreneurial ventures for benchmarking purposes, whereas “superior performance relative to […] (competitors) provides an empirical indicator of competitive advantage” (Schilke, 2014, p. 180). Third, new ventures had to be independently held and not much older than 8 years (Fauchart and Gruber, 2010), although we included a few older firms to clarify how new ventures mature into established firms (Appendix Table 5: ID 9, 16, and 17). Firm age and success are two interrelated variables, due to the extraordinary high probability of failure (Tatikonda et al., 2013). While data about age was simple to collect and verify, “success” meant for this study in general that the interviewed firms reached serial production and faced high (double-digit) revenue growth over several years. Fourth, including a developed (Switzerland) and developing country (China), we targeted to increase external validity of the later identified DCs (Yin, 2003). By the diverse nature of the 18 studied new ventures (Table 2 shows aggregated statistics of the examined firms, whereas firm level demographics are attached in the appendix) external validity of the data is additionally strengthened.

Case studies allow to triangulate data from numerous sources including semi-structured interviews, observations (plant tours, samples of products, prototypes, and components), and firm archives (documents, organizational charts, production statistics), but also the internet. Wherever possible, we validated information obtained from the interviews. In every case one or more semi-structured interviews were conducted (face-to-face, only for one firm by telephone). Observations, e.g., plant tours and product samples, were possible in all cases with exception of the telephoned firm. We interviewed founders (serving as CEOs, COOs, etc.) or managers responsible for setting up external operations during the first 6 to 8 years after incorporation of the new ventures. Unit of analysis was solely the specific new venture (Yin, 2003). We guaranteed confidentiality to reduce eliciting socially desirable responses and other biases. All interviews were done by two investigators (Dubé and Paré, 2003).

Firms were found by internet research and snowball method (Sjoberg and Nett, 1968). In Switzerland there are several start-up competitions to initialize and support entrepreneurial culture. They publish yearly summaries of more than 100 top start-ups on the internet, which served as starting point of our sampling. If the necessary information was not available on the internet, a phone call helped to determine the success of the firms. In the end of the interviews, we asked if other successful manufacturing new ventures could be recommended which organize their operations differently and have substantial operations. Following this process, 12 new ventures in Switzerland were arranged for interviews. In China, we found firms mostly through internet research. The participant lists of various industry fairs were scanned for firms which suited our age and manufacturing criteria. As a result, interviews with six new ventures were conducted. One was rather young (has existed for 4 years), and three were founded 7 to 8 years ago. All these firms had not reached a mature stage in the sense of established firms yet, therefore two older ventures were examined as well (Appendix Table 5: ID 16 and 17).

In all interviews we asked sequentially open-ended questions with follow-up questions to investigate interesting answers more deeply (Fauchart and Gruber, 2010; Spradley, 1979). Questions covered four aspects (Appendix): (i) profile and background information related to the interviewee and the new venture itself; (ii) all major operational topics addressing the upstream SC, including supplier selection, procurement routines, outsourcing decisions, R&D alliances, and partnerships; (iii) topics addressing the downstream SC, including distribution channels, distributors, the usage of logistic service providers (LSP), and customer service; (iv) operational orientation of the founders. For topics (ii) to (iv) we tried to capture time variance by asking for initial conditions and changes over certain years after incorporation. For purposes of influencing and rationalizing the answers we did not asked for DCs or any of the four defined DC dimensions (*Sense*, *Integrate*, *Develop*, *Reconfigure*) directly. Finally, interviewees could add relevant ideas and topics which were not addressed before. Interviews lasted for 45 minutes to 1.5 hours (on average 60 minutes) and were conducted both in English and German (translated into English later).

Table 2: Aggregated statistics of the examined firms

All firms	**Mean**	**Median**	**MIN**	**MAX**	**Std**
Revenues (m USD)	97.7	6.0	0.5	1,154.3	279.3
Firm age (years)	7.6	6.0	2.0	19.0	4.8
Total employees	1,531	28	6	15,000	4,333
Current phase	Stability	Stability	Growth	Stability	--
Years in *start-up* phase	3.13	3.00	2.00	4.00	0.72
Years in *growth* phase	2.44	2.00	1.00	5.00	0.89
Years in *stability* phase	3.00	2.50	1.00	9.00	2.26

3.3.2. Data analysis

Data analysis took place simultaneously and incrementally during data collection (Barratt et al., 2011; Glaser and Strauss, 1967) and followed generally accepted coding procedures (Miles and Huberman, 1994). After the first three interviews, we added the often mentioned topic of research partnerships to the interview instrument (Appendix). Our review of evolutionary ecology theory and especially new venture growth literature indicated the existence of time phases in the evolution of new firms into established ones. Hence, we read through all interview transcripts to identify more or less distinct life phases, which was independently achieved (start-up, growth, and stability phase) and discussed later. Afterwards we followed our a priori constructs (Eisenhardt, 1989) of external operations including upstream and downstream SCM topics to derive matrix-displays (external operations vs. life-phases) as separate files. Two researchers coded independently the final categories. After 18 new ventures theoretical saturation (Denzin and Lincoln, 1994) was reached, a point where no new insights on external operations of new ventures and time variances appeared. Any discrepancies between the two coders could be discussed, which confirms the internal validity of the used conceptual framework. This coding was then used as the main data to derive the findings. To interpret and find common patterns we first analyzed within cases and then across cases. Then we identified DCs in these derived matrices, which match the four dimensions of DCs found in the literature (*Sense*, *Integrate*, *Develop*, *Reconfigure*).

3.4. Findings

Literature agrees that growth of new ventures is not happening homogenously during the first years but in distinct life phases. At the beginning of our analysis we identify three phases which the interviewed founders, CEOs, and managers used to structure the early life of their firms. Then we searched for DCs which the new ventures applied in each of these life phases. Therefore, we analyzed each external operations topic of the conceptual framework (e.g., outsourcing, purchasing, etc.).

3.4.1. New venture life phases

Many scholars have investigated the growth of manufacturing based new ventures and identified life phases like conception, commercialization, growth (Kazanjian and Drazin, 1989), direction, delegation, coordination (Greiner, 1998), start-up, growth, and stability (Tatikonda et al., 2013). Even though terminology is sometimes different, these breakdowns into phases are more or less consistent. Similarly, we could confirm and characterize three main phases of new venture growth from our field interviews:

Start-up phase. All interviewees referred to an initial, early or ramp-up time of their firm. After receiving some funding the manufacturing new ventures had to build or improve prototypes, hire key employees, and manage to get first customer orders. All these steps a new venture goes through until it has a product ready for market release at large scale. We labelled this time span "start-up phase" and collected statistics from the 18 new ventures (durations in years: mean 3.13, median 3.00, std 0.72). The identified phase matches recent empirical results by Tatikonda et al. (2013) and others.

Growth phase. Since our sample consisted of highly successful new ventures, they survived early years to then face strong growth of revenue or at least employment for industries where sales take a long time to kick in, e.g., biotech and medical technology. Interviewees described how production output could hardly satisfy demand growing double-digit percentage per month. Demand growth was fueled by parallel market entries in new countries. These stormy phase was reported to be approximately from the fourth to fifth year after foundation (mean 2.44, median 2.00, std 0.89).

Stability phase. After years of quick growth, new ventures went to their last stage before turning into an established firm, the stability phase. In this phase, ventures already have a large customer base, high growth rates become difficult to maintain and will eventually lower to normal market growth rates. Corporate structures become more formal. Ventures often start the development of new product lines or products derivatives, exploit further countries to maintain high growth rates (Kazanjian and Drazin, 1989) and deal with intensified competition from copycats or larger firms. In most cases, we observed the begin and middle of this "stability phase", but therefore included older firms to capture the transition from new ventures into established firms (mean 3.00, median 2.50, std 2.26).

3.4.2. Influence of dynamic capabilities on new venture growth

To reiterate the DC argument, when a firm grows it requires active *reconfiguration* and extension of its existing resource base. Extension includes the *development* of internal resources and *sensing* and *integration* of external resources, which are in total the four dimensions of DCs. With regard to the upstream and downstream SC of firms, we would expect specific DCs to be responsible for implementing necessary changes of the resource base. Due to the observed high time variance of new venture characteristics (*start-up*, *growth*, and *stability*), our findings suggest different DCs to be relevant in each of the three life-phases. Firstly, we explain in greater detail the DCs identified in the case studies, to secondly summarize them in Table 4.

Upstream operations. Manufacturing based new ventures face resource scarcity compared to established firms, which forces them to leverage external partners for their production and R&D. The following four aspects (outsourcing, supplier selection, procurement routines, and research partnerships) cover the routines described by the informants to setup and management their upstream operations.

Outsourcing. The sum of make-or-buy decisions determines the level of outsourcing of a firm. Production and assembly were sourced out by the new ventures to a highest possible degree. Four firms did not even add any value by themselves due to outsourcing the entire production. Central argument were production cost, since the interviewees stated they cannot produce larger quantities at competitive prices on their own. When the firms industrialized their prototype-production they had to develop an entire operational resource base. Additionally, one could identify an outsourcing decision capability responsible for determining make-or-buy for all processes and components. The share of outsourced operations stayed stable across the life phases without major fluctuations implying that make-or-buy decisions in the start-up phase determine the path for growth and stability phase.

> Everything was extremely lean, but not as a decision, there is just no possibility to make it different. You cannot afford to pay people. There is no choice. (Consumer devices 1, W.K.)
> We own the patents and made the detailed construction plans. We do not produce by ourselves. We only do customer service and sales. (Security Equipment 1, K.O.)
> We still do much more in-house than we intend to. The modification of the products is highly specialized work, we cannot write that in a manual. You have to teach someone for over a month, which is the reason we do it in-house. (Medical devices 1, U.S.)

Supplier selection. In the start-up phase we found among the 18 ventures three main supplier selection criteria: (i) geographical closeness, (ii) technical capabilities, and (iii) flexibility regarding prototyping/small batch sizes. The capability of selecting suppliers consists mainly of the two DC dimensions sensing and integration. Sensing includes the way suppliers are identified and assessed. The interviewed firms used suppliers they already knew from previous working experience or through contacts to minimize risks. In case of missing experience with suppliers, interviewees reported they asked already chosen key suppliers who is capable of delivering the sought component or technology. This way they integrated technological knowledge and capabilities of the supplier into their existing base. In the growth phase, the focus of this supplier selection capability shifted toward readiness-to-deliver and reliability. In the stability phase, start-ups faced first cost pressure due to increased competition or negotiations of industrial clients leading to reconfigurations of the supply base. Then the most relevant selection criteria were cost and transparency. The supplier selection capability allowed four of the ventures to utilize ERP systems of their suppliers as a first step to professionalize own IT resources.

> Cost is a topic of the future. Flexibility is more important. A supplier needs to be willing to try new things and to reserve us some machine time to do tests. (Materials 1, H.M.)
> Know-how defines a supplier and is critical for his selection. Cost are not a focal point with small production numbers. (Measurement and testing technology 1, F.H.)
> We are constantly looking for alternatives. There is a company in Switzerland producing [device], I think XY. They approached us if we wanted to produce at their place. Switzerland is better quality, but it was too expensive. The guys in Poland are our best option right now.
> (Consumer devices 1, W.K.)

Procurement routines. In the start-up phase interviewed firms had no existing procurement routines in place. Therefore, first actions focused on partnering with the chosen suppliers similar to a dynamic alliance management capability (Schilke, 2014). A further integration of external knowledge resulted from the capability to leverage ISO and other certifications of suppliers to gain trust of customers and from hiring procurement experts. The growth phase is characterized by a professionalization of procurement possible due to increasing order volumes. DCs belonging to the dimension *develop* improve the existing supply base by e.g., the introduction of material and revision numbers, second sources for critical components or stricter auditing of single sources, supplier specific technical specifications (resulting from mistakes), checklists and testing of random samples for inbound parts. In the growth and stability phase *reconfiguration* DCs are supplier related adaptations, like introducing framework contracts, renegotiating terms for cost reduction, and switching of suppliers in case of problems.

> Our suppliers do have the constructional plan with all details. We give them everything, since they need the information anyways. It’s a trustful relationship. We do not mind, since the important part is the software. The physical product might be copied but the cost/complexity is at some other place.
> (Measurement and testing technology 2, A.K.)
> From the beginning we implemented our production and quality management according to the ISO 9001. We saw it as a huge opportunity as amateurs in this business. (Medical devices 4, W.W.)
> In case of problems with components and commodities you can always change. But in case of important components or key supplier changing the supplier is not that easy, there you try to solve the problem together. Of course you always search for alternatives, but normally you use the new alternative when you develop a new product. (Measurement and testing technology 3, U.E.)
> […] Another example: front panels. The white shiny things. Often there are scratches. The painter says: “It wasn’t me, they left my workshop in perfect condition.” The printer says: It wasn’t me, they arrived already damaged.” In the end we had to pay everything, throw them away and order new ones. Today the process is different. The printer buys the panels and sells them to the painter, who sells them to the konfektor. All control their incoming products and reject the damaged ones. Since everyone buys the product for themselves none of our money is involved. In the end, the panels come to us. We control them and only then we pay. Basta! Awesome! Nevertheless, it was a lot of work to set up this simple three step process. 3 weeks full time. We needed 2-3 years until it was established.
> (Measurement and testing technology 2, A.K.)

Research partnerships. In general, there was an extensive and close co-operation between new ventures and R&D-partners that started in the start-up phase. The main reason for research partnerships was to complement own missing technological knowledge and do cutting edge research in a both cash and cost efficient way. With national research programs, e.g., Swiss KTI projects, many firms leveraged public funding for conducting R&D with suppliers. DCs allowed the ventures to sense these resources by reviving connections to former universities and to integrate resources such as funds from other public agencies, hiring specialized experts as employees, and prototyping capabilities of research institutions. In the growth and stability phase these research partnerships continued. The level of outsourcing and routines stayed roughly the same. However, with the gained track record and reputation it was now possible to start partnerships with industrial clients and other innovative small firms.

> In the first two years we could use the equipment of our old research institution to fulfil the first customer orders. (Measurement and testing technology 4, S.T.)
>
> For one product we build prototypes with a Swiss partner. From the beginning it was clear: only prototypes no serial production, the cost didn't give us another option. There we did everything right. It was a knowledge transfer from one partner to the next. We used the finished prototype to go to potential suppliers to ask: "This is how it works. Would you produce it and what would it cost?" (Materials 1, H.M.)
>
> We did several KTI projects. Mainly with technical colleges. We profited from these projects. We supervised several study projects. There we profited, too. We could leverage their resources. We were missing the knowledge and later we hired 2 students. So we accomplished a knowledge transfer from the university to us. (Measurement and testing technology 3, U.E.)

Table 3: Quantitative description of new ventures‘ external operations

Characteristic	Yes	No	Not assignable/ not available
Own operations (or just managing a SC)	13	5	0
Truly new product	7	10	1
Relevant R&D partnerships besides suppliers	12	3	3
Usage of distributors	11	5	2

Downstream operations. To bridge the gap between production and customers various elements are required like distribution channels, transportation, and customer service. Similar to the upstream operations, DCs help to identify distribution partners, to integrate external resources like experienced sales staff, means of transportation, and other sales knowledge into the new venture. Later, these and other capabilities are developed and reconfigured as described in the following.

Channel expansion. In the start-up phase one half of the interviewed firms entered into an existing product market without own track record, the other half tried to create a market for a completely new product, which resulted in try-outs of different distribution channels and target customers. Later these first customers and distribution channels were exploited to gain more insights and feedback about the product and customer experience. In the growth phase new ventures transferred themselves from R&D-driven firms to sales-oriented ones. This began by developing capabilities of an own sales/marketing department. On product and country level, experiences from one were transferred to future ones. In the stability phase firms kept on expanding their customer base, but also shifted their sales channels away from direct sales to distributor based sales (DC dimension *reconfigure*).

> Switzerland was our test market. We tested a broad variety of sales channels e.g., pharmacies, hospitals, internet and direct sales. (Consumer devices 2, D.K.)
>
> It makes sense to sell the first products close by. However, often that comes naturally since innovation is often triggered by your customers. That can be research institutions as well, since they are relatively flexible. (Measurement and testing technology 3, U.E.)
>
> First the US market, then the rest of the world. American researchers see the possibility to be the first and to exploit a new technology. He himself has the authority to buy and just buys. (Measurement and testing technology 2, A.K.)
>
> At one point we shifted our focus on sales. After the first years with a team of 5 or 6 members we build-up a sales department. For us it was more difficult than the set-up of the development department, since we had no experience or contacts in that area. (Medical devices 1, U.S.)
>
> We wanted to transfer our experience to other countries. So we wrote manuals and adapted them locally. (Consumer devices 2, D.K.)
>
> (In the stability phase) The expensive sales channels cannot be utilized anymore. You cannot fly to Hamburg for a presentation. We want to introduce a web shop. That comes at the same time as our ERP. (Measurement and testing technology 2, A.K.)

Direct sales. In the start-up phase first sales were generated by the founders in 16 out of 18 firms. These first customers were convinced via specialized trade fairs, cold calls, and specific conferences indicating DCs of the sensing dimension. Other new ventures searched for potential applications of their product and called along these other SCs to find the manufacturing company, who could finally use their product. In the growth phase, firms build-up sales/marketing departments. They described the US market can be accessed via direct sales without problems due to the straightforward buying practice of US customers. Smaller countries were not targeted by direct sales due to low absolute market volumes and cultural differences. In the stability phase sales efforts shifted from direct channel to distributors due to limited scalability of direct sales. However, this resulted in lower gross margins, since selling directly saved the payment of distributor margins. But a reduced direct sales force was still required to stay in close contact with the customers for gaining knowledge to integrate into new products or product improvements. Furthermore, the firms' sales force pushed out competing suppliers at already existing customers by exploiting scaling and experience effects.

> Considering it from the retro perspective, it was a three step process. In the beginning we contacted the brands via cold calls. Since they do not produce by themselves anymore they lead us to their industrial partners. So we contact the industrial partners directly. Those industrial partners produce for several brands. Then we went to them and tried to convince them to use our materials in the other brands as well. These are always direct contacts.
> (Materials 1, H.M.)
>
> With company x we worked together when they asked us to join them to attend a trade fair together. Then we got attention, applied for public research funds. But always we actively approach customers.
> (Security equipment 1, K.O.)
>
> With direct selling you get more margins, but the money comes much, much later.
> (Consumer devices 1, W.K.)

Distributors. In the start-up phase distributors were an important source of liquidity, since they pay upfront. The new ventures utilized distributors to multiply their own sales power (DC dimension *integrate*). Especially Japan, Asia and small countries can be approached best via distributors. Successful distributors were found on trade shows or via references. In general, it was the objective to be the distributors' preferred product in a segment, which could be accomplished by extensive support and sharing margins. In the stability phase sales of especially less complex products were shifted from direct sales to distributors. One very valuable measure was to leverage the own increased sales volume and reputation to push distributors in negotiations to guarantee a minimum purchase volume. This reconfiguration guaranteed revenues and thereby improved planning reliability.

> Distributors aren't all so good. It is their potential and you have to work with them, so that they can perform. They have many products and you have to fight, so that they are selling your product and not others. It is a lot of work on your side but in the end they are showing your product to the clients and that is the only thing on earth you want. (Medical devices 2, S.V.)
>
> Distributors they pay upfront, but they get 10% to 15% on top of the production price. So you get the money immediately but have less margin. (Consumer devices 1, W.K.)
>
> We try to negotiate a minimum purchasing quantity to secure a certain amount of revenues. (Medical devices 3, P.N.)

