Assessment and Management of Complex Risk Structures - Facing Challenges of Digitalization

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FÜR MEINE ELTERN

„Von guten Mächten wunderbar geborgen, erwarten wir getrost was kommen mag …“

[Dietrich Bonhoeffer]

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Abstract

The continuing dissemination of information technology (IT) and information systems (IS), which currently manifests and proceeds in terms of digitalization, keeps on revolutionizing both, business and society. Along with the undoubted advantages of this development, it also yields a lot of challenges. The resulting interconnectedness of humankind, infrastructure, and machinery, combined with the increasing dynamics due to a fast-pacing and competitive market environment, pushed companies to operate within complex risk structures. These structures likewise affect a company's internal management and its external interaction. In terms of a company's internal management, especially risk associated with IT projects still represents a major challenge that has not yet been solved. This particularly becomes relevant, as these projects are the source of a company's progression, and hence crucial to survive in today's market environment. As to the external interaction of a company, particularly the increasing interdependence to other companies, in the context of value creation networks, yields major challenges. An impact that formerly would have only affected a single company, nowadays can spread to assigned companies based on the underlying dependencies. This increases a company's exposure to risk, when being embedded in value creation networks.

With the above considerations in mind, the comprehensive objective of this doctoral thesis is to contribute to the extant body of knowledge in the light of IT-pervaded complex risk structures. It provides means to manage and assess especially relevant risks in the subject areas of IT projects and value creation networks. Particularly, it investigates IT project complexity, which has been considered a major risk for IT project success, and derives a two-dimensional framework for its assessment that provides conceptual clarity and enables to mitigate associated risks (Section II.1). It moreover examines IT project assessment and management. Considering the increasing complexity and interdependence of IT project environments, it proposes a quantitative, integrated approach for IT project assessment, to reduce the risk of wrong IT project appraisals (Section II.2). Moreover, it focuses on risks arising during a project's lifecycle and provides means for a continuous IT project management, to ensure the projects' objectives and corresponding business value (Section II.3). Focusing on the increasing interdependence in the subject area of IT projects, it examines the coherence between interdependencies and corresponding risks. By applying centrality measures to the subject area of IT projects, it enables to determine the most critical IT project of a corresponding IT portfolio, based on the projects' underlying direct and indirect dependencies (Section III.1). Investigating risks arising from interdependencies in

terms of a company's external interaction, it draws on supply networks as one instantiation of value creation networks to examine the propagation and extent of impacts of exogenous shocks. Consequently, it provides means to assess and manage the resilience of the overall supply network and the exposure of each aligned company to dependency related risks (Section III.2). Finally, it summarizes the major contributions and indicates starting points for further research (Section IV).

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I Introduction

I.1 Motivation

Taking a look at the technological change brought by the accomplishments of IT projects over the last decades, it can be constituted that IT nowadays influences almost each service offered by any kind of service provider, as well as each product offered by any kind of manufacturing company. Indeed, IT "has created a more global, faster and more interconnected world" (Buhl, 2013, p. 377), and has leveraged its influence not only to any kind of process in economy, but is omnipresent in today's society (vor dem Esche and Hennig-Thurau, 2014). Humankind currently is in a stage, in which "the generation of wealth, the exercise of power, and the creation of cultural codes came to depend on the technological capacity of societies and individuals, with information technologies as the core of this capacity" (Castells, 2010; Hilbert and Lopez, 2011, p. 60). Revolutionary IT innovations like the Internet and related developments like social media, cloud computing, and e-commerce, as well as mobile phones and the consumerization of IT, lead to an age of digitalization (Bojanova, 2014). Nowadays, we communicate with digital phones and cell phones, read digital newspapers, purchase via digital channels and use social media platforms like Facebook and Twitter to digitally document our lives (vor dem Esche and Hennig-Thurau, 2014). However, these few examples are only the surface of ubiquitous IT solutions that enable companies and individuals to easily acquire, exchange, and generate knowledge, deliverables, and resources. However, besides the beneficial side of IT, it can also have negative implications that can be observed every day in discussions and reports about data privacy, business failures or even economic crises (Buhl, 2013). These negative impacts might arise from both, occurring risks as to a company's internal management and its external interaction.