Transportation. In general, new ventures handled transportation in a straightforward manner. In the start-up phase standard parcels by DHL or FedEx were first choice. The initial production numbers were too low for sophisticated routines. The new ventures suffered from paper work associated with country specific customs rules. Wherever possible, they tried to tap the information pool of local distributors or their transportation providers to avoid those problems. The interviewed firms clearly prioritized agility and speed over cost, which matches their preferences in selecting suppliers. To lower administrative cost, firms created wikis with country specific information and had one employee in the stability phase who dealt with customs and accumulated knowledge in that field. Further, firms reconfigured transportations by outsourcing its management, which freed up internal resources. New transportation partners were then chosen with regard to possible ERP integration and traceability.

> We did a project to professionalize our transportation processes. But it was vain. Our quantities are so small that transportation companies do not read an AFQ. […] in case of a delivery we are supposed to give the transportation companies a call and they say us the price. (Materials 1, H.M.)
>
> One problem was that we never thought about the transportation of our product to the customer. Our first tries were not successful thus we had to develop a special package. One customer demanded these special packages and so one additional product was developed. (Medical devices 3, P.N.)

Customer service. In the start-up phase CEOs normally were the point of contact for customers. Customer service was considered important, due to its ability to collect direct feedback about product quality and differentiation from competitors. In the growth phase customer services was professionalized by developing DCs creating blogs, user manuals or outsourcing the fixing of minor problems to distributors. In the stability phase a high customer service response level was established. Firms introduced video live streaming, regular visits of industrial clients, seminars and workshops to educate their customers about new features or to exchange experiences. In this phase, first customer service departments have been set up.

> Improvement via feedback from failures. (Measurement and testing technology 1, F.H.)
> Marketing/Sales manage the support, the user manual, the website and the blogs. We outsourced nothing. From the beginning we offered this level of support. Standard and premium. In the beginning it does not matter, since we sell every year more products than currently on the market. Of course you have to support the old products but the needed resources are insignificant. (Measurement and testing technology 2, A.K.)
> Of course, the transformation from a research oriented firm to a sales driven one hast to be done systematically and deliberately. Previously there were ad hoc solutions. Depending on the problem the expert was asked. Now we hired someone whose full job customer service is. He just was in China and now goes to India to give instruction courses. (Security equipment 1, K.O.)

The identified DCs across different external operations topics can be assigned to the four DC dimensions *Sense*, *Integrate*, *Develop*, and *Reconfigure*, as shown in Table 4. From a practical perspective, these collected DCs are best-practices for growing a new venture's initial resource base, whereas more theoretically, one can see a shift from dimensions *Sense* and *Integrate* dominating the startup-phase toward *Reconfigure* dominating in the stability phase.

Table 4: Identified patterns of dynamic capabilities

Dynamic capability dimensions	Start-up phase	Growth phase	Stability phase
Sense	• Supplier Selection: technical capability assessment (quality), flexibility, geographical closeness, use of existing contacts, utilize key suppliers to find other suppliers • Feedback sources: first customers nearby or development partners • Sales: specialized trade fairs, cold calls, specific conferences, leading researchers in the field • Revive research connections to former university contacts • Identify applications and trace back SCs to potential customers	• Supplier Selection: readiness to deliver, reliability especially regarding quality, European supply chain focus • Intensify communication to key suppliers • Find new distributors on trade shows or via references	• Identify potential to push out competitors at existing customers • Actively networking with potential suppliers, R&D partners, and distributors
Integrate	• Cooperation with R&D partners in case of missing knowledge • R&D partners utilized to hire specialists • Partnerships with key suppliers for technical capabilities and flexibility, also leverage their ISO certifications in sales • Hire purchasing expert if not in founding team • Leverage of distributors' customer reach and reputation • Tap information pool of local distributors for paper work and customs	• Multiply sales power by approaching successful distributors in other countries • R&D partnerships with big industry corporations and small companies who have a track record	• Leveraging buying power and gained pricing insights at supplier negotiations • Utilize suppliers' ERP systems if possible • Continuation and development of existing R&D relationships
Develop	• Start to build up ISO 900X routines • Test different distribution channels and customers: try industry typical first • Direct sales to existing contacts and experts in the scientific field • Make outsourcing decisions for parts and manufacturing processes	• Introduction of purchasing routines (material numbers and revision numbers); second source for critical components, stricter auditing of single sources; checklists, testing of random samples • Transfer start-up experiences to new countries and customers • Build-up of own sales force and marketing department • Distributor development • Customer service: blogs, user manuals, complaint management process • Build-up of customs specific knowledge and routines (wiki etc.)	• Develop a low budget product line • Focus on key customers (volume and R&D partnerships) • Differentiation from competitors/ copycats by high quality customer service (video live streams, regular visits of industrial clients), formation of a customer service department • Prepare ERP solution that integrates upstream and downstream flows
Reconfigure	• No existing resources to reconfigure yet	• Negotiate framework contracts with suppliers to stay flexible, renegotiate existing terms • Switch commodity suppliers in case of issues	• At the latest, outsourcing of organization of transportation and customs • Shift from direct sales to distributor-based sales for mass products, push for guaranteed purchase quantities • Increase SC traceability • Huge efficiency gains: sea freight instead of air freight, less partial or express delivery

3.4.3. Dynamic capability dimensions of new ventures

In the following we characterize the DC dimensions found in new venture growth and derive propositions for future research.

Sense. In the start-up phase new ventures have to identify relevant external resources that could complete their own and often scare resource bases. Focusing on operations related topics, components, technological knowledge, and customer feedback are highly required. An assessment of suppliers completes the initial set of DCs to sense resources. In later stages, partnering capabilities become relevant to manage the relationships with existing and new suppliers, R&D-partners, and distributors.

> ***Proposition 1a:*** The focus of sensing DCs of new ventures lies in the start-up phase on identification and assessment and shifts toward partnering in the stability phase.

Integrate. DCs are the main set of routines to integrate external resources into the new venture. In the beginning, these are primarily key personal, technological knowledge and public R&D funds, whereas later sales power of distributors and resources of stronger R&D partners become important.

> ***Proposition 1b:*** Growth of new ventures results from integration of external resources into the resource base.

Develop. Firms internally grow their existing resource base by development DCs. Whereas in the beginning knowledge and routines have to be build-up, later entire departments have to be formed out of loose organizational structures and e.g., IT systems developed. Similarly, the development of new product derivatives is the result of development DCs.

> ***Proposition 1c:*** During the growth phase new ventures professionalize their resource base by developing routines, departments, and later product derivatives.

Reconfigure. Strong growth of new ventures requires especially in the stability phase major rescaling, adjustments, and implementation of first customer learnings on the resource base.

> ***Proposition 1d:*** During growth and stability phase new ventures reconfigure their resource base by altering routines, suppliers, and distributors.

We observed how different DCs allow new ventures to build up their resources base and facilitate strong growth. Figure 1 provides a stylized overview of new venture growth and varying relevance of the four identified DC dimensions over time.

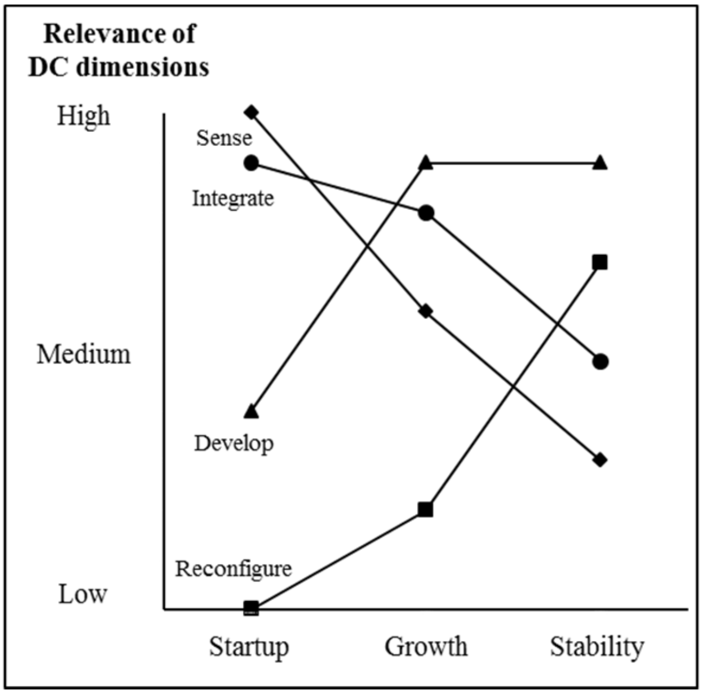

Figure 1: Relevance of DC dimensions

3.4.4. Extension to the analysis: path dependence of capability development

By investigating DCs we analyzed the capability and resource base development of new ventures across their initial 6 to 8 years after incorporation. Initially new ventures face resource scarcity. The founding team itself represents most of the human resources, few machinery are owned but lots of knowledge of the founders including intellectual property (IP) was front-loaded before incorporation in years of work and scientific experience of the founders. On this resource base new ventures solve problems to a large part intuitively by non standardized methods like improvisation, trial and error, and experimentation as well as imitation (Zahra et al., 2006).

> As a start-up you never have enough money to do what you want. So you have to start playing and it is a daily juggling with your resources. It is not a big company, there are no rules. You take things the way they are. And search for better ideas. And try to impact the market with half the money your competitors have. That is the start-up life. (Medical devices 2, S.V.)

A vast stream of learning literature suggests an incipient accumulation of experiences and learning that determines the path of future learning (Cohen and Levinthal, 1990; Autio, Sapienza and Almeida, 2000). Since capabilities are learned processes and routines, and there are two types of them, resource base utilizing (operational) and altering (dynamic), one would expect path dependent learning effects for capabilities as well. Indeed, we observed a transition from intuitive problem solving to standardized or professional routines that determined to large part resource base and possibilities to grow in consecutive life phases. This has two effects, resource bases get less variable due to high lock-in or switching cost after outsourcing decisions, supplier selection, and distribution channel selection. But also the applied DCs, which lead to these decisions (*Sense*, *Integrate*, *Develop*, *Reconfigure*), become more stable through learning effects: supplier selection and procurement rules get introduced, best-practices for distribution, customs, and transportation are applied to newly entered markets. So we could observe a stabilization of the firms resources but also the way it utilizes and alters them. This confirms earlier research proposing capabilities result from "interpretations and outcomes of actions" (Schilke, 2014, p. 181) rather than being intentionally planned (Zahra et al., 2006). Schreyögg and Kliesch-Eberl (2007) mention learning problems in highly changing environments, but in our cases no such hyper dynamic environments could be observed when looking at e.g., innovative niche markets, global market access, and market stability in Switzerland and China. Figure 2 summarizes a conceptual framework for capability development. Propositions 2a and 2b focus on the development of DCs across the life of new ventures.

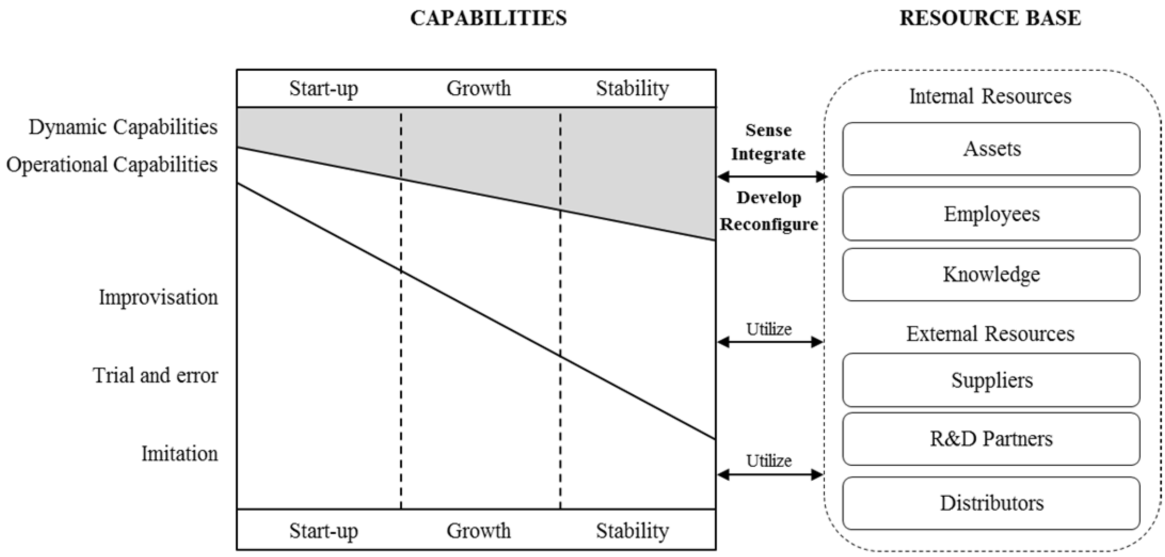

Figure 2: Schematic model of capability development

Proposition 2a: The older new ventures become, the more dynamic (and operational) capabilities they apply.

Proposition 2b: DCs are path dependent, meaning they result from actions and learnings in the past and remain quite stable over time.

3.5. Discussion and conclusions

3.5.1. Theoretical and practical implications

Despite a plethora of recent research which investigates the nature and role of DCs in general (Barreto, 2010; Helfat and Winter, 2011; Schilke, 2014; Stadler et al., 2013) and in the field of entrepreneurship in particular (Zahra et al., 2006), our research addresses several calls in the literature by presenting an in-depth analysis of real-world DCs of new ventures (Tatikonda et al., 2013) and consolidating the variety of notations and meanings used for DCs (Barreto, 2010; Makkonen et al., 2014). Nevertheless, by theoretical induction new-venture-specific setups allow to better understand the nature of DCs for firms in general (Schilke, 2014).

We began this study by identifying three time-phases in the life of 18 analyzed new ventures. An initial *start-up phase* of approximately three years includes activities as prototype development, first sales, and hiring of key employees. Important decisions are realized by DCs, such as the selection of first suppliers or the testing of distribution channels. This develops a resource base capable to supply strong revenue growth in the subsequent *growth-phase*, in which numerous routines are implemented to professionalize operations and allow scalability for entering markets in new countries and distribution channels, and more generally grow in headcount and assets. Thereafter, the *stability-phase* covers how new ventures mature and grow profitable with product derivatives, in additional countries, and often under increased competition. All these phases show quite distinct characteristics and help to structure the life span of new ventures. They confirm and update life-cycle concepts and time phases reported in the literature (Gilbert et al., 2006; Greiner, 1998; Tatikonda et al., 2013).

Our case studies shed light on the relevance of external operations for new ventures in general, and DCs in particular. After answering questions of financing and marketing, founders ask themselves: How to operationalize their dreams? With nine analyzed SCM/Operations Management (OM) topics it was possible to cover key decisions and issues determining up- and downstream operations. In each of them, the build-up of the resource base and operational capabilities was carried out by DCs. We identified and detailed four distinct dimensions of DCs – *Sense*, *Integrate*, *Develop*, and *Reconfigure* (see Table 2 and 4). Besides making the theoretical topic of DCs more tangible, this helps the stream of DC literature to become more empirical and show its universal applicability (Barreto, 2010; Schilke, 2014).

Results presented in this research impact the SCM/OM field in two ways. First, the scope for investigating DCs is further broadened to new ventures instead of only established firms. New ventures' high rate of change in the initial years and a path dependence of learning experiences allow to understand the development of DCs much better than studying merely the outcome at established firms. Especially, since learning results from intuitive actions and outcomes, to subsequently form routines and capabilities (Zahra et al., 2006). Second, DCs are not just crucial for the transition from resource scarcity to an established resource base, but with increasing firm age the majority of resource base changes results from DCs. We found a higher relevance of development and reconfiguration DCs in later life-phases of new ventures, indicating internal efforts like improvement, innovation, and change management are most important for upgrading the resource base of established firms compared to external efforts (e.g., R&D-partners, suppliers, distributors).

Besides giving a starting point for theory building to explain operations of new ventures, our results are beneficial for founders of new ventures and managers of corporate ventures in at least two ways. First, the case studies offer patterns of directly applicable DCs, which are best-practice capabilities of highly successful manufacturing based ventures from Switzerland and China. As firm environments and starting positions are manifold, these patterns mainly help to prioritize professionalization efforts and benchmark the own development against competitors and cross industry. Second, it provides a systematic approach for explaining and communicating the build-up of operations. For example, life phases help to structure the rapid expansion and shift foci to most likely upcoming operational issues like product derivatives, supplier contract renegotiation, or ERP preparation in the stability phase. In contrast, new ventures with a low level of outsourcing should evaluate steps to free internal resources, like working capital or employees, by integrating external resources of possible R&D-partners, suppliers, or distributors.

3.5.2. Limitations and opportunities for future research

This study comes with limitations which need to be considered when interpreting the results. Explorative case studies hold many weaknesses from a methodological viewpoint. Although we tried to maximize heterogeneity in the firm sample and achieved a theoretical saturation in the findings, aspects like external validity, idiosyncratic conclusions, and the direction of causality (Fauchart and Gruber, 2011) are typical issues to improve with future large scale empirical studies. More rigorous surveys or archival resources should build on this foundation and validate the identified DC dimensions and life phases. We took DCs and more broadly the RBV as a theoretical lens to understand resource base development of new ventures, but also other factors or mechanisms might cause the observed resource changes. One could think of investors and other stakeholders influencing decisions to expand resources or join R&D-, supplier-, or distributor-partnerships. Furthermore, a country-bias (Switzerland, China) and a survivor-ship-bias (resulting from selecting only highly successful ventures about 8 years after foundation) might have inflated or deflated the observed effects.

Additional alleys for future research could include the following. Besides characterizing the nature of DCs, more insights are required on how to improve and actively manage them in practice. Especially, since antecedents and factors influencing the development of DCs are hardly known yet. Although our research hints the location of such factors at the founders, future studies could explicitly target the origin of DCs. Finally, service based new ventures and their operations seem to be a promising field of research from a DC perspective (Tatikonda et al., 2013).

3.5.3. Conclusions

DCs became a key concept for explaining performance differences among firms, yet the state of knowledge about how they evolve is still nascent (Barreto, 2010; Schilke, 2014; Stadler et al., 2013). Literature to date especially failed to empirically verify and detail the concept of DCs in real-world settings. Our study aimed at answering these questions by presenting a systematic description of external-operations-related DCs across the life-phases of new ventures. We used an explorative research design to specify four DC dimensions (*Sense*, *Integrate*, *Develop*, *Reconfigure*), their relevance, and development over time. The provided typology of DC dimensions encourages a consolidation of research fronts and might be applicable to established firms as well.

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3.7. Appendix

Interview instrument

External Operations of New Ventures: Supply-side, Distribution, and operational orientation

Profile information

- Related to the **interviewee** (role, time with the firm, responsibilities, experience especially in SCM and operations)
- Related to the **new venture** (foundation, revenue, employees, products, technology, core competency, SCM positioning, main customers, management team)

A) Supply-Side/Procurement/Outsourcing/R&D Alliances

1. Evolving **supply chain** (Supplier, OEMs)
    - When and how did you selected your **first suppliers**? Why did you end up choosing those back then? Do these suppliers still supply you today?
    - During steep production ramp up, did you selected suppliers by **price or their flexibility**?
    - How do you manage supplier after your firm stabilized?
    - **Procurement routines** (e.g., evaluating suppliers, long short list, ABC, plant visits, supplier meetings..)
    - When you ramped up production to which extend did you **share information** with your suppliers?

2. Inter-organizational **partnerships**: How and when to **exploit resources and capabilities of partners**?
    - If you have **partnerships with other firms or e.g., universities**, please name few examples how they positively affected your production and R&D? Explain.

3. When **opt in and out of partner and outsourcing relationships** (capacity availability/development of operational capabilities)
    - Did your suppliers cope with increased demand?
    - What did you do in case of problems? Switch? Develop in-house?

B) Distribution/Transportation/LSP/Customer Service

1. When did you set up each of your different **distribution channels**? Which key employees, customers, distributors, and knowledge helped you? How exactly? Did they change over time? (agility / cost) ?
2. **Transportation / LSP**
    - How do you physically get the product from your factory to the customer? Do you deliver yourself or use an LSP
3. What kind of **customer service** does your company provided and when?
4. Did you experience **backorders during phases** of strong growth? How did you cope with them?

C) Operational orientation

1. Influence of individual entrepreneur's "operational orientation" on operational capabilities and ability to shift operational foci
2. Examine trade-offs between operations/other functions
    - How important was operations in the initial phase of your start-up compared to Finance and Marketing?

Chapter IV

Real Option-Based SC Project Evaluation and Scheduling

Abstract

Supply chain departments spend their time managing numerous projects that will improve and maintain their supply chains. Recent literature has most frequently described the content of these projects and their scheduling but neglected to include risk and uncertainty in the expected cost, profits, and time durations of these projects. In this article, we have introduced real option valuation (ROV) to supply chain project scheduling as a flexible method to quantify those risks. Our proposed two-step framework links ROV to all relevant constraints of a multi-project setup by binary fuzzy goal programming. We applied the framework to a real life case study data of 21 projects that were facing numerous risks and resource constraints. The results show how scheduling performance improved in comparison to methods ignoring risk and uncertainty (e.g., net present value-based scheduling). For validation we conducted hypothesis tests and sensitivity analysis, and provide an in-depth discussion. The findings contribute to research and practice by capturing project-related risks and managerial flexibilities in general and in supply chains in particular.

Keywords: Supply chain management; Real option; Project scheduling; Binary fuzzy goal programming

4.1. Introduction

Since the 1970s, supply chain management (SCM) has evolved from a purely administrative function, where it played a passive and isolated role devoted to optimizing the sourcing silo, to a strategic function that deserves top-level management attention. This switch in the management's mentality is attributable to the substantial impact of SCM on the firm's overall performance (Croom et al., 2000, Schoenherr et al., 2012). In terms of value, approximately 50% of a manufacturing company's operational expenditures are devoted to supply chain activities (SCAs) (Sopher and Roth, 2010). In a rapidly changing and competitive business environment it is essential to continue improving and implementing new technologies in the SC (e.g., roll-out of a new order management software, integration of new production facilities). Whereas most research in SCM develops concepts and methods for such improvements, there is a stream of literature trying to determine which of these concepts to select and how to schedule the resulting projects without overburdening the organization. The majority of the work focuses on software selection. Wei et al. (2007, p. 627) pointed out that the selection of "adequate SCM project[s] remains a major concern". They criticized commonly used methods such as scoring, ranking, mathematical optimization or programming for their ability to handle only quantifiable attributes and recommended replacing it with a fuzzy selection framework. Padhy and Sahu (2011) suggested a model for similar project selection problems in the field of Six Sigma. Thereby a selection from a portfolio of potential projects brought substantial benefits for the organizations implementing Six Sigma concepts. The steadily increasing complexity of SCs requires a new project proposal to be both effective and resource efficient. Since the management faces firm-specific resource constraints, it is a task in itself to select an optimal subset of projects for implementation.

From a financial perspective, SC projects should be seen and evaluated as large capital investments into the SC of a firm. Capital investments are characterized by (1) an uncertain project value at the time of completion due to unforeseen events and changes of the business environment, (2) partial or complete irreversibility, and (3) flexibility during the project time span through periodical investment decisions of the total investment amount or even abandonment before completion (Teisberg, 1993). In theory and practice such capital investments are most commonly evaluated by net present value (NPV) methods (or discounted cash flow – DCF). NPV uses an interest rate to discount all future cash flows of an investment into a present value at the beginning. The interest rate is used to model investment-related risks, such that risky investments are discounted by a higher interest rate and low risk or risk-free investments by a low or risk-free interest rate. In its simplest form, positive NPVs signal reasonable capital investments, or competing capital investments are selected by comparing NPVs. Although NPV is the most straightforward method for capital investment evaluation, the literature mentions clear shortcomings which require a search for superior approaches (Smit and Ankum, 1993; Hult et al., 2010). First, all cash flows are assumed to be certain in their amounts and times, which is not given in a daily changing SC setup characterized by supply and demand uncertainties. Using a uniform interest rate per capital investment does not allow representation of varying uncertainty of the estimated cash flows across projects. Second, managerial flexibility of changing the investment-related cash flows by extending budgets, altering scopes, or delaying parts cannot be considered. At the beginning all flexible decisions have to be determined so that they can be evaluated. Obviously, uncertainty and flexibility as two main capital investment characteristics are insufficiently represented by NPV. They might work well in deterministic environments of complete certainty but not under uncertainty of rapidly changing SCs. The literature indicates two distinct types of uncertainty: A risk uncertainty that can be reduced by information over time and a genuine uncertainty (Scherpereel, 2008). In this study we will refer to them, for the ease of discussion, as risk and uncertainty. In the SC literature there have been many attempts to evaluate risks, but as Hult et al. (2010, p. 435) point out, there is “a lack of investigations that center on SC investment decisions when facing high levels of risk uncertainty”. On the one hand, numerous SC risks can affect investment payoffs and need to be analytically combined for decision making. On the other hand, SC managers continually adjust SCs and their investment projects; this requires some managerial flexibility. Capturing risk and flexibility in SC investment decisions would deepen the understanding of both in literature and in practice.

Recent literature has made real option valuation (ROV) the most popular solution for strategic decision making and projects characterized by high levels of uncertainty (e.g., Driouchi and Bennett, 2011; Liang et al., 2012; Wallace and Choi, 2011). Projects are often multi-staged decisions, which makes them according to modern financial theory “options –‘real’ options, as opposed to financial options – in which managers have the right but not the obligation to invest” (Copeland and Tufano, 2004, p. 90). This flexibility can be used to model managerial decision flexibility to defer, abandon, expand, stage, or contract capital investments. Hult et al. (2010, p. 435) have recommended ROV as “an appealing theoretical lens” for SC risk uncertainty. Investigating SC investment decisions with the help of real options would fit into a promising stream of literature on successful applications of ROV in the field of SCM (Dobson et al., 2012; Kodukula and Papudesu, 2006; Su et al., 2009; Tiwana et al., 2006; Tiwana et al., 2007). In addition to the application of ROV, this article proposes a solution that considers the resource constraints that each firm faces when improving its SC. Therefore the study focuses on two research questions:

- How can SC projects be evaluated as real options with their cost, time structure, and related risks?
- How can a portfolio of SC projects be selected and scheduled with considerations of the risk, time, cost and criticality of all projects subject to the constraints of the firm?

Our approach broadens the applicability of the ROV concept in SCM towards SC project investments. Combining ROV with a binary fuzzy goal programming algorithm contributes to the literature by linking two concepts that have been intensively discussed in finance and operations management with the field of SCM. Hence, we present another case where a multi-disciplinary and multi-method approach is better suited to meeting the contemporary challenges in SC practice (Sanders and Wagner, 2011). On a more practical level, we reveal a complexity reduction of decision making by introducing a step-wise method for scheduling SC projects. The method captures the managerial flexibility and uncertainty for each project. It lifts optimization to the level of the entire SC project program by making each project analytically comparable in the four dimensions of risk, time, cost and criticality. With case study data we demonstrate how a large set of project decisions in a SC is derived by following the method proposed. The results show how scheduling performance improved compared to methods ignoring risk and uncertainty, e.g., NPV-based scheduling.

The rest of this article is organised as follows. In Section 2 we provide a concise review of relevant ROV and project scheduling literature and develop hypotheses pertaining to the applicability of ROV. Section 3 proposes and details a two-step framework which includes the use of ROV to evaluate and fuzzy goal programming to schedule SC projects. In Section 4 we introduce the case of an automobile manufacturer for validating the framework with data from 21 large projects. In Section 5 we test the hypotheses. Finally, we summarize the contributions of our article and suggest future research opportunities.

4.2. Literature review and hypotheses

When linking two concepts from financial engineering (ROV) and operations management (scheduling algorithms) there are two domains of academic literature that explore aspects of the research questions: (1) ROV for projects in general and SC projects in particular, and (2) scheduling approaches for multi-goal setups. To address questions of superiority of ROV and its application we derive three hypothesis for testing on case study data.

(1) There is a large stream of literature focusing on real options in projects and capital investments. Most work has applied ROV to multi-stage R&D or software projects due to high uncertainties associated with those decisions. Since “the level of visibility and control can be reduced significantly” (Tang and Tomlin, 2008, p. 13), SCs spanning multiple suppliers and customers likely produce greater risk uncertainty (Hult et al., 2010; Dobson et al., 2012). Most recently Liang et al. (2012) and Wagner et al. (2012) stressed the impact of analysing and managing risk and uncertainty on value creation in SCs. As many authors point towards real options for dealing with high levels of risk and uncertainty (e.g., Driouchi and Bennett, 2011; Wallace and Choi, 2011), there are numerous recent examples of successful applications of ROV in SCM (Dobson et al., 2012; Kodukula and Papudesu, 2006; Su et al., 2009; Tiwana et al., 2006; Tiwana et al., 2007). For example, Costantino and Pellegrino (2010) have suggested a real option-based operations strategy to answer the question of whether to

procure the item from a single supplier or from multiple suppliers, which shows an elegant way to incorporate risk into SC decisions. Hult et al. (2010) place ROV in SCM on a sound empirical basis by testing predictions of real option theory in a SC context surveying 273 SC managers. Findings that SC managers "use real options thinking when encountering risk uncertainty" (Hult et al., 2010, p. 447) encourage further implementations of ROV. However, they call for more research on differences of real options in SC and modern financial theory.

To explore the applicability of ROV and important theoretical assumptions of ROV, three hypotheses are formulated below. Testing these hypotheses with case study data (Section 5) can support the establishment of ROV in the field of SCM.

In general, managers use NPV analysis as rule of thumb for estimating a project's value that neglects several types of risks. However, numerous authors (e.g., Mun, 2006; Liang et al., 2012) have advocated the use of ROV for estimating project values under stochastic market conditions. An advantage provided by ROV over passive NPV approaches is high risk predictability, which helps to identify and exercise options embedded in the projects, provide flexibilities of exercising (or abandoning) an option under a time horizon, and most importantly evaluate the project considering various uncertainties. We propose a hypothesis whether distinguishing NPV from ROV shows the superiority of one approach (Perlitz et al., 1999; Mun, 2006):

H_1: The ROV of SC projects is equal to the NPV of SC projects, i.e. ROV = NPV.

In ROV, risk is measured as implied volatility (IV), which is the current value of an underlying asset per quarter perceived by the management divided by volatility of a project. This is an indicator of sharp and frequent fluctuations of investment cash flows.

Implied volatility is a critical price determinant of stock options subsequent to the price itself. An alternative risk measure is the coefficient of variation (COV) of a project, the standard deviation divided by average investment per quarter. To investigate the difference between the two risk measures, we hypothesize:

> H_2: COV of SC project investments per quarter is equal to IV of SC project investments per quarter.

The two valuation methods used in ROV are either closed-form Black-Scholes-like approaches or binomial lattices (Mun, 2006). Lattice-based models give flexibility as to exercise, where the relevant rules can be set at each node. As time passes, the binomial lattice solution will closely approach Black-Sholes results. For instance, five or more time increments will be sufficient and will not be significantly different from the Black-Scholes solution (Kodukula and Papudesu, 2006; Padhy and Sahu, 2011). Thus, to test this assertion we propose the following hypothesis:

> H_3: The ROV using Black-Scholes approach is equal to the ROV using binomial lattices approach for the SC projects, i.e. ROVBS = ROVBL.

(2) From the plurality of models developed in empirical and quantitative research, one can derive insights for effectively scheduling projects in SCM. Several authors (e.g., Elimam and Dodin, 2013; Li and Jiang, 2012; Miltenburg, 2009; Wang and Shih, 2011) have obtained optimal production and distribution schedules of jobs using various analytical methods (e.g., mixed integer (non-linear) programming, constraint programming, genetic algorithm, heuristic and simulation models). Streams of interest

include processes and technology (e.g., batch production, mass production, and continuous production) (Li et al., 2009; Zhou et al., 2009), sourcing (e.g., vertical integration, outsourcing, single versus multiple sourcing, supplier selection, supplier relationship, and cooperation, coordination and collaboration with partners) (Meena et al., 2011; Ming-Lang et al., 2009), and planning and scheduling in general (e.g., processes, products, jobs, services, batches, and orders) (Paksoy and Özceylan, 2012; Santa-Eulalia et al., 2012; Wang and Shih, 2011). Each of these scheduling algorithms can substantially improve a firm's overall performance.

Subsequently, the field of SCM holds various starting points for deriving better scheduling and control of projects. Existing models considering cost, time, and interrelations do not focus on SCAs or projects (Autry et al., 2010), rarely quantify risk (Liang et al., 2012), or simplify operational flexibilities (Elgazzar et al., 2012; Hult et al., 2010). It is still a challenging task in both research and practice to prepare schedules of projects under stochastic market conditions (Govindan et al., 2012). Ideas for how to build risk and project features into common scheduling algorithms can be found in Mukhopadhyay and Ma (2009), who developed a mathematical model for joint procurement and production decisions in remanufacturing under quality and demand uncertainty. For a perishable product with a predetermined lifetime, a heuristic model for the joint determination of the price and the inventory allocation has been proposed by Chew et al. (2009). For the inclusion of fuzzy logic into algorithms, Chen and Wang (2009) cite an example in SCM for using the fuzzy VIKOR method. They have proposed an efficient delivery approach for evaluating potential suppliers. In summary, our work contributes to the literature by attaching real options as an input to a powerful project scheduling algorithm. This overcomes the shortcomings of NPV approaches which neglect risk. Due to its flexibility we suggest a binary fuzzy goal programming algorithm. Proposing an integrated framework we allow for identifying, modelling and conducting risk-balanced investment schedules in SCM.

4.3. Methodology to schedule SC projects

4.3.1. Framework

To achieve a schedule of projects that meets time and criticality, project sequence, and budgetary constraints, we propose the following two-step framework, in which we (1) identify and value SC projects using real options, and (2) schedule SC projects by binary fuzzy goal programming (Figure 1). The methodology is based on two research fields – real options and scheduling – and links them in a defined step-wise framework applied in a SC context. After giving an overview of the framework, Sections 3.2 and 3.3 will offer detailed theoretical insights on the most relevant steps in the framework. Finally, project data generated in a case study with a large automobile manufacturing company are demonstrating and validated in Section 4.

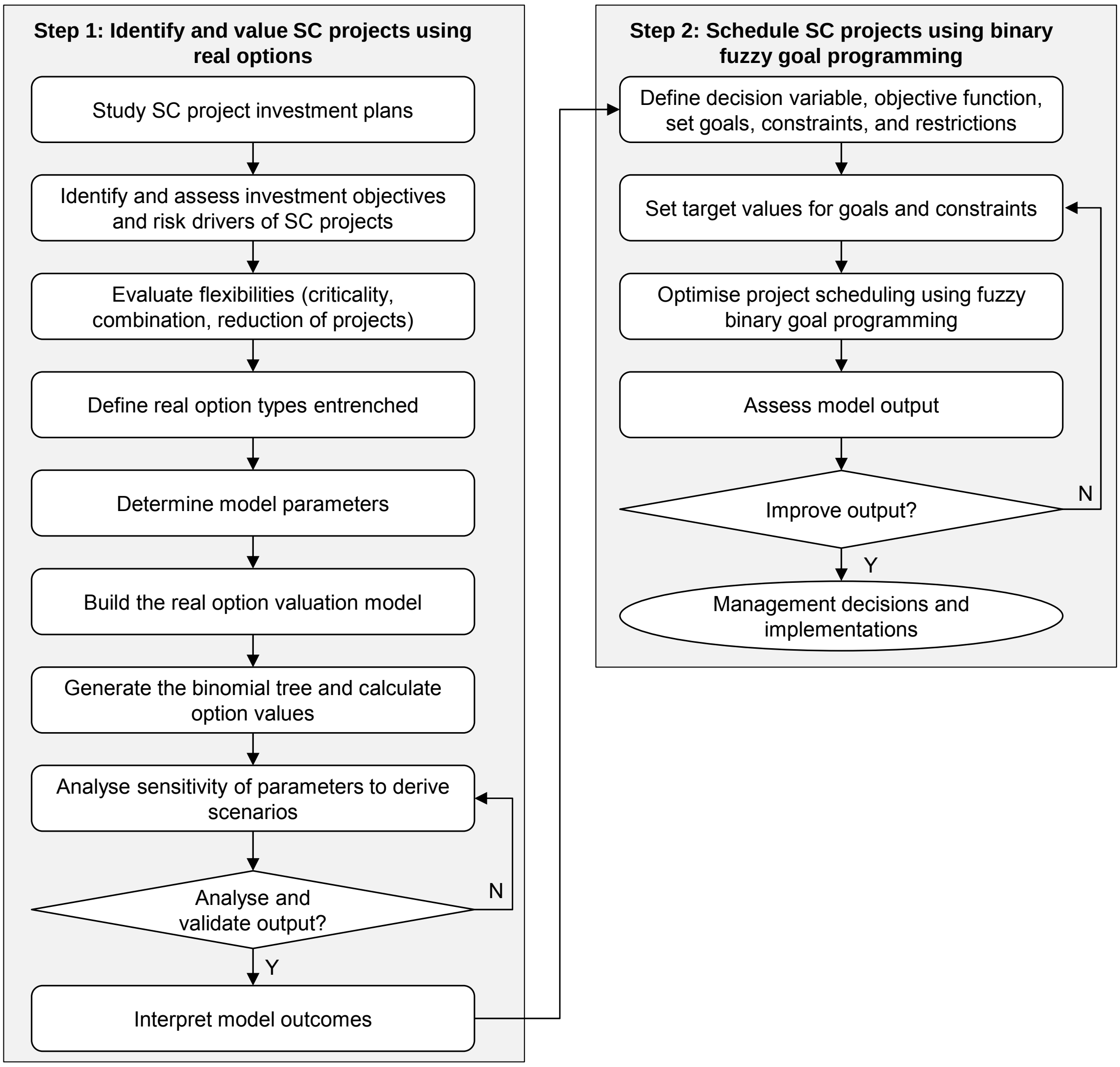

Figure 1: Proposed SC project scheduling framework

Step 1: Identify and value SC projects using real options

For all projects of a planning horizon that concern SCAs, investment plans have to be studied or even set up, including expected investments and payoffs which should be followed by the identification of investment objectives, requirements, and critical sources of risk drivers. These components help to understand and quantify the flexibilities of each project pertaining to time (duration, starting dates, sequence regarding other projects) and budget, which can be seen as real options being contained in the projects itself. The option to wait or defer, is virtually embedded in almost all SC projects. Subsequently, types and parameters have to be derived for all projects being considered. However, the major challenge a practitioner faces in calculating option values is estimating the input parameters. Six input parameters are needed for the valuation of SC projects: (1) Current value of the underlying asset or project (*Ro*), (2) Strike price/option's exercise price (*X*), (3) Volatility of the asset or project value (σ), (4) Option life (*t*), (5) Risk-free interest rate/rate of return on a risk less asset or project during the life of the option (*r*), and (6) Chosen interval size (δt). Afterwards, generation of a binomial tree and calculation of the option values at each node of the tree is performed, using the backward induction method. Software is used for calculating real option values of the projects and sensitivity analysis is applied for validation. These real option values will serve as input parameters for the scheduling optimization of step 2.