In terms of a company's internal management, the challenges of such an increasingly complex, dynamic, interdependent, and especially fast pacing environment pushes companies to continuous progression as to efficiency and innovation. Progression however implies to change current practices. Since change in turn is enabled by projects all along, they increasingly gain importance (Watson, 2012). Although, there is no common definition of a project in general, most researchers agree that a project is a nonrecurring intent with defined objectives, limited resources, and limited time (Lassmann, 2006; Hansen et al., 2015). Considering these characteristics, it becomes obvious that change precipitated by projects and progression are not necessarily the same. The alignment of the project's objectives to the overall objectives of the company is a necessary condition for a project to contribute to a company's progression (Buhl and Meier, 2011). Furthermore, it has been proved an adequate means, to draw on so called *project management*, that composes knowledge, abilities, tools, and techniques, to actually accomplish the defined project objectives (Laudon et al., 2010). Project management has been used to support the implementation of projects since about 1950 and has been adapted by several industries like arms, construction, or computer industry in subsequent years (Williams, 2005; Kwak and Anbari, 2009; Pellegrinelli, 2011; Turner et al., 2013). Since the increasing market pace and pressure lead to a growing number and importance of projects, the relevance of project management has risen accordingly. Nowadays, project management is an integral part of almost each project implementation across all industries. To foster existing knowledge and experiences gained in the context of project implementation in practice, organizations like the Project Management Institute or the German Association for Project Management have been founded (Morris et al., 2006). The former one thereof has published the *Project Management Body of Knowledge*, which probably is the most known accumulation of project management practices and provides information and methods for almost each field of knowledge in the context of project management (Williams, 2005). Complementary, research has yielded several methods to support and promote the practical expertise in the different project management knowledge fields.

One of these knowledge fields has been dedicated to risk management, as projects involve a high degree of uncertainty and risk (Chapman, 1998; Conroy and Soltan, 1998; Baccarini et al., 2004; Marle et al., 2013). Though, what do people mean when they talk about uncertainty and risk? Uncertainty and risk generally might exist, when there are manifold outcomes to a course of action. In this context, uncertainty is used to describe a state where the probability of an outcome is unknown, whereas risk is used if the probability of an outcome is known (Bussey, 1978; Merrett and Sykes, 1983; Merna and Al-Thani, 2011). However, there are different views on whether the step from uncertainty to risk requires a threat e.g. some kind of damage (Kaplan and Garrick, 1981) or whether risk is simply the possible deviation of a targeted value, which is a prevalent perspective when it comes to risk quantification and measurement (Rothschild and Stiglitz, 1970). In the field of project management, it generally is noted that risk can possibly have a positive or a negative impact on a project's objectives (PMI, 2008). Nevertheless, risk mostly is considered to be the "chance of an event occurring that is likely to have a negative impact on project objectives" (Baccarini et al., 2004, p. 287). Therefore, risk management has been identified to be a crucial means to successfully manage

IT projects (Tuman Jr, 1994; Remenyi, 1999). Besides some small differences in denominations and delimitation, there is consensus that the *risk management process* can be subdivided into four separate stages: *risk identification*, *risk assessment*, *risk treatment*, and *risk monitoring* (Stoneburner et al., 2002; Hallikas et al., 2004; PMI, 2008). For each of those stages, there are plenty of tools and techniques presented in order to support risk management (PMI, 2008). Additionally, several authors strive to enrich the existing knowledge base in each of the risk management stages by investigations based on exploratory studies, questionnaires, interviews, or any other kind of methods (e.g. Wideman, 1992; Whittaker, 1999; Sumner, 2000; Hallikas et al., 2004; Baccarini et al., 2004; Olsson, 2008; Marle et al., 2013; Keller and König, 2014)

However, despite this profound body of knowledge existing in the area of project management, there is still a relatively high percentage of project failures. Projects are considered a failure, if they are not accomplished in time or budget, do not deliver the defined objectives, or are even canceled before completion (Hartman and Ashrafi, 2002; Tesch et al., 2007; Al-Ahmad et al., 2009). In recent years, especially IT project failures have drawn great attention in practice and research. The miserably failed virtual case file implementation of the United States Federal Bureau of Investigation (FBI), which accounted for a $170 million loss before it was officially discarded in 2005 (Eggen and Witte, 2006), and the failed implementation of an Enterprise Resource Planning (ERP) system that finally lead to the insolvency petition of Schiesser (Brück and Schnitzler, 2009), the market leader among the German underwear specialists, in 2009, are just two out of several examples. From the specific perspective of a single company, IT project failures thus are able to cause devastating problems that even can lead to business failure (Flyvbjerg and Budzier, 2011). Generally, many studies investigating IT project failures have been published. One of the most quoted studies in this context is the yearly published chaos report of Standish Group. This report states that about 60% of all IT projects are not completed on-time and on-budget (Standish Group, 2013). Another study from the IT Governance Institute states that about 20% of all IT investments are terminated before implementation (ITGI, 2011). Furthermore, a study by the Project Management Institute shows that in 2011 about 36% of projects fall short on their initial business intent and corresponding objectives (PMI, 2012). Given that the worldwide IT spending is supposed to reach $ 3.8 trillion in 2015 (van der Meulen and Rivera, 2015), it becomes obvious that IT project failures generally cause an enormous global value destruction.