Step 2: Schedule SC projects using binary fuzzy goal programming

Determining the period in which each of the selected projects should be executed makes the optimization process the vital module of the proposed scheduling framework. Therefore, a binary fuzzy goal programming approach is adopted, where the major inputs to the optimization model are real option values of projects, project implementation periods, project cost, and critical projects' cost. All of these are treated as goals to be maximized or minimized based on the management's requirements and targets. Target values can be processes from intervals due to fuzzy goal functions. In addition to a few constraints (rigid and flexible) such as budget, project duration, interdependencies among the projects, predecessor–successor based relations are also considered to obtain a more reliable schedule. Software is used for selecting and scheduling the projects according to the framework and algorithm shown in detail in Section 3.3. Finally, the proposed framework advocates a set of projects that should be exercised in the planning horizon to obtain superior performance under the firm's constraints.

4.3.2. Identify and value SC projects using real options (step 1)

1) Study investment plans and evaluate investment objectives and risk drivers of SC projects

Once clarity about the planned SC project investments has been established, the objectives and inherent risks of the projects have to be evaluated. In general, projects are vulnerable to numerous types of risks. In order to understand potential variations of SC projects, a brief analysis of categorizations of risk and vulnerability in SCM is warranted. Several researchers have proposed comprehensive risk frameworks or classifications. For instance, Cavinato (2004) has suggested five groups of risks: physical, financial, informational, relational, and innovational. Kleindorfer and Saad (2005) have identified operational risks, natural hazards and social and political instability as the main causes of disruptions in SCs. Tang and Tomlin (2008) make distinctions among supply, process, demand, intellectual property, behavioral, and political/social risks in a SC. Finally, Wagner and Neshat (2010) proposed that SC vulnerability can reside in the demand side, supply side, and the SC structure.

2) Evaluate flexibilities and define real option types entrenched in the SC projects

Projects as capital investment decisions can be valued as real options, due to included rights, but not obligations to take certain actions on it (Copeland and Tufano, 2004). ROV not only takes into account risk and uncertainty about the future development of parameters that determine the value of a project, but also considers decision makers' ability to respond to the development of the parameters. This variability could concern project sizes (option to expand, option to contract, and both), project periods (deferment options, option to abandon, and sequencing options), and project operation (output mix options, input mix options, operating scale options). There are many similarities in the types and modelling of real options and financial options: Call options of a project are rights to defer, expand, continue or switch the investment, whereas put options include the rights to abandon, or reduce a project (Dobson et al., 2012; Volkart, 20011). Investments, in general, can be modelled as real options, when fulfilling the following conditions: irreversibility of investments made, existing initial risk uncertainty that becomes reduced over time, and flexibility of the management to exercise the above mentioned actions after the project has started (Su et al., 2009; Tiwana et al., 2006; Tiwana et al., 2007).

3) Determine model parameters and build real option valuation model

Here we explain the parameters, their relevance, and the procedure of calculating these parameters for SC projects (e.g., Kodukula and Papudesu, 2006; Mun, 2006) and apply them in a sample project of the case study in Section 4.

Current value of the underlying asset (Ro): The price of an option hinges on the market price (current value) of the underlying asset – in this case a project. If the price of the underlying asset increases, the premium of a call option will go up and put option go down (Mun, 2006). The current value of a project is estimated from the cash flows the project is expected to generate, which is equivalent to the present value of the future cash flows and is computed using NPV (or DCF) techniques.

Strike price (X): The strike price of a project is the present value of all future investments made during the project's life cycle (Mun, 2006).

Volatility of the asset value (σ): Volatility expresses the expected fluctuations in the price of the underlying asset, or the NPV of expected project payoffs respectively. Since volatility influences the probability of the option ending in the money, it determines the value of an option and pay off at expiry. Apparently, volatility is the most difficult variable to estimate (Kodukula and Papudesu, 2006; Padhy and Sahu, 2011). The option price will rise if the volatility of the project's expected NPV increases. There are several suggested approaches – logarithmic cash flow return, project proxy approach, market proxy approach, and management assumption approach – for estimating the volatility of the asset value (e.g., Kodukula and Papudesu, 2006; Mun, 2006; Padhy and Sahu, 2011). Of these, we have adopted the management assumption approach based on its simplicity and consensus-based decision making (Padhy and Sahu, 2011). Thereby, management estimates optimistic (S_{opt}) and pessimistic (S_{pes}) expected payoffs for a given project of lifetime *t* in addition to the budgeted payoffs. Assuming payoffs follow lognormal distribution:

$$\sigma = \ln\left(\frac{S_{opt}}{S_{pes}}\right)/(4\sqrt{t})$$

Option life of the project (t): In general, for real options, the timespan to exercise is unknown. Hence, the option life has to be long enough to mitigate the risk uncertainty and at the same time not so long that the option value becomes obsolete because of potential external risks. Usually expected project duration or planning horizon of the overall schedule are used for *t*.

Risk-free interest rate (r): The risk-free interest rate concerns a risk-free asset during the life of the option and is regularly determined on the basis of the treasury spot rate returns. The maturity of the treasuries is chosen according to the option's time to expire.

Chosen interval size (δt): The chosen interval size (or time increment) defines the shortest time span to update parameters and exercise options by the management.

4) Generate the binomial tree and calculate the option values

The binomial options approach uses a lattice to demonstrate alternative possibilities over time (Dixit and Pindyck, 1993). The starting point is the present value of future cash flows. Subsequently, binary conditions (one up and one down) can result. An initially expected value, *Ro* moves either up, i.e. *Rou*, with probability *p,* or down, i.e. *Rod*, with probability *1-p*, in a fixed interval Δt. One selects the highest value of exercising or waiting to receive the option value. The same process is repeated until the beginning to get the option price of the selected project (OV0). For calculations and further detail we refer to the case in Section 4.

5) Analyze sensitivity of ROV parameters to derive scenarios

Often results need to be for multiple operations scenarios – such as optimistic, base and worst cases or risk-neutral, moderate risk and high risk. For alternative scenarios it is necessary to know which model parameters have the highest leverage. By applying a sensitivity analysis to the ROV model, one can identify the most sensitive input parameters for a specific company setup. A Mann-Whitney U test at 95% CIs is an appropriate method to test for significant differences among scenarios. The outlined desirability approach is useful in finding parameter settings for additional scenarios based on these sensitivity analysis results.

1. Identify influence parameters by sensitivity analysis: $x_{1,}x_{2,}\ldots,\ x_n\ \forall\, n \in N$. The values of the influence parameters are set at three levels: High (+1), Normal (0), and Low (-1) based on ±10% of the obtained data.
2. Identify response variables: $Y_1, Y_2,\ldots, Y_i\ \forall\, i \in \delta\ with\ Y_i = f_i(\, x_{1,}x_{2,}\ldots, x_n)$.
3. Set desirability function $d_i(Y_i)\ \forall\, i \in\ \delta,\ d{:}\,\mathbb{R} \rightarrow\ [0, 1]$. Alternative desirability functions $d_i\ (Y_i)$ can be used depending on whether a particular response Y_i is to be assigned to a target value, maximized, or minimized. For maximizing desirability functions of a response variable $d_i(Y_i)$:

   $Maximise\ d_i(Y_i) =$

   $$\left(\frac{Y_i(x_n)-L_i}{T_i-L_i}\right)^{t_i} \quad for\ L_i \le Y_i(x_n) \le T_i$$

   Where, L_i, U_i, and T_i are the lower, upper, and target values, respectively, that are desired for the response Y_i, with $L_i \le T_i \le U_i$ with the exponent 't' determining how important it is to hit the target value.
4. Compute overall desirability $\max\limits_{x_1,\ldots,x_n} D\ (x_1, x_2,\ldots,x_n) = f(d_1, d_2,\cdots, d_\delta)$, D $: [0, 1]^\delta \rightarrow [0, 1]$
5. The individual desirability is then combined using the geometric mean, which gives the overall desirability $\max\limits_{x_1,\ldots,x_n} D\ (x_1, x_2,\ldots,x_n) = [d_1(Y_1) \times d_2(Y_2) \times \cdots \times d_\delta(Y_\delta)]^{1/\delta}$ with δ denoting the number of responses.

4.3.3. Schedule SC projects using binary fuzzy goal programming (step 2)

Scheduling derives an optimal setup to exercise projects considering risk, time, cost and criticality characteristics for all projects plus constraints of the firm. Binary fuzzy goal programming is used to define this optimization problem and its four competing goals.

Notation

i Project index, $i = 1, 2, \ldots, I$.

q Critical project index, $q = 1, 2, \ldots, Q$, where $Q \leq I$.

k Resource type index, $k = 1, 2, \ldots, K$.

t Time period index, $t = 1, 2, \ldots, T$.

m Rigid constraint index, $m = 1, 2, \ldots, M$. (considering there are 'M' rigid constraint)

x_{it} and x_{qt} are binary decision variables $= \begin{cases} 1 \text{ if project } i \text{ and } q \text{ are selected} \\ 0 \text{ otherwise} \end{cases}$

Goals

G_1 Risk (real option value): The total real option value from exercising a set of SC projects should be approximately equal to the total estimated real option value for all the projects in the planning horizon (Chen, 1994; Padhy and Sahu, 2011; Wang and Hwang, 2007).

$$G_1 = \sum_{i=1}^{I} \sum_{t=1}^{T} ROV_i x_{it} \geq ROV_t^U \quad (1)$$

Assuming that ROV_t^L and ROV_t^U are the lower and upper boundary limits of the fuzzy goal G_1 and the linear membership function μ_{G_1} for the first fuzzy goal is defined as:

$$\mu_{G_1} = \begin{cases} 1, & \text{if } G_1 \geq ROV_t^U, \\ \left(G_1 - ROV_t^L\right) / \left(ROV_t^U - ROV_t^L\right), & \text{if } ROV_t^L < G_1 < ROV_t^U \\ 0, & \text{if } G_1 \leq ROV_t^L. \end{cases} \tag{2}$$

$$\left(ROV_t^U - ROV_t^L\right) \times \mu_{G_1} - \sum_{i=1}^{I} \sum_{t=1}^{T} ROV_i x_{it} + ROV_t^L \leq 0$$

$$\forall i = 1, 2, ..., I \tag{3}$$

G_2 Time: The implementation period should be approximately equal to the estimated period for all the projects in the planning horizon.

$$G_2 = \sum_{t=1}^{T} t_i x_{it} \geq t_i^U \tag{4}$$

Assuming that t_i^L and t_i^U are the lower and upper boundary limits of the fuzzy goal G_2 and the linear membership function μ_{G_2} for the second fuzzy goal is defined as:

$$\mu_{G_2} = \begin{cases} 1, & \text{if } G_2 \geq t_i^U, \\ \left(G_2 - t_i^L\right) / \left(t_i^U - t_i^L\right), & \text{if } t_i^L < G_2 < t_i^U \\ 0, & \text{if } G_2 \leq t_i^L. \end{cases} \tag{5}$$

$$\left(t_i^U - t_i^L\right) \times \mu_{G_2} - \sum_{t=1}^{T} t_i x_{it} + t_i^L \leq 0 \qquad \forall i = 1, 2, ..., I \tag{6}$$

G_3 Cost: The total project cost considering underlying asset and strike price from a set of selected SC projects must not exceed the total estimated project cost in the planning horizon.

$$G_3 = \sum_{i=1}^{I} \sum_{t=1}^{T} P_{it} x_{it} \leq P_t^U \tag{7}$$

Assuming that P_t^U and P_t^L are the upper and lower tolerance limits of the fuzzy goal G_3 and the linear membership function μ_{G_3} for the third fuzzy goal is defined as:

$$\mu_{G_3} = \begin{cases} 1, & \text{if } G_3 \le P_t^U, \\ \left(P_t^U - G_3\right) / \left(P_t^U - P_t^L\right), & \text{if } P_t^L < G_3 < P_t^U \\ 0, & \text{if } G_3 \ge P_t^U. \end{cases} \tag{8}$$

$$\left(P_t^U - P_t^L\right) \times \mu_{G_3} + \sum_{i=1}^{I} \sum_{t=1}^{T} P_{it} x_{it} - P_t^U \le 0 \tag{9}$$

G_4 Criticality: The total project cost from a set of critical SC projects must not exceed the total assigned project cost in the planning horizon.

$$G_4 = \sum_{q=1}^{Q} \sum_{t=1}^{T} P_{qt} x_{qt} \le PQ_t^U \tag{10}$$

Assuming that PQ_t^U and PQ_t^L are the upper and lower tolerance limits of the fuzzy goal G_4 and the linear membership function μ_{G_4} for the fourth fuzzy goal is defined as:

$$\mu_{G_4} = \begin{cases} 1, & \text{if } G_4 \le PQ_t^U, \\ \left(PQ_t^U - G_4\right) / \left(PQ_t^U - PQ_t^L\right), & \text{if } PQ_t^L < G_4 < PQ_t^U \\ 0, & \text{if } G_4 \ge PQ_t^U. \end{cases} \tag{11}$$

$$\left(PQ_t^U - PQ_t^L\right) \times \mu_{G_4} + \sum_{q=1}^{Q} \sum_{t=1}^{T} P_{qt} x_{qt} - PQ_t^U \le 0 \tag{12}$$

Constraints

Time and criticality constraints: Each selected project must be started and completed once during the planning horizon. In addition, the *critical* projects have to be selected:

$$\sum_t x_{it} \le 1, \forall\, i \in I;\ \sum_t x_{qt} = 1, \forall\, q \in Q \tag{13}$$

In SC project scheduling, each project can be started only between its earliest and latest start time.

$$x_{it} \equiv 0 \; if \; t < l_i \; or \; t > u_i \tag{14}$$

Additionally, no project can be started until all its predecessor projects have been completed:

$$x_{it} \equiv 0 \; if \; t < max_{b \in P_i} \; (l_{ib} + d_{ib}) \tag{15}$$

Besides, no project can be finished ahead of its earliest permissible completion time:

$$x_{it} \equiv 0 \; if \; t < e_i \tag{16}$$

Interdependence among projects

$$\sum_{t=1}^{T} x_{it} \geq \sum_{t=1}^{T} x_{yt} \tag{17}$$

$$\sum_{t=1}^{T} tx_{yt} + (T+1) \times \left(1 - \sum_{t=1}^{T} x_{yt}\right) - \sum_{t=1}^{T} tx_{it} \geq d_i \sum_{t=1}^{T} x_{it}, \forall i \in P_y \tag{18}$$

Where, P_y is the set of precursor projects for a particular project y ($y = 1, 2, \ldots, Y$).

Project sequence: Let project i be preceding project n, and t_i and t_n be their earliest start times, respectively.

Then we have

$$\sum_{t=l_i}^{u_i} tx_{it} + d_i \leq \sum_{t=l_i}^{u_i} tx_{in} \, , i \in P_{in} \tag{19}$$

Selected projects should be finished within the planning phase

$$\sum_{t=1}^{T} tx_{it} + d_i \leq T + 1, \forall \; i \in I \tag{20}$$

Budget constraints: In any given period k, the budget used on all projects cannot exceed the financial resources available:

$$\sum_{i=1}^{I} \sum_{t=1}^{T} B_{i,k+1-t} x_{it} \leq R_k, \forall \; k \in T \tag{21}$$

Non-negative restrictions

$$x_{it} = 0 \;\; or \;\; 1 \qquad \forall \;\; i = 1, \; 2, ..., \; I \;\; and \;\; t = 1, \; 2, ..., \; T \tag{22}$$

$$1 \geq \mu_G \geq 0, \;\; \forall G \tag{23}$$

Objective function

The objective function is to maximise the achievement of sub-goals G_1 to G_4 over the planned horizon:

$$Maximise \;\; G = (\mu_{G_1}) + (\mu_{G_2}) + (\mu_{G_3}) + (\mu_{G_4}) \tag{24}$$

4.4. Case study

This article is quantitative in nature and requires data for the analytical validation of the framework proposed in Section 3. We collected data from an Indian automobile manufacturer (Automak; to ensure confidentiality, the actual name has been cloaked and figures changed) having full-fledged SC projects. Automak is headquartered in New Delhi and operates three manufacturing sites across India. Considering high output – about 4,500 cars per month – automated production lines and advanced SCAs are used. According to the 2011 annual report, surrogate revenue was up to 78.75 billion INR, net income 3.86 billion INR, SC and logistics expenditure 33.50 billion INR, and headcount was approximately 1,500 employees. Two characteristics made Automak worthy of consideration for demonstrating the applicability of the proposed framework: First, corporate key figures are in line with large manufacturers and suggest high complexity of the SC. Second, Automak's management aims to select a set of projects (project scopes and objectives are specified in Appendix 1) for preparing an investment schedule for the next two years. Interestingly, we found high agreement between SCAs of the case study and the analyzed literature (Autry et al., 2010). In particular, the challenge is to select, from a set of 21 projects over a period of 24 months (8 quarters), the most crucial ones and schedule them under trade-offs between highest performance and lowest risk within the limitations of available resources. A detailed budget description of the projects is reported in Table 1. In the next two sub-sections, the case study walks through the framework and applies first ROV (step 1) to the projects and later the scheduling algorithm (step 2).

Table 1: Supply chain projects at Automak and financial details

Project no.[1)]	Related supply chain activity	Budget requirement (in million INR)								Present value of future cash flows	Management estimates	
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8		(S_{opt})	(S_{pes})
1 (C)	Inventory management	1.53	1.31	1.62	1.93	1.10	1.98	-	-	9.29	16.32	8.30
2 (C)	Finance/accounting and auditing	3.92	3.62	3.91	2.61	2.03	2.08	-	-	15.69	25.68	13.94
3	E-Procurement	1.56	1.47	1.61	1.67	1.63	1.45	0.84	-	10.23	17.80	6.30
4	Resource planning	1.36	0.96	1.81	0.97	0.81	1.65	1.24	-	9.23	15.78	7.06
5	Market research and forecasting	6.90	6.85	6.58	5.93	6.11	5.23	-	-	35.38	48.12	30.23
6 (C)	Tracking technology	4.49	4.75	4.50	4.47	4.08	4.32	4.54	4.62	33.81	48.97	30.41
7 (C)	Capacity planning	4.66	3.86	3.87	3.89	5.08	4.30	3.97	3.45	28.61	50.59	26.78
8	Order management	1.99	1.92	1.96	2.91	2.87	3.28	4.04	-	20.32	37.69	17.68
9	Distribution and marketing	2.76	2.68	2.35	2.69	3.30	3.46	3.56	-	20.27	41.35	14.01
10 (C)	Customer relationship management	1.68	2.68	2.53	2.64	2.84	2.31	2.50	2.79	20.97	47.66	15.78
11	Warehouse management	4.54	3.87	2.71	2.22	2.03	2.33	2.37	2.85	25.34	45.60	22.13
12 (C)	Quality management and control	1.55	1.64	1.72	1.73	1.56	2.16	2.75	2.63	13.87	29.46	9.34
13 (C)	Energy contract management	2.69	2.12	1.96	2.09	2.06	2.07	-	-	13.79	34.13	10.32
14	Network management	2.11	1.60	1.74	2.44	2.14	1.80	1.90	2.65	16.34	33.84	12.95
15	Performance management	0.87	0.99	1.01	1.29	1.85	1.71	1.72	1.64	9.26	17.57	8.14
16	Materials management	2.41	2.10	2.04	1.96	1.85	1.49	1.36	1.56	12.94	23.87	10.82
17 (C)	Operations planning and scheduling	1.19	1.21	1.76	1.39	1.17	1.31	1.46	1.67	9.86	17.52	7.87
18	Enterprise resource planning	1.21	0.66	0.90	1.26	1.74	1.97	2.04	1.98	9.57	16.65	7.19
19	Lean manufacturing	1.39	1.46	1.44	1.44	1.42	1.42	1.42	1.43	11.26	18.43	8.53
20 (C)	Marketing and sales management	1.61	1.62	1.71	1.53	1.47	1.32	1.05	-	10.47	17.44	8.19
21 (C)	Transportation and logistics control	1.59	1.58	1.47	1.43	1.41	1.44	1.44	1.44	11.94	23.92	10.03
Quarterly budget requirement		52.01	48.95	49.20	48.49	48.55	49.08	38.20	28.71	Average budget required = 45.40		
Quarterly budget available		40.25	41.00	44.55	42.00	43.35	44.72	32.50	25.30	Average budget available = 39.21		
Quarterly budget flexibility over availability		10%	7.5%	5%	5%	5%	5%	7.5%	10%	Average flexibility = 6.875%		

[1)] C: Critical project

4.4.1. Real option valuation (step 1)

In order to demonstrate the proposed ROV procedure we use a sample project from the complete list of 21 projects, project no. 3 – E-Procurement. Later in scheduling the complete set of projects is used.

Current value of the underlying asset (Ro): The project shows a present value of future cash flows of *Ro*=10.23 million INR (as provided by the management). However, there are risk factors or uncertainty, which may prevent the project from delivering the projected monetary profits.

Strike price (X): For the E-Procurement project, the quarterly budget requirement (BR_1 through BR_7) is given in Table 1 (third column) and the strike price is calculated considering a quarterly discount rate (r) of 1%. The quarterly discount factor is calculated using formula $1 / (1 + r)^t$, where t is the number of time intervals (t = 7 quarters in case of project no. 3). Thus, the present value (*PV*) of the future budget requirement for the E-Procurement project equals 7.36 million INR using the NPV method.

Volatility of the asset value (σ): The E-Procurement project shows a volatility (σ) of 9.8%/quarter and optimistic payoffs S_{opt} = 17.8 million INR, signifying that there is 95% probability and that payoffs will not exceed 17.8 million INR; whereas S_{pes} = 6.3 million INR, resulting in only 5% probability and that payoffs will be less than 6.3 million INR; t = 7 quarters (Table 1).

Option life of the project (t): The eight quarters (24 months) have been considered as *option life* (t) of the set of SC projects, given in Table 1. The option life (or time) for the E-Procurement project is t = 7 quarters.

Risk-free interest rate (r): In India, risk-free rate can be inferred from 3- to 6-month Treasury bill rates which was at 4% per annum or about 1.0% per quarter (*www.bloomberg.com*, dated August 21, 2012).

Chosen interval size (δt): For the E-Procurement project, δt = 1 quarter.

Finally, all option parameters, functions, and case values are summarized in Table 2. Descriptive statistics of the ROV elements are provided in Table 3.

Table 2: Option parameter values

Parameter	Index/function	Case value of E-Procurement project
Underlying asset value	Ro	10.23 million INR
Strike price	X	7.36 million INR
Volatility	$\sigma = \ln\left(\frac{S_{opt}}{S_{pes}}\right)/(4\sqrt{t})$	9.8% per quarter
Option life	t	7 quarter
Risk-free interest rate	r	0.01 or 1% per quarter
Interval size	δt	1 quarter or 3 months
Up factor	$u = \exp(\sigma\sqrt{\delta t})$	1.103
Down factor	$d = 1/u$	0.907
Risk-neutral probability	$p = (\exp(r\delta t) - d)/(u - d)$	0.526

Table 3: Descriptive statistics of real option valuation elements

Element	Mean	Std. Dev.	Skewness	Kurtosis	Min–Max	A-D test (*p value)
NPV	4.603	2.766	0.790	-0.060	1.421–10.431	0.927 (0.015*)
ROV_{BL}	6.632	4.028	0.842	-0.052	2.090–15.340	1.032 (0.008*)
$BROV_{BS}$	6.598	4.005	0.831	-0.054	2.062–15.132	1.031 (0.008*)
BCOV	0.194	0.095	-0.130	-0.680	0.014–0.364	0.286 (0.592*)
BIV	0.004	0.002	-0.260	-0.700	0.008–0.074	0.251 (0.708*)

We used Real Options Super Lattice software for calculating the real option values of the projects (*www.realoptionsvaluation.com*). For the E-Procurement project, Figure 2 shows a binomial lattice spanning seven steps for seven quarters, where the upper and lower values at each node represent asset and option values, respectively.

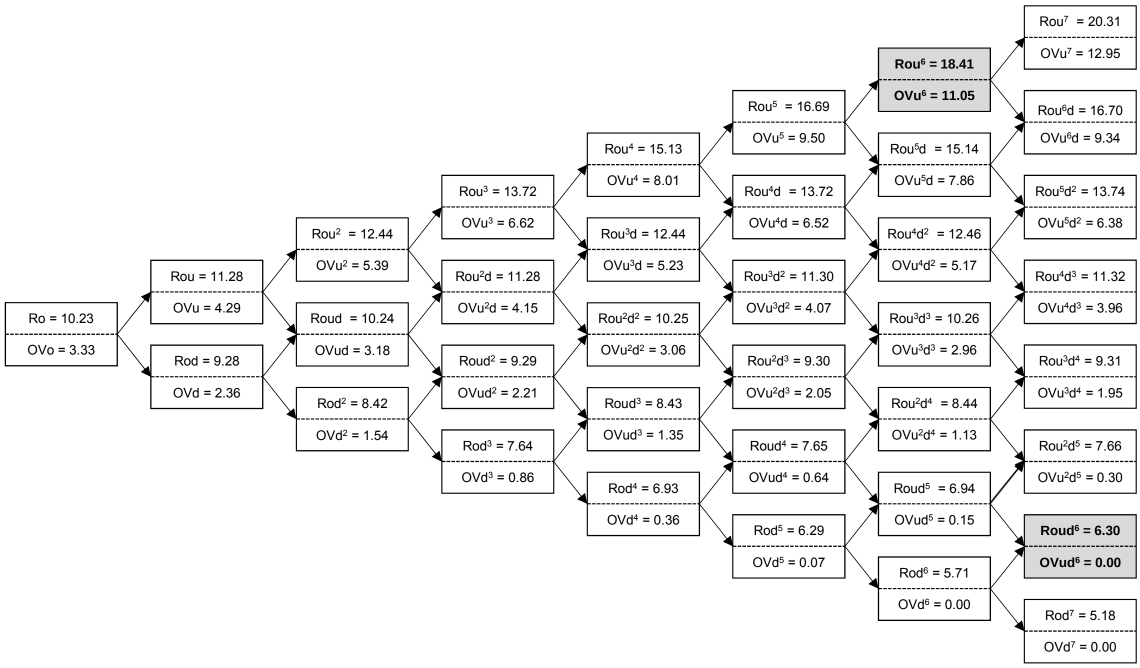

Figure 2: Binomial tree of option valuation for the E-Procurement project

Beginning with this initial value, the expected payoff was assumed to follow a binomially distributed multiplicative diffusion process. Starting with *Ro* at the very first node on the left, we multiply it by the up factor and down factor to obtain $Ro \times u$ (10.23×1.103 = 11.284) and $Ro \times d$ (10.23 × 0.907 = 9.279), respectively, to receive the first quarter's values. Afterwards, we have calculated option values using backward induction method. For example, option value at node 6 is calculated following the steps shown in Figure 3. For the E-Procurement project, starting at terminal nodes, i.e. node Rou^7, the expected asset value equals 20.31 million INR, if 7.36 million INR for the project will be invested. The net asset value is (20.31 – 7.36) = 12.95 million INR. Hence, the option value at this node will be 12.95 million INR.

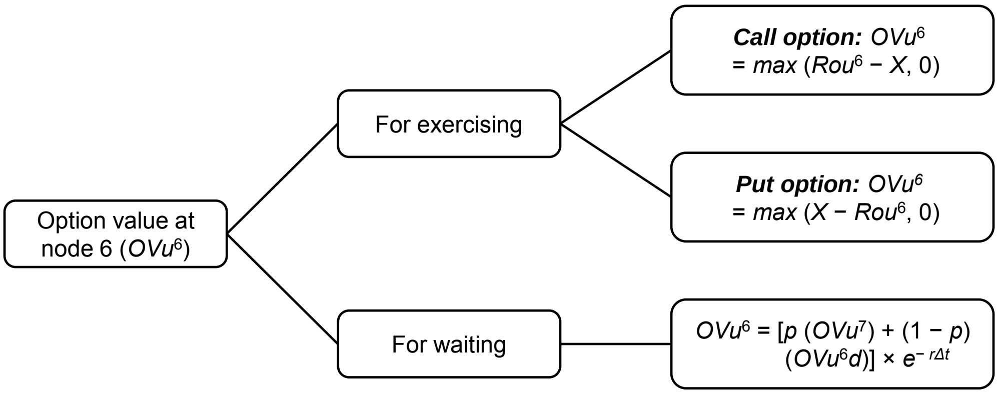

Figure 3: Option value calculation at node 6

At node $Roud^6$, the expected asset value is 6.30 million INR, if an investment of 10.23 million INR is made, resulting in a net loss of 3.93 million INR (Figure 2). Therefore, the decision at this node will be not to invest, which means the option value at this node will be 0. The next step, the intermediate nodes, is one step before the final time step. Starting at node Rou^6, the expected asset value for keeping the option open has been calculated. This is the discounted (at the risk-free rate) weighted average of potential future option values using risk-neutral probability *p*. The value at node Rou^6 is:

$$p(Rou^7) + (1-p)(Rou^6 d) \times exp\ (-r\delta t)$$

$$= [0.526(20.31) + (1-.526)(16.70)] \times exp(-0.01)(1) = 18.41.$$

If the option is exercised at this node by investing 7.36 million INR, the payoff would be 18.41 (the asset value at Rou^6), resulting in a net asset value of 11.05 million INR (Figure 2). Since keeping the option open shows a higher asset value (18.41 million INR), one will not exercise the option, but instead continue to wait. Hence, the option value at this node becomes 18.41 million INR. In a similar manner, the option value can be calculated at each node.

After computing the final option values of the projects, we perform a sensitivity analysis on ROV parameters and a desirability approach to derive three operations scenarios (risk-neutral, moderate risk, high risk). Of the six ROV input parameters, four parameters – Ro, X, σ, and r – are sensitive and significantly change Automak's ROVs. The results indicate with ±10% change of real option parameters, one obtains a set of ROVs, which are significantly different from one another. We confirmed that by conducting a Mann-Whitney U test at 95% CIs.

1. Identify influence parameters by sensitivity analysis: For the case under consideration n = 4 (four out of six real option evaluation parameters – RRo, X, σ, and r – were chosen to evaluate the operations scenarios). Considering $3^4 = 81$ different settings (four parameters at three levels each).
2. Identify response variables: For the case under consideration δ = 2, i.e. Y_1: Contract period and Y_2: ROV. The analysis of variance (ANOVA) of contract period and ROV were conducted based on their main effects and it was found that they are significant at 5% level of significance and *studentised residuals* approximate the normality assumption (a requisite for ANOVA) of the error in the model.
3. Set desirability function $d_i(Y_i)\ \forall\ i \in\ \delta$, d: For maximizing desirability functions of contract period: $d_1(Y_1)$ and ROV: $d_2(Y_2)$:

   $Maximise\ d_1(Y_1) =$

   $$\left(\frac{Y_1(x_n)-L_1}{T_1-L_1}\right)^{t_1}\ for\ L_1 \le Y_1(x_n) \le T_1, and \quad 0\ if\ Y_1(x_n) < L_1\ and\ 1,\ if\ Y_1(x_n) > T_1$$

   $Maximise\ d_2(Y_2) =$

   $$\left(\frac{Y_2(x_n)-L_2}{T_2-L_2}\right)^{t_2} for\ L_2 \le Y_2(x_n) \le T_2, and\ 0\ \ if\ \ Y_2(x_n) < L_2\ \ and\ 1,\ \ if\ \ Y_2(x_n) > T_2$$

For example, for Automak's SC project no. 3, the values of L_i, U_i, and T_i are 2.43, 3.75, and 3.33. And t_1 and t_2 are equal to 3 and 5, respectively.

4. Compute overall desirability $\max_{x_1,\ldots,x_n} D\ (x_1, x_2, \ldots, x_n) = f(d_1, d_2, \cdots, d_\delta)$, D : $[0,1]^\delta \rightarrow [0,1]$

5. The individual desirability: For SC project no. 3, $\delta = 2$ and $D = \sqrt{[d_1(Y_1) \times d_2(Y_2)]} = 0.897$ for the best possible parameter settings.

The output of the desirability approach suggests several scenarios, of which we have provided a list of the three best possible (Appendix 2). The high-risk scenario includes high current value of the underlying asset (+10% of normal), risk-free interest rate (+10% of normal), volatility of asset value (+10% of normal) and low strike price (-10% of normal) helping to achieve a desirability value of 89.7%, which is 10.1% higher than that of the risk-neutral ROV obtained before. The moderate risk one includes high current value of underlying assets (+10% of normal), risk-free interest rate (normal), volatility of asset value (normal) and low strike price (-10% of normal) achieving a desirability value of 85.4%, which is 5.8% higher than the risk-neutral ROV. However, the risk-neutral parametric values yielded a desirability of 79.6%, which is obtained from the proposed practice of the company. Hence, we can conclude that the current value of underlying asset and strike price are inversely proportional. Moreover, a high strike price, high risk-free interest rate, high volatility, and low underlying asset value will increase the ROV.

4.4.2. Scheduling (step 2), results and discussions

Using equations (1) through (23) and considering the financial details of the SC projects for the planning horizon (Table 1), along with the requirements set by the Automak management for each goal and constraint (provided in Table 4), the optimization problem was solved using Lingo 13.0 software package. Figures 4a, 4b and 4c depict optimal schedules of SC projects for the different scenarios (risk-neutral, moderate risk, and high risk).

Table 4: Requirement stated by the Automak management

Fuzzy goal	High	Low
Total real option value	ROV_t^U = 110% of estimated present value of future cash flow	ROV_t^L = 100% of estimated present value of future cash flow
Implementation period	t_i^U = 8 quarters	t_i^L = 6 quarters
SC project cost	P_i^U = 110% of total budget requirement	P_i^L = 90% of total budget requirement
Critical SC project cost	PQ_i^U = 105% of total budget requirement	PQ_i^L = 95% of total budget requirement
Financial constraint	Given in Table 1 (last three rows)	
Interdependencies	SCP 7 followed by SCP 8	
	SCP 5 and 9 followed by SCP 20	
	SCP 17 and 18 followed by SCP 11 and 1	

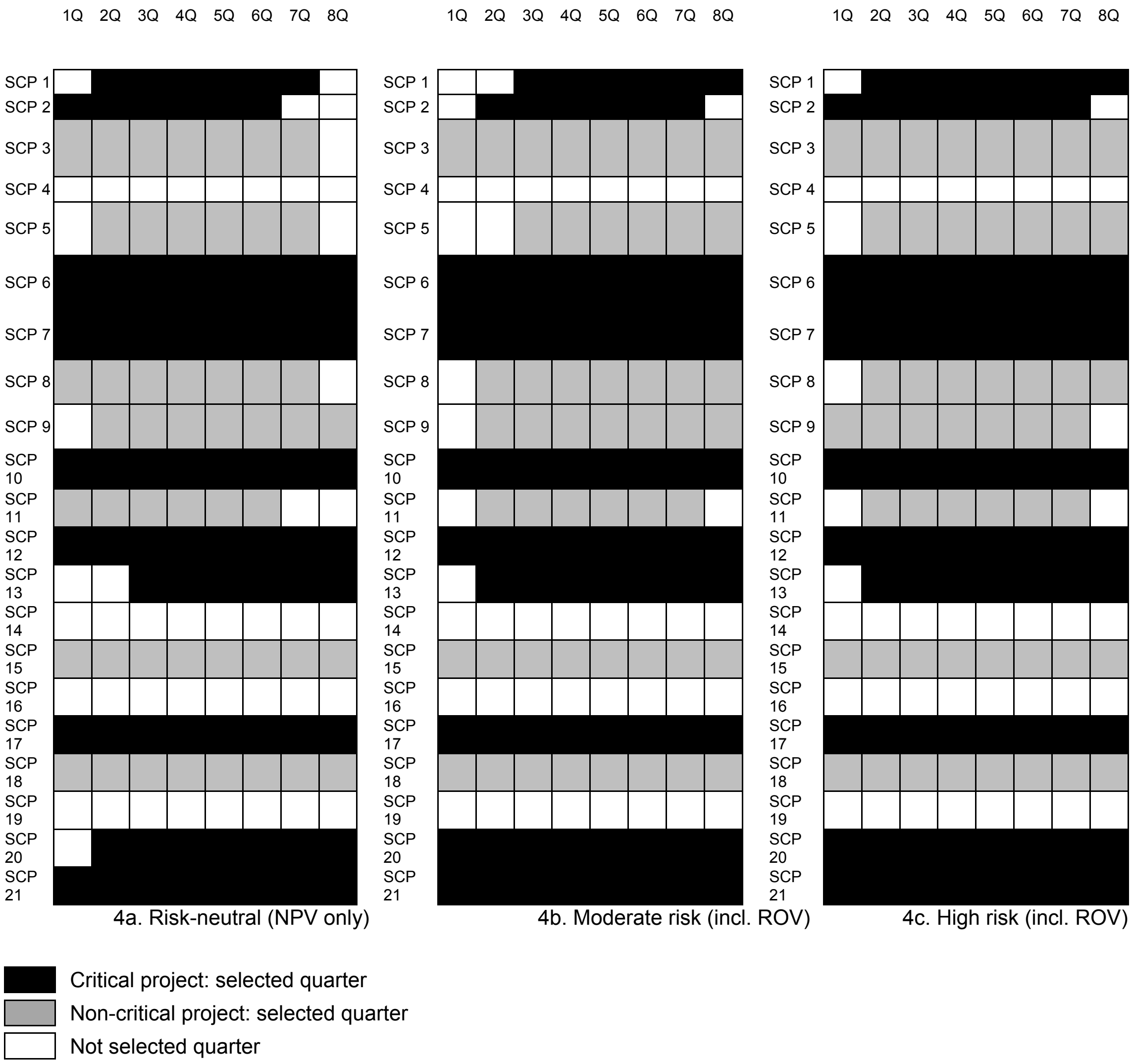

Figure 4: Operations scenarios for optimal scheduling of SC projects

Risk-neutral scenario: This scenario is a risk-ignoring approach like NPV-based scheduling and serves as base case against ROV-based scheduling (moderate and high risk). The objective function value was found to be $G^* = 3.045$. Achievement values of the four fuzzy goals are: $\mu_{G_1} = 0.714$, $\mu_{G_2} = 0.683$, $\mu_{G_3} = 0.648$, and $\mu_{G_4} = 1.000$. The optimal solution meets the fourth goal; the first, second, and third goals are under achieved by slight margins. The results of the optimal schedule of SC projects shown in Figure 4a imply, that resource planning (SCP 4), network management (SCP 14), materials management (SCP 16), and lean manufacturing (SCP 19) projects are not selected out of 21 projects, instead investments go into advanced technological projects, such as ERP, tracking technology (e.g., RFID).

Moderate risk scenario: The objective function value was found to be G^* = 3.248. Achievement values of four fuzzy goals are: $\mu_{G_1} = 0.802$, $\mu_{G_2} = 0.798$, $\mu_{G_3} = 0.648$, and $\mu_{G_4} = 1.000$. The optimal solution meets the fourth goal; the first, second, and third goals are underachieved by slight margins. The optimal schedule of the SC projects is shown in Figure 4b. In addition to the four projects dropped in the risk-neutral scenario, in this scenario the schedule is prepared considering real option values and project duration flexibilities of three projects: E-Procurement (SCP 3), Energy contract management (SCP 13), and marketing and sales management (SCP 20), whose duration and real option values are increased based on the moderate risk scenario values obtained from desirability analysis (Appendix 2). There Automak's management has to invest additional 3.2% of the risk-neutral scenario's budget to yield 6.7% increment over the objective function value. That includes extension of project duration of above three SC projects and real option value by 12.3% and 16.8%, respectively.