Extensive studies within this context found that the prevalence of IT project failures is related to the lack of appropriate managerial approaches rather than to the information technology per se (Jaafari, 2003). Classical project management approaches are not able to cope with the accelerated change prevailing in the context of IT projects (Jaafari, 2003). Although IT projects are not precisely delimitable from other kinds of projects, they are supposed to feature specific characteristics like invisibility, abstractness, complexity, and changeability (Ewusi-Mensah, 1997; McDonald, 2001; Milosevic et al., 2006; Al-Ahmad et al., 2009) that make them additionally complicated to manage. Furthermore, as IT projects are rather accomplished within an integrated portfolio of several IT projects, they feature manifold dependencies compared to projects that are realized isolated or pairwise (Graves et al., 2003). *Therefore, to cope with increasing complexity and dynamics as to companies' internal management, they need to assess and manage their IT projects more holistically. Yet, since classical tools of project and risk management are considered to be of limited utility in the light of these challenges, appropriate means and approaches need to be developed.*

Existing dependence structures are even further intensified, as market pace and competition pressure force companies to continuous innovation efforts in order to maintain their competitiveness (Keizer and Halman, 2007; Nguyen and Mutum, 2012). Therefore, IT projects that formerly would have been accomplished as one big IT solution are subdivided into several standalone IT solutions, which however feature more dependencies but are able to generate separate customer impacts. These increasing dependencies and associated risks pose additional challenges regarding a company's internal management (Blumberg, 2012). Also in terms of a company's external interaction, they represent a major challenge. Dynamic interdependencies that are featured by the interpenetrating dissemination of IT (Buhl, 2013) are, among others, causal to negative impacts like supply shortfalls or even economic crises. Besides the increasing interdependence, these negative impacts are also fostered by globalization, which, combined with an accelerated technical development, led to a fast pacing market environment that is continuously driven by competition, specialization, and technology (Silvius and Schipper, 2010). This development is even boosted by recent aspirations in the context of digitalization that not only intensify classical competition, but also yield completely new concurrent business models (Wirtz et al., 2010; Berman, 2012). The emerging IT-based network structures, which can be found all over the world across different business areas, inherit a great level of risk for the participating companies. Since based on the inherent dynamic dependencies of these structures, negative impacts of a particular company can spread over the entire network, they do not only increase the risk exposure of a particular company, but can also threaten every other interconnected company of the underlying network (Rice and Caniato, 2003; Hallikas et al., 2004). This phenomenon is known as *systemic risk* and although it has already been recognized for instance by Hallikas et al. (2004), it especially arose awareness during the financial crisis of 2008/2009 and the resulting spread to the real economy. *To survive and ensure competitiveness in today's fast pacing market environment, companies need to handle this kind of risk, emerging from increasing interdependencies in various business areas. Though, classical tools and techniques that were assigned to the different stages of the risk management process are not adequately capable to face these challenges.*

However, since "a major challenge for IS research lies in making models and theories that were developed in other academic disciplines usable in IS research and practice" (Benaroch and Kauffman, 1999, p. 84), there are approaches in other research areas like mathematics, informatics, biology, or physics that might be adapted to investigate systemic risk and the underlying dependency structures in business environments. In this context for instance centrality measures that are based on graph theory are considered as an appropriate means for network analysis purposes across different scientific areas (Borgatti and Li, 2009). As a formal modelling technique of informatics that features graphical visualizations, also Petri Nets have been proven an adequate means to model dynamic systems across different areas of application (Wu et al., 2007). Moreover, there are network investigation approaches in physics that initially were designed to depict dynamics of loads in specific networks (Motter and Lai, 2002). However, since these loads can be considered as any kind of quantity, the applicability of these approaches is widespread (Moreno et al., 2002). Some approaches belonging to aforementioned scientific areas have indeed already been applied to business issues. For instance Borgatti and Li (2009) and Kim et al. (2011) use centrality measures to investigate supply chain networks. Within the same subject area, for instance Wu et al. (2007) use Petri Nets to quantify the risk of disruptions in supply chains. Furthermore, in the context of the financial crisis, several authors refer to cascade failure algorithms, which generally use loads to simulate cascades of failures in network structures, to finally investigate dependencies and resulting systemic risk in banking systems (Nier et al., 2007; Battiston et al., 2012[a]; Battiston et al., 2012[b]).