High-risk scenario: The objective function value was found to be G^* = 3.786. Achievement values of four fuzzy goals are: $\mu_{G_1} = 1.000$, $\mu_{G_2} = 1.000$, $\mu_{G_3} = 0.786$, and $\mu_{G_4} = 1.000$. The high risk solution meets the first, second, and fourth goal, whereas the third goal is under achieved by a slight margin. The optimal schedule is shown in Figure 4c. In addition to the four projects dropped in the risk-neutral scenario and increment of project duration of three projects discussed above, the schedule is prepared considering real option values and project duration flexibilities of three more projects: inventory management (SCP 1), finance/auditing and accounting (SCP 2), and market research and forecasting (SCP 5). There Automak's management has to invest an additional 4.1% of the risk-neutral scenario's budget to yield 24.3% increment over the objective function value. That includes extension of project duration of above six SC projects (including three of moderate risk scenario) and real option value by 40.0% and 54.3%, and 21.3%, respectively.

Summarizing, we conclude, that ROV successfully added a risk dimension to the solution space of scheduling tasks and achieves higher objective function values. Additionally, scheduling offers flexibility to decision makers who are searching for multiple optimal solutions under chosen operations scenarios. Hence, this framework offers a synergy of two flexible approaches.

4.5. Hypotheses tests: Assessment of real option valuation methods

Based on the project data from the case study it was possible to test the theoretical hypotheses.

To test H_1, that the ROV of SC projects is equal to the NPV of SC projects (i.e. ROV = NPV), we conducted a non-parametric Mann-Whitney U test (as the elements data do not follow normal distribution, shown in A-D test, Table 3). There we reject H_1 at the 95% CI (-3.438, 1.101) with p value of 0.0327. In fact, there is a significant difference between the mean NPV and ROV of projects. ROV yielded superior outcomes than did the NPV approach for project investment under uncertainties, i.e. $ROV > NPV$.

To assess H_2, which states that COV of SC project investments per quarter is equal to IV of SC project investments per quarter, we conducted an F-test, as the data follows a normal distribution (Table 4). Here we assess the equality of variance between COV and IV and observe that $F_{0.05,21,21} = 0.036$ is less than the tabulated value of 2.07. Hence, both elements have equal variance. Next, we conducted a t-test to validate *H₂* and observed that $t_{0.05,21} = -7.45$, which is less than the tabulated t-value of 1.721, i.e. $|t_{0.05,21}| > |t_{tabulated}|$. Considering the test results, we reject the null hypothesis at the 95% CI in favor of the alternative that, in fact, there is a statistically significant difference between the mean COV and IV of projects. Moreover, the IV approach yielded superior outcomes to invest under risk compared to COV, i.e. COV > IV.

Finally, to assess H_3, that the ROV using Black-Scholes approach is equal to the ROV using binomial lattices approach for the SC projects (i.e. ROVBS = ROVBL), we conduct a non-parametric Mann-Whitney U test since the data does not follow a normal distribution (see A-D test in Table 3). This test also vindicates that risks across the SC projects are non-linear in nature. In light of these test results, we accept H_3 at the 95% CI (-1.938, 1.872) with $p < 0.05$. Hence, there is no statistically significant difference between the mean ROV_{BS} and ROV_{BL} for more than five time steps, i.e. ROVBS = ROVBL.

4.6. Contribution

By applying real options to SC projects, the study makes three distinct contributions. The first one lies in capturing all project risks and uncertainty with analytical rigor known from financial disciplines. Prior research stopped after identifying risk factors, missing the opportunity to quantify them. The suggested approach takes risk and uncertainty quantification from firm level (a general interest rate accounts for all business risks and uncertainty) to project level (estimated fluctuation of each project's cash flows due to risks and uncertainty). Updating the estimated project data over time and rerunning the framework allows to dynamically adjust the project schedule. Second, real options, unlike the more rigid NPV approaches, can model the flexibility inherited in future managerial decision making. Third, the framework includes all relevant elements of project scheduling at once, which was not reached prior to this, but is frequently required as a minimum in real world decision making situations (budget constraints, project interrelations, multi-factorial risk, time and criticality constraints).

Moreover, this study empirically verified three methodological claims: (1) ROV method provides superior outcomes compared to NPV method under conditions of risk and uncertainty, (2) coefficient of variation (COV) is an inferior method for risk evaluation compared to implied volatility (IV) method, i.e. IV provides a better outlook than passive COV method for risk evaluation of multi-period project investments, (3) Black-Scholes and binomial lattices models provide similar outputs for ROV for five or more time steps.

4.7. Conclusions and future research

We consider two limitations before summarizing our results and proposing future directions for research. First, the proposed framework adds complexity to scheduling decision making due the introduction of two analytical concepts (ROV and binary fuzzy goal programming). To achieve a quantification of risk and uncertainty requires additional effort and courage to overcome existing practices. Second, the stepwise illustration of the framework at a single manufacturing case cannot serve as empirical proof. Therefore, to provide a solid scientific origin, the framework was derived from a literature review and analytics.

This research presents an ROV approach to capture the financial risk dimension of SC projects. This reinforces earlier believes of superiority over passive NPV approaches through empirical verification. ROV visualizes and includes the opportunities of investment under volatile conditions, i.e. high profit or loss. Although well established in academia, the majority of practitioners still use a passive NPV approach. Hence this article can be used as toolkit for project investments and scheduling under risk in general and SC projects in particular. The article used binary fuzzy goal programming and suggested three operations scenarios – risk-neutral, moderate risk, high risk. Thereby the risk-neutral scenario came out as a base case and the other two scenarios are steppingstones which yielded 6.7% and 24.3% improvements, respectively. Therefore the management has to spend 3.2% and 4.1% additional budget to execute them, which is well under the tolerable limits set by the management. Thus, we conclude that a synergy of two flexible approaches (ROV and scheduling) can yield superior outcomes in industrial applications.

In future, our research could be extended by investigating the issues related to scheduling of multiple SC projects under a multiple sourcing environment, which is a NP hard problem and could be solved through genetic algorithm (GA) methods. Increasing the dimensions of the problem to more SC projects and splitting of projects in different time periods will be another area of research which could be addressed using GA methods.

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4.9. Appendix

Table 5: Supply chain projects at Automak

Project no.	Related supply chain activity	Project type[1)]	Project scope	Key benefit(s)
1	Inventory management	O	Improve the existing systematic approach to control inventory in the supply chain	Reduction of freight and distribution cost, reduction of inventory
2	Finance/accounting and auditing	B	Refine financial and auditing processes	Increased efficiency of financial tasks
3	E-Procurement	T	Activities to get an electronic system for sales and purchasing of supplies, work, and services started	Lean purchasing routines
4	Resource planning	O	Implementation of a new resource-requirements-planning system	Increased productivity
5	Market research and forecasting	B, S	Providing valid market data to design and size the supply chain	Reduces risk of incorrect planning
6	Tracking technology	T	Introduce software and hardware used for tracking and identification of resources and products	Efficiency gains by easier allocation and less errors
7	Capacity planning	O	Improve an existing allocation and monitoring of forecasted and actual resources	Efficient use and design of resources
8	Order management	O, S	Improve an existing system used for order entry and processing	Less handling effort and consistency in order treatment
9	Distribution and marketing	O, B, S	Implement and adjust a new physical distribution system	Besides cost also customer service
10	Customer relationship management	B	Automating and synchronising marketing, sales and other support services	Customer service on technical basis implemented
11	Warehouse management	O	Improve measures to organise storage and associated transactions	Reduces storage and handling costs
12	Quality management and control	O	Improvement of standardized processes for quality assurance and control	Improves product/service quality
13	Energy contract management	O, S	Renegotiating energy contracts	Implements a routine for reduces energy costs
14	Network management	B, S, O	Enlargement of computer networks	Increased security and performance
15	Performance management	H	Better align firm resources to strategic targets	Real-time update of over- and underperformance
16	Materials management	O, S	Implement an automated materials handling	Reduced cost of material handling
17	Operations planning and scheduling	O, S	Improve mapping of resources to limited logistics capacity	Cost optimised resource and logistics usage
18	Enterprise resource planning	O, S	Improve an existing technology-based methodology for resource planning	Gains in productivity
19	Lean manufacturing	O, S	Introduction of additional approaches for avoiding waste and eliminating non-value adding activities.	Waste reduction
20	Marketing and sales management	B, S	Run additional networking and promotion to increase sales of products	Increase sales, revenue, and market penetration
21	Transportation and logistics control	O, S, T	Performance improvement to monitor and operate transport and logistics resources	Reduced asset base in transport and logistics

[1)] B: Business advisory, H: Human resource, O: Operations, S: Strategy, T: Technology

Table 6: Parameter sensitivity – Three best operations scenarios for SC projects

Project no.	Related supply chain activity	Scenarios	*Ro*	*X*	*r*	*σ*	Project duration	ROV	Desirability
1	Inventory management	High risk	+1	-1	+1	+1	7	4.12	88.6%
		Moderate risk	+1	-1	0	+1	6	3.83	85.1%
		Risk-neutral	0	0	0	0	6	3.50	80.7%
2	Finance/Accounting and auditing	High risk	+1	-1	0	+1	7	3.19	90.4%
		Moderate risk	+1	-1	0	+1	6	2.88	87.2%
		Risk-neutral	0	0	0	0	6	2.73	85.3%
3	E-Procurement	High risk	+1	-1	+1	+1	8	3.75	89.7%
		Moderate risk	+1	-1	0	0	8	3.58	85.4%
		Risk-neutral	0	0	0	0	7	3.33	79.6%
4	Resource planning	High risk	+1	-1	+1	+1	7	4.78	81.3%
		Moderate risk	+1	-1	0	0	7	4.67	80.5%
		Risk-neutral	0	0	0	0	7	4.43	79.8%
5	Market research and forecasting	High risk	+1	-1	+1	+1	6	15.91	87.4%
		Moderate risk	+1	-1	+1	0	6	15.57	84.2%
		Risk-neutral	0	0	0	0	6	15.34	82.1%
6	Tracking technology	High risk	+1	-1	+1	+1	8	14.15	86.7%
		Moderate risk	+1	-1	0	+1	8	13.97	84.8%
		Risk-neutral	0	0	0	0	8	13.93	83.7%
7	Capacity planning	High risk	+1	-1	+1	+1	8	8.88	83.2%
		Moderate risk	+1	-1	+1	0	8	8.83	83.1%
		Risk-neutral	0	0	0	0	8	8.81	83.1%
8	Order management	High risk	+1	-1	+1	+1	7	11.57	78.9%
		Moderate risk	+1	-1	0	0	7	11.19	75.2%
		Risk-neutral	0	0	0	0	7	11.06	73.3%
9	Distribution and marketing	High risk	+1	-1	+1	+1	7	9.54	91.1%
		Moderate risk	+1	-1	0	0	7	9.35	90.5%
		Risk-neutral	0	0	0	0	7	9.13	89.4%
10	Customer relationship management	High risk	+1	-1	+1	+1	8	11.51	87.2%
		Moderate risk	+1	-1	0	+1	8	11.37	86.2%
		Risk-neutral	0	0	0	0	8	11.21	85.8%
11	Warehouse management	High risk	+1	-1	+1	+1	8	12.96	82.7%
		Moderate risk	+1	-1	+1	0	8	12.79	81.8%
		Risk-neutral	0	0	0	0	8	12.61	81.7%
12	Quality management and control	High risk	+1	-1	+1	+1	8	5.26	84.2%
		Moderate risk	+1	-1	0	0	8	5.18	83.5%
		Risk-neutral	0	0	0	0	8	5.00	83.1%
13	Energy contract management	High risk	+1	-1	+1	+1	7	8.13	86.2%
		Moderate risk	+1	-1	0	0	7	7.99	85.1%
		Risk-neutral	0	0	0	0	6	7.34	83.7%
14	Network management	High risk	+1	-1	+1	+1	8	7.62	86.4%
		Moderate risk	+1	-1	0	0	8	7.51	85.7%
		Risk-neutral	0	0	0	0	8	7.45	84.8%
15	Performance management	High risk	+1	-1	+1	+1	8	3.25	87.7%
		Moderate risk	+1	-1	0	+1	8	3.11	86.8%
		Risk-neutral	0	0	0	0	8	2.92	85.7%
16	Materials management	High risk	+1	-1	+1	+1	8	4.05	78.9%
		Moderate risk	+1	-1	0	+1	8	3.93	77.7%
		Risk-neutral	0	0	0	0	8	3.55	76.3%
17	Operations planning and scheduling	High risk	+1	-1	+1	+1	8	3.89	88.2%
		Moderate risk	+1	-1	0	+1	8	3.45	85.5%
		Risk-neutral	0	0	0	0	8	3.29	80.3%
18	Enterprise resource planning	High risk	+1	-1	+1	+1	8	3.12	89.4%
		Moderate risk	+1	-1	0	0	8	2.97	87.5%
		Risk-neutral	0	0	0	0	8	2.88	85.6%
19	Lean manufacturing	High risk	+1	-1	+1	+1	8	5.12	87.6%
		Moderate risk	+1	-1	+1	1	8	4.93	86.1%
		Risk-neutral	0	0	0	0	8	4.86	82.1%
20	Marketing and sales management	High risk	+1	-1	+1	+1	8	4.92	88.4%
		Moderate risk	+1	-1	+1	1	8	4.76	85.2%
		Risk-neutral	0	0	0	0	7	4.49	83.3%
21	Transportation and logistics control	High risk	+1	-1	+1	+1	8	5.78	86.7%
		Moderate risk	+1	-1	0	+1	8	5.55	85.8%
		Risk-neutral	0	0	0	0	8	5.37	84.7%

Chapter V

Risk Mitigation in Supply Chains: A Quantitative Approach

Abstract

Financially distressed suppliers are more likely to cause stock-outs and deliver bad quality. From similar observations, we know that supply chain (SC) risks are connected. Quantifying the direction and magnitude of risk connectivity can help in reducing the impact of failures and hence improve the overall performance of SC operations. Therefore, the paper studies a simple model for risk in SCs. First, all relevant risks are captured by Adjacency Matrices (AM) for 12 manufacturing SCs. Second, we simulate the impact of mitigation measures on these risks. The results show how varying connectivity of risks leads to bottlenecks for risk reduction. Based on the developed model, reducing the connectivity of potential risks in a SC at initial design and redesign would decrease risk most effectively. From a statistical perspective, we found that rates of risk reduction follow power-law functions. The approach can be used for modelling risk and evaluating mitigation measures in corporate practice.

Keywords: Supply chain management; Risk management; Adjacency matrix; Power-law

5.1. Introduction

Exposure to risk is inherent within all businesses. Managers devote most of their efforts to avoid and mitigate risks for meeting their targets. Thereby, *risk* is a negative consequence or loss that materializes with a certain probability (e.g., Wagner and Bode, 2006, 2008, 2009; Tang and Musa, 2011). The higher the loss and probability of a risk, the higher is the negative impact on a firm's performance. Supply Chains (SC) of firms are inherently vulnerable to risk. While SCs have become more complex and globalized during the past decades, more severe SC incidents are reported in the news and academic world. The number of negative events affecting SCs exceeds by far the memorable natural hazards like the Japanese tsunami or hurricane Katrina in the US. Two main *impacts of SC risks* have been confirmed by several authors. On the one hand, Hendricks and Sighal (2005) observed a negative impact on *financial performance* of a firm after SC risk incidents. On the other hand, materialized risks have a negative *impact* on the *operational performance* of a SC (throughput, service level, lead times, etc.) (Wagner and Bode, 2008). Hence, SC risks must be considered by firms as seriously as other business risks (Elkins et al., 2005; Wagner and Bode, 2009).

In a mature stream of literature on *SC risk* (e.g., Peck, 2005, 2006; Wagner and Bode, 2006; Pettit, Croxton, and Fiksel, 2013), various kinds of risks have been identified and classified. For instance, Chopra and Sodhi (2004) in their seminal work, characterized nine risk sources in SCs (disruptions, delays, systems, forecast, intellectual property, procurement, receivables, inventory, and capacity). Whereas, a simpler categorization by Jüttner (2005) comprises demand side, supply side, and environmental risks. Rao and Goldsby (2009) and Sodhi, Son, and Tang (2012) found that most of the articles are considered to be either qualitative or conceptual. For quantitative descriptions of SC risks, one can find the following methodological approaches: optimization, multivariate analysis, stochastic programming, simulation, and real options (Tang and Musa, 2011). This demonstrates a certain difficulty to find a uniform or standardized method for describing SC risks and leaves great potential for developing applicable models for decision making. Since risks in practice are rather manifold, simultaneously hard to assess, and hidden along the entire SC, it is impossible to fit them all into a specific risk model. As an illustration, managers face multiple risks depending on their viewpoint: A financially distressed supplier holds the risk of getting bankrupt, but at the same time, it is also likely that it causes stock-outs or delivers bad quality. Similarly, natural disasters can affect the operations of a firm itself but also its suppliers and third-party logistics providers. In the second case, impact and required recovery time will be much higher than is forecasted for the firm itself. Both examples reveal the need for models to take connectivity of risks into account. Such a perspective has to go beyond adding losses, delays, or similar performance indicators for each potential risk. Starting points for linking risks along the SC can be found in the work on risk correlations (Wallace, Keil, and Rai, 2004; Han and Huang, 2007) or copula functions (Babich, Burnetas, and Ritchken, 2007; Wagner, Bode, and Koziol, 2009). A SC model integrating all risks and their connectivity would allow one to build more realistic risk models of SCs and investigate their dynamic behavior. Therefore, the study's first research questions focuses on:

- How much are SC risks interconnected (risk connectivity)?

In our work we focused on supply-side risks. Empirically informed by an experts group, we identified all relevant risks on the supply-side of manufacturing SCs and describe their connectivity with Adjacency Matrices. Using a rank order clustering algorithm of

King (1980) we discovered clusters among these risks. For simulation purposes later we were able to randomize risk clusters and vary the number of them.

Moreover, this paper aims to quantify the impact of commonly practiced *risk mitigation measures* (e.g., redundant suppliers, increased inventory) on frequently occurring SC risks. SC risk literature is still limited with regard to modelling responses to SC risks. Recently, Talluri et al. (2013) called for investigating especially the effectiveness of risk mitigation measures. Therefore, the study's second research questions focuses on:

- How does risk connectivity determine the success of risk mitigation in a SC?

The target is to shed light on how connectivity of risks affects risk reduction. In other words, is the effectiveness of risk mitigation measures driven by the dependency of risks? First, we link risks and possible mitigation measures by interaction matrices with the help of the same experts group. Randomizing these dependencies, we could simulate numerous mitigation attempts taken place at SCs of predefined risk connectivity. Here we found fat-tailed distributions for lowering risk in SCs, which means it is increasingly harder to mitigate clustered risks.

The rest of the paper is structured the following: First, a review of the relevant literature looks into SC risks and their management. At this point we identify the most important risks and mitigation measures on the supply-side of a SC. Second, methods are explained and data collected from a group of SC experts. A detailed simulation investigates the impact of mitigation measures on total SC risk. Finally, theoretical and practical applications are discussed in the conclusion section.

5.2. Supply-side risks and risks management

When investigating risks and the impact of mitigation measures in SCs, there are two areas of academic literature that support the research questions: (1) Risk in general and supply-side risks in particular, and (2) Risk Management.

(1) *Risk* is a negative consequence or loss that materializes with a certain probability (Wagner and Bode, 2006; Tang and Musa, 2011). The higher the loss and probability of a risk, the higher the negative impact on firm performance. Several researchers have identified supply chain risks (e.g., Chopra and Sodhi, 2004; Wagner and Bode, 2009; Hopp, Iravani, and Liu, 2012). *Supply-side risks* are of highest importance due to the high cost share of the procurement function. Since supply-side risks are a mature field of research, we conducted a literature survey in the selected management review, operations management, and MS/OR journals using Google scholar and Scopus. The search included articles from the years 2004 to 2014. In total, we identified 33 comparatively different risks reported in these articles. Based on the frequency of occurrences, Table 1 lists the top ten most important ones. The given risks are still highly aggregated as more like domains or areas of risk. It is possible to find many sub-risks in these for further analysis. *Risk connectivity* is the degree of interdependency of risks occurring at the same level or node of the SC. Risks, even at the same level or node of a supply chain, are interconnected: supplier default risk can be connected with supplier quality risk or supplier capacity risk; socio-political risk can be connected with supplier default or quality risk.

Table 1: Important supply-side risks based on literature survey

Supply-side Risks	Selected Sources
Contract risk	Elkins et al. (2005); Van Weele (2010)
Natural hazard risk	Manuj and Mentzer (2008); Wagner and Bode (2009; Tang and Musa (2011)
Technology, process, and infrastructure risk	Olson and Wu (2010); Ritchie and Brindley (2009); Ivanov and Sokolov (2010)
Supplier default risk	Ritchie and Brindley (2007); Van Weele (2010)
Supply quality risk	Chopra and Sodhi, (2004); Tuncel and Alpan, (2010)
Logistics/transportation risk	Zsidisin, Ragatz, and Melnyk (2005); Wagner and Bode (2009)
Supplier capacity risk	Peck (2005); Bode and Wagner (2009)
Pricing risk	Hallikas et al. (2004); Zsidisin, Ragatz, and Melnyk (2005); Wagner and Bode (2009)
Supplier lead time risk	Talluri et al. (2013)
Socio-political risk	Tang and Musa (2011); Ivanov and Sokolov (2010)

(2) *Risks Management* is an essential research area (Tang and Musa, 2011; Turner, 2011; Thun and Hoenig, 2011). The aim is to identify the potential risks and to implement measures that reduce the impact and probability of the occurrence of risks (Hong and Lee, 2013). More specifically in the case of procurement, risk management focuses on improving the operational performance of the upstream SC or supply-side when conditions become uncertain. As firms have to operate safely and in compliance with local regulations while meeting targets for efficiency and effectiveness, they need to eliminate their exposure to uncertainties by managing the risks in the SC. This includes the identification and assessment of potential risks as well as the implementation of appropriate measures to steer and monitor them (Chopra and Sodhi,

2004; Sodhi, Son, and Tang, 2012). In the past, the most common method of dealing with supply-side risks was to rely on buffers in the form of safety stock, extended lead times, and excess capacity (Zsidisin, Ragatz, and Melnyk, 2005). Later, multiple sourcing and selection of optimal number of suppliers and corresponding lot sizes became a commonly practiced strategy by firms in the case of unreliable sources and suppliers (e.g., Meena, Sarmah, and Sarkar, 2011). In addition, spot market, option and financial hedging, market prediction, and other market forecasting approaches have been suggested by several authors (e.g., Guo, Fang, and Whinston, 2006; Ni et al., 2012; Hong and Lee, 2013) to handle risks in the presence of supply and price uncertainty. Nevertheless, the presence of other behavioral risks in supply networks, like opportunistic behavior or conflict between partners, as reported by Seiter (2009), can be mitigated through improving the confidence and trust of SC partners (Christopher and Lee, 2004). Jüttner and Ziegenbein (2009) and Zsidisin, Ragatz, and Melnyk (2005) have suggested *supply chain mapping* as a technique to visualize potential risks, which produces a transparent overview of the structure of the SC, with its related organizations and processes. Furthermore, a recent survey of 1,322 risk managers about excellence in risk management indicates that the approach of cross-functional teams in risk management is gaining acceptance to manage supply-side risks (Elowe, 2012). Recently, Ivanov, Sokolov, and Pavlov (2013) included risk in their study by investigating quantitatively the optimal distribution planning for upstream networks under uncertainty and structure dynamics. Thus, the adoption of PRM for supply chains risk reduction, both qualitatively and quantitatively, has been an intense area of research for more than a decade. Our study tries to contribute to this stream of literature by providing a better understanding of the impact of PRM measures on SC risk. By following a simulation approach, we study risk connectivity as an additional challenge in risk management.

Preferably, supply-side risks can be prevented or mitigated using proactive and reactive types of risk management measures (Kleindorfer and Saad, 2005; Zsidisin, Ragatz, and Melnyk, 2005; Thun and Hoening, 2011). Proactive measures take effect before the risk has materialized, whereas reactive measures are planned in advance for crisis management (Dani, 2009; Zsidisin, Ragatz, and Melnyk, 2005). Researchers have proposed several classifications (Jüttner and Ziegenbein, 2009; Wagner and Bode, 2009; Zsidisin and Ellram, 2003). Of these, a five-category generic classification – risk avoidance, risk prevention, risk mitigation, risk transfer, and risk retention – of measures is adopted by many (e.g., Waters, 2011; Olson and Wu, 2010). However, each supply chain has its own attributes and needs a specific set of measures. These must always be adapted to the circumstances of the particular firm (Hendricks and Singhal, 2005; Ritchie and Brindley, 2007; Kleindorfer and Saad, 2005; Chopra and Sodhi, 2004). Otherwise, measures that mitigate one risk can end up exacerbating another (Chopra and Sodhi, 2004).

For our further analysis we derived from a second literature survey a comprehensive list of commonly applied measures to mitigate the supply-side risks depicted in Table 1 (e.g., Tang and Musa, 2011; Olson and Wu, 2010; Chopra and Sodhi, 2004). The measures are shown in Table 2 along with selected sources. Numeration I-X indicates measures used for further analysis in Section 3.

Table 2: Commonly applied Risk mitigation measures (I-X for further analysis)

Supply-side Risk	Commonly applied Risk Mitigation Measures (from expert survey)	Selected Sources
A. Contract management risk	Outline the activate point(s) at which contract review (e.g., monthly, quarterly, annually) becomes necessary due to underperformance [I]	Elkins et al. (2005); Van Weele (2010)
	Record any arising concerns, how and by whom to be managed	
	Further detail specific clauses in the contract for addressing concerns	
B. Natural hazard risk	Standardization of the outsourced materials (procurement of off-the-shelf goods) [II]	Berger et al. (2004); Gualandris and Kalchschmidt (2013)
	Multiple sources for critical materials	
	Coordinate demand and procurement across the corporate group	
C. Technology, process, and infrastructure risk	Take preventive measures like a cost-benefit analysis aimed at reducing the overall risk [III]	Olson and Wu (2010); Ritchie and Brindley (2009)
	Identify and assess risk of critical assets to specific threats	
	Identify and prioritize risk reduction activities	
	Establish special structures to respond in case of such risks	
D. Supplier default risk	Conduct regular supplier audits [IV]	Tang (2006); Ritchie and Brindley (2007); Van Weele (2010);
	Define decision process for supplier selection with the stakeholders of the outsourcing project	
	Assess each supplier concerning the identified risks	
	Active management of supplier portfolio (across the corporate group)	
E. Supply quality risk	Enforce regulations concerning the packaging for transport and help to optimize the packing [V]	Chopra and Sodhi (2004); Tuncel and Alpan (2010)
	Provide suppliers with clear standards and requirements	
	Control the preparation and approval of test protocols from suppliers	
	Conduct trainings concerning quality and processes for the suppliers	
F. Logistics/ Transportation risk	Making variety of logistics transactions, SKUs, supplying and distribution partners, countries, and origin-destination pair permutations transparent [VI]	Zsidisin, Ragatz, and Melnyk (2005); Wagner and Bode (2009)
	Assess levels and tiers in a logistics system	
G. Supplier capacity risk	Selectively holding inventory and/or building responsive production and delivery capacity [VII]	Peck (2005); Sodhi and Lee (2007); Chopra and Sodhi (2012)
	Practising flexible production system	
	Use of centralized production system	
H. Pricing risk	Pooling of procurement volume (compare locations, material groups, technologies, logistics requirements, etc.) [VIII]	Hallikas et al. (2004); Zsidisin, Ragatz, and Melnyk (2005); Wagner and Bode (2009)
	Foster long-term agreements with selected suppliers	
	Support the suppliers in the procurement of raw materials (with know-how, contracts and volume)	
	Review selection of the parts for outsourcing in Western and Eastern Europe, and for make-or-buy decision respectively	
I. Supplier lead time risk	Integrate time buffers in the production and delivery schedules for the customers of the firm [IX]	Wagner and Bode (2009); Van Weele (2010); Tang (2006)
	Avoid critical geographic regions when selecting suppliers	
	Establish stock of inventory	

J. Socio-political risk	Avoid political and social risk pre-emptive risk mitigation plans, or dropping projects with low risk-return ratios [X]	Tang and Musa (2011); Tang (2006)
	Follow political risk insurance plans	
	Follow internal and external reporting for sound decision-making	

To illustrate the concepts of risk, risk connectivity and risk mitigation measures we suggest a one-dimensional SC-model. The upper half of Figure 1 shows how two mechanisms (growth of trees and wild fires) create an equilibrium density of trees in a forest (Newman, 2007). Below a simple SC has a low risk exposure whereas a more complex SC is more vulnerable to risks (Wagner and Bode, 2006). One can also find two opposing mechanisms: In a robust and safe SC managers will aim for further exploitation. Adding more suppliers, products and other elements will increase the complexity over time. On the other hand, in a highly complex SC managers will introduce multi-sourcing, backups and other mitigation measures to simplify and lower the risk exposure. Since risk mitigation measures cost money and exploitation earns money, a SC will swing around a complexity and risk level that is profitable in the long-run.

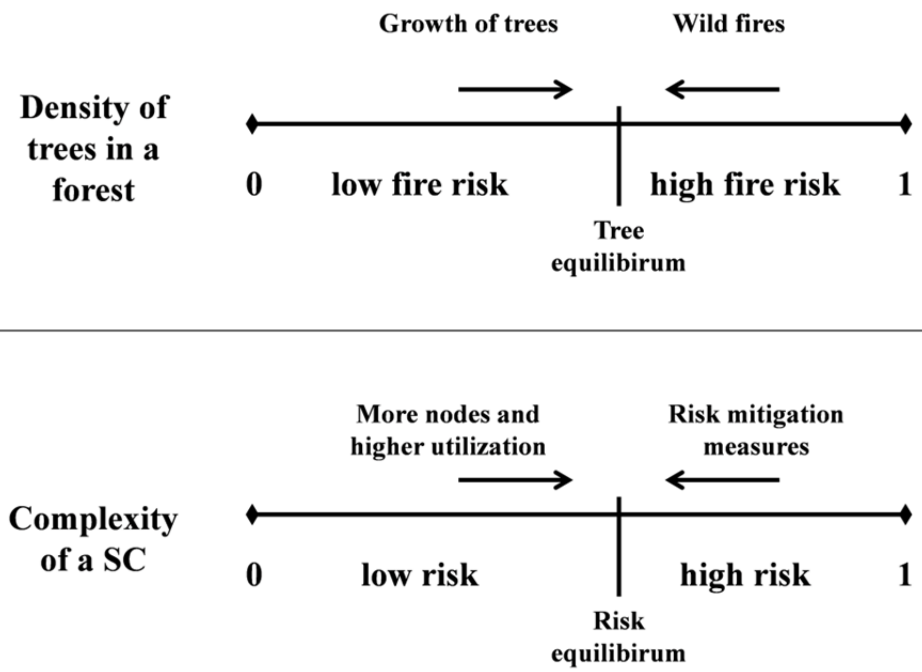

Figure 1: Conceptual Model for Complexity and risk in a SC

5.3. Methodology and PRM framework

5.3.1. Methodology

Recently, several researchers (e.g., Ritchie and Brindley, 2007, 2009; Wagner and Bode, 2009) have suggested a four-step framework – identification, assessment, steering, and monitoring of risks – for proactive PRM. We will fit our data collection, analysis, and simulation into this framework (3.2-3.5) to allow researchers and managers better understanding and reproducibility. To collect data and validate the results of our literature survey, we chose a workshop-based approach (Tazelaar and Snijders, 2013). The workshop was conducted with 12 procurement executives and supply chain experts, as given in Table 3. The participants had more than ten years of experience in handling procurement-related issues and were from Germany and Switzerland, but they and their firms operate internationally. Most of them deal with commodities in manufacturing industries. The focus of investigation was on purchasing departments of independent business units and their supply networks. From a methodological perspective, data collection was done by experts filling out binary (0, 1) and numerical (0…1) matrices. These matrices were sorted using a rank order clustering (ROC) mechanism. This method is commonly used for identifying connectivity in matrices. These matrices were fed into a simulation as inputs for nodes in a direct network, with links as dependencies of each risk to those that are connected to it.

Table 3: Break-down of workshop participants

Industry Sector	N	Job Title	Function
Automotive and Parts	1	Vice President	Procurement
Chemicals, Plastics and Rubber	3	Manager, Senior Expert	Procurement/SCM
Electronic and Electrical Equipment	2	Director, Department Heads	SCM
Healthcare	2	Managers	SCM
Household Goods and Personal Goods	2	Department Head, Manager	Procurement
Pharmaceuticals and Biotechnology	2	Manager, Senior Expert	Procurement
Total	12		

5.3.2. Identification of risks

As described in Section 2, we conducted a literature survey to identify the most important risks on the supply-side. Table 1 provides a list of the ten most important ones. We verified the list with the 12 workshop participants to gather a consensus among them regarding the selection of risks (Tazelaar and Snijders, 2013).

5.3.3. Assessment of risks

Based on the established list of supply-side risks, these risks are assessed and then clustered. To assess the connectivity of the risks, a binary scale was chosen for simplicity, where 1 signifies a relationship and 0 indicates no relationship between risks. We asked each of the 12 participants (Table 3) to fill in such a matrix, as shown in Table 4.

Table 4: Procurement Risk Interaction Matrix

Procurement Risks	A	B	C	D	E	F	G	H	I	J
A. Contract management risk	0	1	0	0	1	0	1	0	1	1
B. Natural hazard risk	0	0	0	1	0	1	1	1	1	1
C. Technology, process, and infrastructure risk	1	1	0	0	0	1	0	0	1	0
D. Supplier default risk	1	1	0	0	0	1	1	0	1	0
E. Supply quality risk	1	1	0	1	0	0	1	1	0	0
F. Logistics/transportation risk	0	1	1	1	0	0	1	1	1	1
G. Supplier capacity risk	0	1	1	1	0	0	0	1	1	0
H. Pricing risk	1	1	1	0	1	1	1	0	0	0
I. Supplier lead time risk	0	1	1	1	0	1	1	0	0	0
J. Socio-political risk	1	0	0	1	0	1	0	1	0	0

After obtaining the binary interaction matrices (or Adjacency Matrix, AM), risk clusters can be computed using a rank order clustering (ROC) mechanism (King, 1980). Below we provided a five-step methodology for graphically clustering the supply-side risks.

(1) Read each row of the supply-side risk matrix as a binary number (e.g., the first row is 0100101011). Convert each binary number to the corresponding decimal number. Based on the decimal numbers, rank the rows in descending order.

(2) If there is no change in the row order, stop the procedure. Otherwise, go to the next step.

(3) Rearrange the rows based on the ranking of the rows. Read each column of the matrix as a binary number (e.g., first column is 0011100101). Convert each binary number to the corresponding decimal number. Based on the decimal numbers, rank the columns in descending order.

(4) If there is no change in the column order, stop the procedure. Otherwise, go to the next step.

(5) Rearrange the columns based on the ranking of the columns. Go to step 1.

Performing the above methodology repetitively (for the case under consideration, seven times rows operations and eight times columns operations were performed), we obtained a risk cluster matrix as shown in Figure 2B. Three clusters of risks could be identified, highlighted in Figure 2B. For the first cluster, Figure 2A provides a graphical representation of the adjacency matrix for risk connectivity. The main observations of Figure 2 are: (1) Supply-side risks in general and clusters in particular are not independent to one other; (2) The overlapping two risks – Socio-political (J) and Logistics/transportation (F) of the middle cluster – are influencing other clusters, which makes them highly critical risks.

Nevertheless, the other two risks (B and E) of the central cluster are also critical for a SC risk reduction as they are acting as links to other risks of the same cluster; (3) Lastly, the obtained three clusters are significantly different from the risk categorizations suggested by several authors (e.g., Chopra and Sodhi, 2004; Wagner and Bode, 2009; Tang and Musa, 2011). When procurement executives and supply chain experts establish such clustering, they can understand where a SC is most risky (Wu and

Blackhurst, 2009). Certain risks will prove of central importance, while other risks are small enough to be tolerable. In this way, clustering supports an effective management under budget constraints.

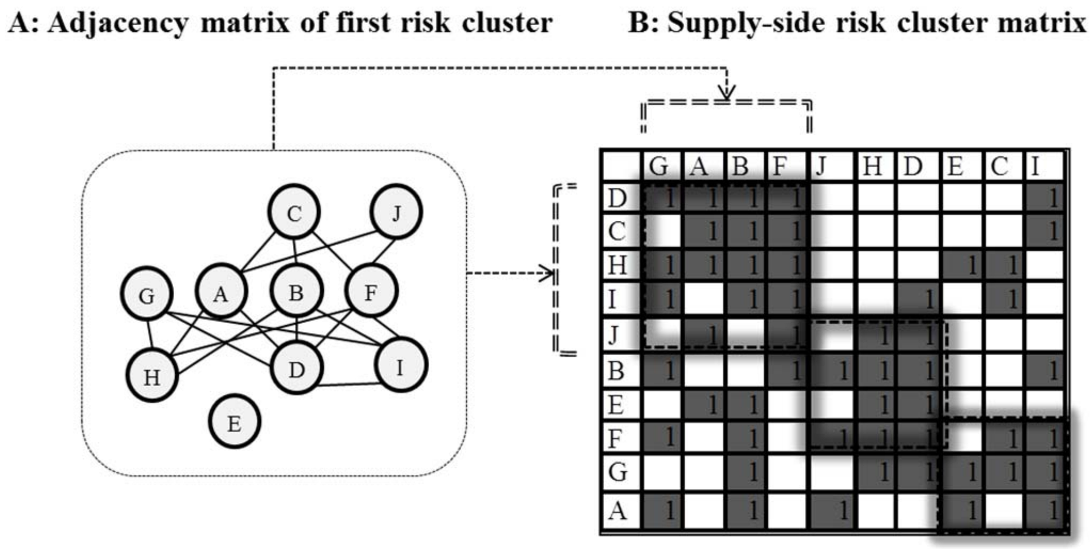

Figure 2: From Adjacency Matrix to Cluster Matrix

We observed from our workshop data in Figure 2 the existence of risk connectivity *d*. For a simulation we require many matrices like in Figure 2 as inputs, which have defined levels of risk connectivity *d*. Then one could analyze how much risk connectivity hinders or supports the success of risk measures. An approach proposed by Newman (2005) allows for random generation of a certain amount of connectivity in matrices, which is explained in the next section.