Despite these first attempts to assess systemic risk in business environments, this topic is still relatively unexplored. It will take a lot more investigation to enable companies to adequately handle the dynamic interdependencies and the resulting systemic risk they are increasingly exposed to in various business areas. Therefore, the German Informatics Society (Gesellschaft für Informatik e.V.) announced the management of systemic risk within IT-braced global network structures as a grand challenge for the next years (GI, 2014). Against this background, the doctoral thesis at hand focuses on the assessment and management of increasingly IT-pervaded complex risk structures, to mitigate failures and reduce the resulting global value destruction in the age of digitalization.

I.2 Scope of the Doctoral Thesis

The outlined development affects several different areas of economy and society. Even though the scope of this doctoral thesis is narrowed to the assessment and management of complex risk structures in an economic context, there remain various research questions within each of the affected economic areas that are not feasible to investigate within a single doctoral thesis. Therefore, the scope of this thesis requires further delimitation. Risk assessment and management in general refer to several different areas of risk. Hull (2012) for instance categorizes risk as follows: *credit risk*, *market risk*, *operational risk* and *liquidity risk*. Moreover, operational risk is considered to encompass *IT risk*, *process risk*, *personnel risk*, and *exogenous risk* (Hull, 2012). Although *systemic risk* is stated as a separate kind of risk, it is not explicitly assigned to one of the aforementioned risk categories. However, since it is supposed to most likely fit operational risk in this context, it henceforth is considered correspondingly. Since the encompassed kinds of risks are considered to be of special relevance against the outlined background, the scope of this doctoral thesis is restricted to operational risk. To be more concrete, it selectively examines generic operational risks that are supposed to be especially relevant, but difficult to manage and therefore still insufficiently covered in the existing risk management body of knowledge. The generic operational risks are exemplified by the specific subject areas of IT projects and value creation networks, which represent particularly affected areas of the aforementioned development. Figure I.2-a illustrates the research context and the research scope to enhance clarity and understandability.