Random generation of risk cluster matrices with defined connectivity d

Considering a square matrix like Figure 1, we generated 1,000 matrices 10×10 randomly as an initial sample. We colored each square of the matrix like in Figure 2 based on its value equal to 1. Suppose that the independent probability of putting a color in a square of a risk-measure matrix is p, so that on average a fraction p of them are colored. Now we look at the clusters of colored squares. If that square is not colored, then no risk connectivity exists between two risks. Otherwise, there is a connectivity of risks. Thus, we have two possible cases; i.e., when p is small, only a few squares are colored, and the mean area ⟨r⟩ of the matrix represented by a colour is small. Conversely, if p is large—almost 1, then most squares are colored and connected together in one large cluster of a matrix. This means if a mean area $\langle r \rangle$ of the colored cluster of a matrix is large, you have a high corresponding p value. There is a positive correspondence between p and $\langle r \rangle$ values. Now consider the entire distribution of the colored areas in a matrix, where *p(r)* represents the probability that a randomly chosen square belongs to a colored cluster of area *r* in a matrix; and the risk connectivity is defined on [0, 1] and $\sum_r p(r) = 1$ with an assumed *PDF* that for small values of p_r has the form $f(p_r) \propto p_r^{\gamma-1}$ and the $CDF, F(p_r) = \int_0^{p_r} f(p)dp \propto p_r^{\gamma}$ (Newman 2005). The exponent γ is a parameter specific for each SC setup. It is influenced by, for example, the SC structure or the risk reduction effort of an organization. These randomly generated matrices will be used as an input for the SC risk simulation.

5.3.4. Steering of risks

With a clear view of the clustered risks in Figure 2, risk mitigation measures can be initiated. Risk steering is the third step in the PRM framework (Jüttner and Ziegenbein, 2009). Based on the established list of risk measures in Table 2, we asked the workshop participants to review and complete the list of measures for mitigating supply-side risks. Similar to a scorecard-based approach, we then derived interaction matrices, where the first row represents ten selected measures (I, II, …, X) from Table 2 and the first column represents selected risks (A, B, …, J) from Table 1. Each participant was asked to give a score between 0.00 to 1.00 in accordance with the effect of each measure to risk impact. Thus, we obtain 12 matrices, one from each participant, for which a sample matrix is shown in Figure 3. This supports the finding of Bode et al. (2011); i.e., firms respond differently to different risks, not just because their SC designs are fundamentally dissimilar, but because there is a difference in their organizational culture and responsiveness to risks.

	Measure									
Risk	I	II	III	IV	V	VI	VII	VIII	IX	X
A	0.89	0.13	0.28	0.23	0.51	0.92	0.58	0.25	0.17	0.96
B	0.01	0.46	0.70	0.29	0.57	0.13	0.33	0.96	0.26	0.91
C	0.51	0.85	0.59	0.30	0.29	0.69	0.66	0.59	0.48	0.70
D	0.46	0.18	0.05	0.41	0.04	0.58	0.66	0.11	0.15	0.08
E	0.69	0.21	0.92	0.05	0.43	0.43	0.96	0.08	0.42	0.77
F	0.60	0.93	0.43	0.52	0.17	0.79	0.71	0.60	0.61	0.90
G	0.39	0.64	0.68	0.70	0.74	0.69	0.61	0.75	0.77	0.52
H	0.43	0.04	0.42	0.26	0.57	0.40	0.03	0.47	0.46	0.79
I	0.23	0.82	0.02	0.74	0.85	0.53	0.76	0.47	0.34	0.42
J	0.42	0.53	0.09	0.27	0.37	0.59	0.10	0.31	0.24	0.82

>0.7 = Green
>0.5 and <0.7 = Blue
>0.2 and <0.5 = Orange
<0.2 = White

Figure 3: Sample of a Risk-Measure Interaction Matrix

The main observation from Figure 3 is that measures are independent to one another. They affect different risks with different impacts. Thus, it is difficult to suggest a selected few measures to mitigate the clusters of risk. There are two reasons why measures are not independent but have a randomly distributed impact: First, measures don’t have a one-to-one relationship with risks. Second, managers practice measures in a daily trial-and-error approach. There is a chance to evaluate SC risk over time when measures are executed on a trial-and-error basis, because randomness can be generated through the simulation approach. There are analytical techniques to randomly generate matrices from known probability distribution functions (PDFs). Such a PDF was built out of the 12 independently collected matrices of the workshop participants.

5.3.5. Monitoring of risks

The final step in the PRM framework is risk monitoring. The primary duties of risk monitoring are the continuous verification of the effectiveness of the practiced (or implemented) risk-handling measures as well as the identification of emerging risks and internal or external changes (Hallikas et al., 2004). Moreover, risk monitoring can be undertaken to ascertain the effectiveness of the measures and the corresponding risks. Therefore, it is important that firms not only implement risk-handling measures, but that they also review their measures based on the SC risk reduction and performance improvement (Zsidisin, Ragatz, and Melnyk, 2005).

Hence, the idea of risk monitoring and objective evaluation of risk measures was discussed among the 12 workshop participants. Based on their 33 suggested measures or selected 10 measures (shown in Table 2) for handling 10 types of risks, which can be implemented in a combination of 33! ways or in 10! i.e., 3,628,800 ways, it seemed impossible to evaluate the measures manually. Thus, to assess them with their corresponding risks, we developed a simulation framework that helps to gain insights into the measures adopted and their effect on risk reduction. In addition, supply chains have generally numerous supply-side risks (apart from the top ten risks suggested) and several possible mitigation measures. The quantity of data to analyze can become quite a cumbersome and tedious task. However, monitoring a significant number of risks can be visualized and explained through statistical distributions of risk, which helps to draw some insightful behavior of the data for better understanding and explanation of the underlining principles.

Simulation Framework for Risk Monitoring

A supply chain design is exposed to n risk factors, where each of these factors i has a certain amount of risk e_i'. The total risk v of the supply chain results from the summation of all such risks: $v = e_1' + e_2' + \cdots + e_i'$. Newly implemented risk measures can reduce certain e_i'. The risks are not independent from each other regarding both their probability and amount of loss (Figure 2B). Hence, controlling one risk not only affects the total risk, but also influences the other connected risks. Here we are considering risks as nodes in a directed network with links as dependencies of each risk to those that are connected to it (Figure 2A). An adjacency matrix (AM) can alternatively characterize the relationships between the nodes and links; that is, a $n \times n$ square matrix with entries in rows r and columns c (see Figure 2 and 3).

A four-step algorithm for simulating risk reductions is as follows (McNerney et al., 2011):

(1) Select a random risk r.

(2) Use the risk cluster matrices AM – obtained through the random generation of risk cluster matrices with defined connectivity d – to identify the cluster of risks $A_r = \{c\}$ that influences r.

(3) Develop a set of risk mitigation measures and employ a new risk mitigation attempt p_c' for each risk $c \in A_r$ with a risk reduction impact taken from a *PDF f*.

(4) If the sum of the new risks, $e'_r = \sum_{c \in A_r} p'_j$, is less than the current sum, e_r, then each p_c is replaced with p'_c. Otherwise, the risk mitigation attempt was not successful and its measure is dropped. Go to Step 1.

The aim of the simulation is to reduce the total risk in a SC to almost zero. The simulation starts with risk clusters of a defined connectivity *d*. These are generated following the approach shown in the steering section. Then we apply as many (randomly generated) mitigation attempts as needed to reduce the sum of all supply-side risks to zero. The impact of these mitigation attempts is picked randomly from the empirically informed PDF of the experts. The algorithm connects all matrices generated in the assessment and steering section: Step 1 starts with the randomly generated risk cluster matrices and picks a risk. Step 2 identifies which other risks belong in a cluster of this chosen risk. Step 3 picks single mitigation measures and assigns them a certain amount of risk reduction impact from the empirically informed *PDF* function. As mentioned earlier in the steering section, such a *PDF* was built out of the 12 independently collected matrices of the workshop participants. If the new risk mitigation attempt reduced the total supply-side risk, then it is kept, otherwise the old set of measures remains. These steps are repeated for *t* iterations, *t* = 1,000.

The simulation is of two parts: (*i*) The first part is as simple as possible and keeps risks independent of each other. So the connectivity *d*=0. The rate of total risk reduction is already following a fat tail distribution, which means high risk reduction in the beginning and lower reduction rate after time. The statistical pattern can be explained by a power-law function. (*ii*) The second part introduces connectivity of risk *d* = (1…5). This means there is one or more risk clusters in the SC. The rate of risk reduction follows strong power-laws for increasing connectivity of the risks. It is increasingly harder to run down a risk reduction learning curve if risks are connected. Finally, we vary risk connectivity between $d*$ = [1, 5]. This means that the number of clusters changes with iterations over time. Then risk reduction follows unsteady amplitude at the tail of the distribution, which shifts from steady reduction to more rapid reductions after phases of steadiness.

Independent Risks

At the beginning we are considering the simplest case of n independent risks, which is unlikely to happen in reality, but for illustration purposes, we are using this as our first step. For example, consider risk reduction e_i' of mitigation attempt p_c' at attempt (or iteration) *t,* where t is the minimum value of independent and identically distributed random variables of a *PDF* (Muth, 1986; McNeil, 1999). Following Euler's gamma function, the expected risk with respect to time (w.r.t.) can be represented as (McNerney, et al. 2011):

$$E[v(t)] = \Gamma\left(1 + \frac{1}{\gamma}\right)\left(\frac{t}{n}\right)^{-\frac{1}{\gamma}}, \tag{1}$$

where $\Gamma(e)$ represents Euler's gamma function. Let's consider $\gamma = 1$ that yields a low reduction of expected risk $E[v(t)]$ by $\Gamma(\frac{2n}{t})$. This reduction of expected risk naturally follows a power-law distribution *w.r.t* time (Newman, 2005), which is shown in Figure 4A on a log-log scale. The inserted risk-measures matrices in Figure 4 include the independency of risk-measure relationships from one another by mapping only the diagonal relationships. That means that each measure corresponds to the mitigation of one risk (selected from Table 2). An analytical derivation for the reduction of an average risk over time $e(t)$ can be found at McNerney et al. (2011), who looked into the cost reduction of technical components of products over time, showing a scaling of:

$$e(t) \sim (\frac{1}{t}) \text{ as } t \to \infty \quad (2)$$

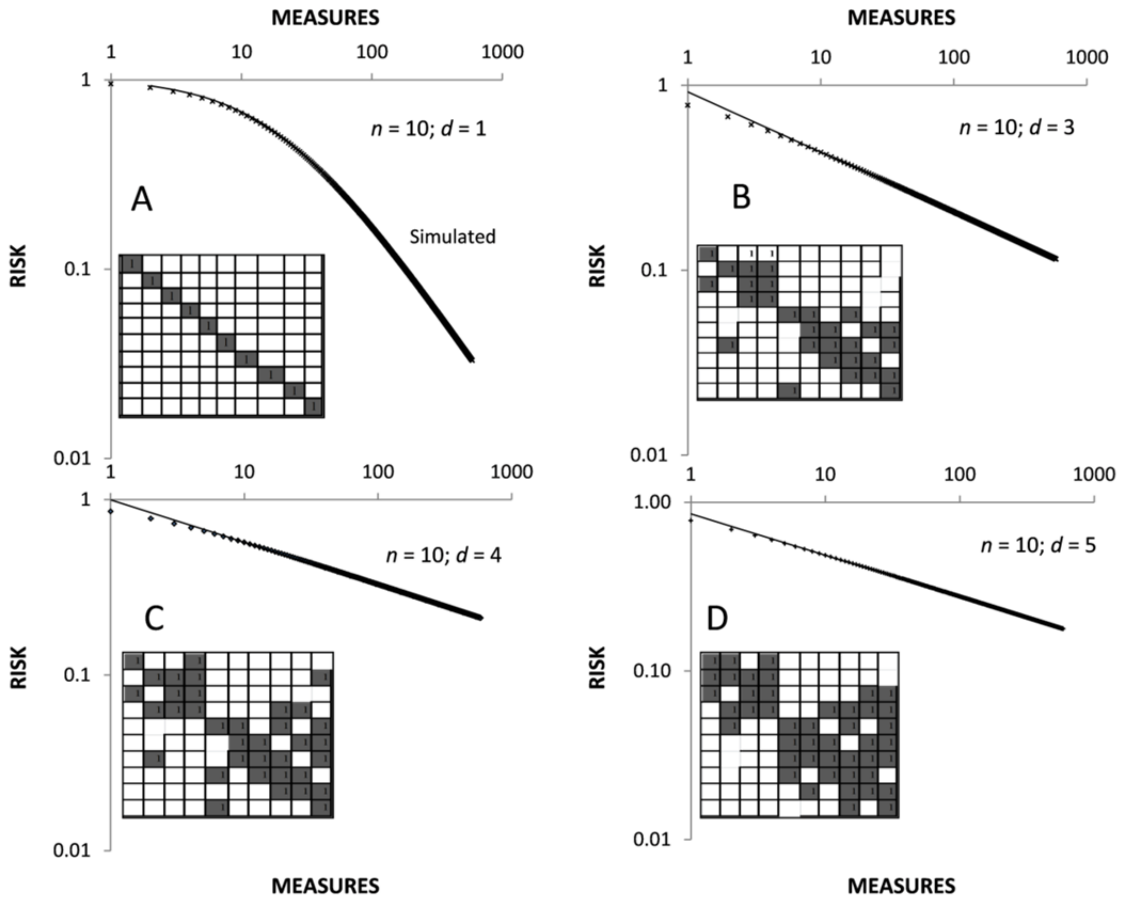

Figure 4: Simulated total risk for fixed risk connectivity *d*

Interacting Risks

We consider a more complex and realistic *n* factor system with risks which are connected to each other; i.e., each risk influences *d*-1 other risks as observed. Analytically, the total risk *v* can be decomposed as (McNerney et al., 2011):

$v = \sum_c^n p_c = \sum_{r,c} AM_{cr}^{-1} e_r = \sum_r^n v_r e_r$, where $e_r = \sum_{c \in A_r} P_c$ is the sum of risks of cluster r and $v_r \equiv \sum_c AM_{rc}^{-1}$. Because the interaction of risks inside the same cluster is much stronger compared to risks in different clusters, clusters evolve nearly independently. According to McNerney et al. (2011), a differential equation for $E[v]$ yields:

$$E[v(t)] = \left[\left(\frac{d}{n}\right)^{\gamma d+1} \frac{\gamma d}{1+\gamma d}\left(\frac{(\gamma n^{\gamma})^{d}\Gamma(\gamma)^{d}}{\gamma d \quad \Gamma(\gamma d)}\right) \times t + 1\right]^{-1/(\gamma d)} \quad (3)$$

This equation can be validated for the shown case of independent risks of d=1: Initially, all risks p_r are set to $1/n$, which gives a risk at the start of p (0) = 1, when $\gamma = 1$ for simplicity. Equation (3) predicts the asymptotic power-law of the simulated risk curves (Figure 4A). Interestingly, the exponent of a power-law $\alpha = 1/\gamma d$ of the risk curve is directly related to the connectivity d, which can be viewed as a measure of the complexity of the SC and its risks, and γ, which characterizes the effort of reducing risks (McNerney et al., 2011; Newman, 2005).

Then we run the simulation for fixed connectivity d = (1…5) among risks: The results are shown in Figure 4B-4D. The inserted risk-measures matrices in Figure 4B through 4D suggest that risks like supplier lead time, logistics/transportation, and contract management are the most influential for SC risk reduction, which can be visualized from the last three columns of each matrix. Apart from that, clusters of four factors (J, G, D, and E) – with small connectivity among them – at the north-west corner and cluster of six factors (B, C, H, I, F, and A) – with large connectivity among them – at the south-east corner of each matrix suggest that at least two or multiple mitigation attempts are required to mitigate risks. The amount of connectivity makes the issue more complex and influences the SC risk reduction, which can be visualized from the gradual decay in the slope of Figure 4B through 4D.

When the number of risk clusters is varying (connectivity *d* varies with time), risk reduction becomes more fluctuating (Figure 5), as it is difficult to find the optimal risk-measure combination instantly. Analytically, the variable connectivity *d* with time can be represented by picking *d** (new risks connectivity) independently from a uniform probability distribution function, shown in Figure 5A and 5B. In Figure 5, the trajectories fluctuate in both cases, but the breadth of fluctuations is higher in Figure 5B compared to Figure 5A on a log-log scale. A higher value of *d** yields the slowest risk reduction in Figure 5A and 5B, respectively. Moreover, in both cases, the head of the distributions follows straight lines, whereas the tails are more fluctuating due to the varying risk connectivity, which can be explained by increasingly more effort to catch the remaining risks that are randomly connected compared to steady ones.

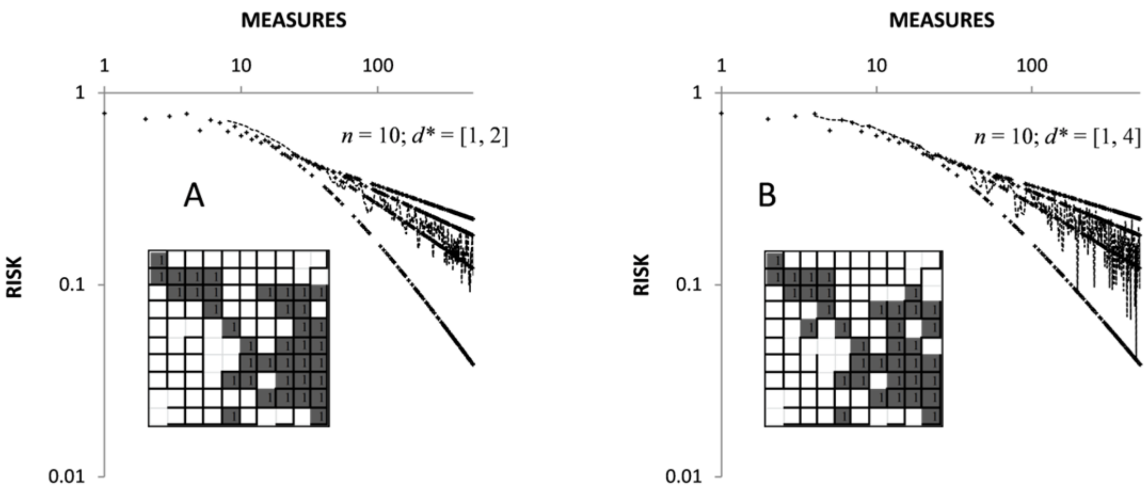

Figure 5: Total risk for variable risk connectivity *d**

5.4. Conclusions

We developed a model for the mitigation of risk in SCs. The simulation analysis makes a unique contribution by linking the literature on risk and risk measures into one numerical model. In contrast to the previous work, we also quantified connectivity among risks. If risk measures are used on a trial-and-error basis, one can observe risk reduction curves following a power-law behavior with exponent $\alpha = 1/(\gamma[d, d^*])$, where d and d^* are fixed and variable connectivity and γ describes the effort of reducing risk. The results show how varying connectivity of risk factors leads to bottlenecks for risk reduction. This suggests that, for academics as well as managers, reducing the connectivity of potential risks in a SC at initial design and redesign would decrease risk most effectively. The applied tools were adjacency matrix for supply-side risks, risk-measure interaction matrix answer calls for simple methods, and decision-making techniques for corporate practice (Tang and Musa, 2011).

Whereas our study focused on the risk of the upstream part of SCs, an implementation of the framework should include the downstream SC as well (Ivanov, Sokolov, and Pavlov, 2013). Another extension lies in the specification of sub-risk factors and related sub-measures that detail the identified ones in the literature survey and experts study. Such specialized risks and measures may be necessary for industries, business units, and even products (Pettit, Croxton, and Fiksel, 2013). Using a binary scale for measures does not allow to consider negative impacts of risk mitigation. Here a different scaling could improve a future analysis. Similarly, we related different risks only positively (risk connectivity), which could be implemented for negative correlations as well.

5.5. References

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