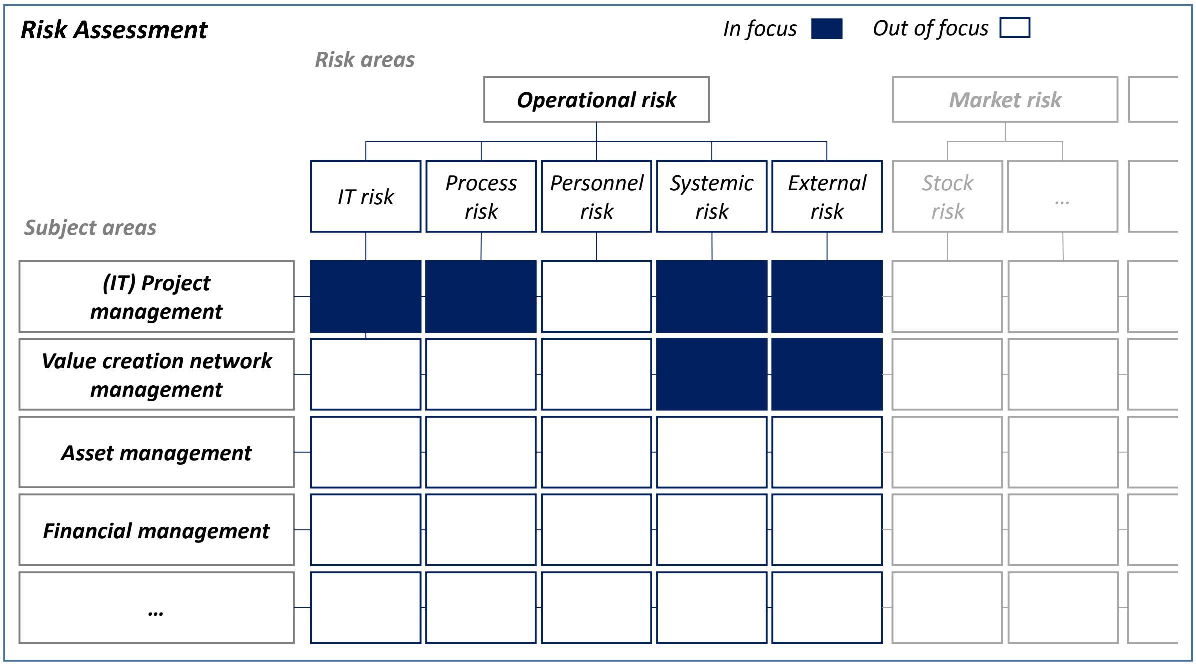

Figure I.2-a - Delimitation of research scope

I.3 Research Context and Objectives

As mentioned before, this doctoral thesis focuses on particular risks that are supposed to be especially relevant as to the increasingly complex, dynamic, and interdepend structures in the light of digitalization. Drawing on the subject area of IT projects, it particularly investigates operational risk as to complexity and dynamics in the context of IT project evaluation (Section II). It furthermore draws on the subject area of IT projects as well as on the subject area of value creation networks, to investigate systemic risk as a prevailing phenomenon in an increasingly interdependent business environment (Section III). As to the different stages of the risk management process, it thus focuses on *risk assessment* and *risk treatment*, whereas some parts of the presented methods and means might also serve for specific activities of the other adjacent steps of this process. Subsequently, this section embeds the aforementioned risks in the research context, allocates them to the sub-categories of operational risk where possible, and outlines the research objectives.

Enhancing IT Project Evaluation to Cope with Emerging Risk (Section II)

Taking a closer look at the subject area of IT projects, Section II strives to enhance IT project assessment and management to cope with risks of increasing complexity and dynamics, challenging a company's internal management in the light of digitalization.

In particular, ***Section II.1*** focuses on IT project complexity that is considered a major risk for IT project success (Baccarini, 1996; Xia and Lee, 2004; Parsons-Hann and Liu, 2005; Vidal and Marle, 2008). With the considerations of Section I.1 in mind, increasing complexity of a company's business environment likewise affects a company's projects as the source of its progression. In this context, many studies investigated the prevalence of IT project failure and constitute a coherence to the lack of managerial approaches that are able to cope with the increasing complexity of IT projects (Jaafari, 2003). However, it is a very vague concept and there is no consensus about what is meant when people talk about IT project complexity, neither in practice nor in academia (Vidal et al., 2013). Yet, it is most commonly agreed that IT project complexity describes the interaction of several different characteristics like dependency or diversity. These can either be considered as individual risks or any other kind of aspects that somehow complicate the accomplishment of IT projects. Therefore, IT project complexity cannot be classified into one specific sub-category of operational risk, but rather encompasses different aspects of various operational risk sub-categories. For instance, an inappropriate controlling of the projects rollout that increases the projects complexity would probably be classified as *process risk*, while the manifold use of different planning systems that also boosts the projects complexity would rather be considered within the sub-category of *IT risk*. This makes IT project complexity difficult but also important to assess. Moreover, IT project complexity is prone to human perception (Schlindwein and Ison, 2004). Thus, it is controversial whether it can be objectively conceived in general. Nevertheless, the increasing complexity of IT projects reinforces the companies need for adequate management approaches. In order to conclude on underlying causalities, Section II.1 examines aspects that are supposed to somehow relate to IT project complexity in extant literature. Consequently, it strives to provide conceptual clarity to the construct of IT project complexity *[Objective II.1]*. Furthermore, it endeavors to mitigate the risk of IT project failures by providing means to realize and manage the complexity of IT projects *[Objective II.2]*. It thus aims to answer the following research question:

- *How can complexity in IT projects be assessed with respect to its influencing factors?*

Section II.1 of the doctoral thesis is a slightly modified and improved version of Neumeier and Wolf (2015), which has been submitted to an academic journal for publication.

Considering the increasing complexity and dynamics as challenges to a company's internal management, ***Section II.2*** outlines the necessity for an integrated IT project quantification. To decide whether an IT project should be implemented or not, most companies formerly especially focused on the project's cost (e.g. Boehm et al., 2000). Nowadays, since IT has become a strategic success factor, most companies start to consider also possible benefits related to an IT project in corresponding investment decisions. However, the consideration of benefits in an ex ante business case of an IT project is still rather exception than norm (Buhl, 2012). One reason might be, that particular in case of IT projects, benefits are especially vague and difficult to grasp in monetary units. This additionally is complicated, as benefits are usually not realized before the project’s completion (Buhl, 2012). Another reason might be that the risk whether an undertaken investment is rewarded with a corresponding return is supposed to be quite high in the increasingly complex and dynamic environment of IT projects (Denne and Huang, 2003; Melville et al., 2004; Neumeier and Müller, 2015). Therefore, most business case calculations are still focusing on expert estimations of future cost, while benefits are often not considered adequately (Blumberg et al., 2012). To mitigate the risk of wrong IT project appraisals, business case calculations should also consider other project related aspects. Existing dependencies or other aspects that might result in an increased project risk are oftentimes completely neglected (Zimmermann, 2008), although they are crucial in today´s complex and dynamic project environment (Buhl, 2013). Consequently, companies need to evaluate their IT projects more holistically. Such an evaluation can be considered as part of the project controlling and issues related to the project controlling can be considered to belong to the category of *process risk*. Accordingly, the corresponding risks regarding the evaluation of IT projects might be assigned to this sub-category of operational risk. Despite the claimed importance of a holistic evaluation of IT projects, there is a lack of appropriate methods that likewise consider the relevant project variables, while upholding practical applicability (Ward and Daniel, 2006). Thus, Section II.2 strives to provide means for a quantitative assessment of benefits of IT projects *[Objective II.3]*. Moreover, it endeavors to develop likewise rigor and practicable means for an integrated quantification of IT projects *[Objective II.4]*. It consequently addresses the following research questions:

- *How can benefits of IT projects practically and quantitatively be assessed for business case calculations?*
- *How can different aspects of IT projects like cost, benefits, risk, and dependencies can be evaluated in an integrated quantification approach, which likewise upholds scientific rigor and practicability?*

Section II.2 of the doctoral thesis is equivalent to Beer et al. (2013) that is already published in the proceedings of the 11th International Conference on Wirtschaftsinformatik.

Particularly addressing the increasing dynamics as challenge to a company’s internal management, ***Section II.3*** examines the necessity for a continuous IT project steering to ensure the projects' objectives and corresponding business value. A famous saying by Warren Buffett states "Prize is what you pay, value is what you get". However, especially in the context of IT projects, it is not quite sure whether the prize that was paid is rewarded with actual value (Melville et al., 2004). As IT projects bear a lot of uncertainty and risk during their time of implementation, their ex ante estimated business value, which is represented by the defined and anticipated project objectives, is quite uncertain (Müller and Neumeier, 2015). This uncertainty even increases with the size of the corresponding IT project. Since large scale IT projects take more time for implementation and feature many functionalities, they bear a lot of space for changes in the projects' environment that might lead to changes in the projects requirements. These changes in turn can have an impact on the business case of the project, since some functionalities might need to be adopted, others need to be added and again others need to be discarded (Cheng and Atlee, 2009). However, as it is rule rather than exception to evaluate an IT project only once during the planning phase, there is no possibility to reevaluate whether the project in its current state is still able to deliver the determined project objectives (Buhl, 2012). Consequently, the probability that an IT project fails to deliver its determined objectives and corresponding business value is quite high, based on current methods and practices. Since the continuous management of IT projects can be considered as part of the project controlling as well, the corresponding risks might also be assigned to the sub-category of *process risk*. To mitigate the depicted risks, companies require tools and methods to continuously evaluate and monitor the progress of an IT project and to enable the initiation of adequate countermeasures when specific business case limits are triggered. Thus, Section II.3 strives to provide means for a continuous quantitative assessment and management of IT projects *[Objective II.5]*, to diminish associated process risks arising during the projects' lifecycle. Consequently, it addresses the following research question:

- *How is it possible to reduce process risks arising during the lifecycle of IT projects?*

Section II.3 of the doctoral thesis is an editorially improved version of Fridgen et al. (2014), which is a follow-up on Beer et al. (2013) and is already published in the ACM Transactions on Management Information Systems. It extends Beer et al. (2013) by introducing a dynamic cash flow perspective and developing a method for continuous project evaluation and steering based on the integrated IT project assessment of the preceding research paper (Beer et al. 2013).

Managing Dependencies to Mitigate Systemic Risk (Section III)

Almost every area of today's business environment is becoming increasingly interlaced. Among others, one major reason is the dissemination of underlying, interconnected IT solutions (Buhl and Fridgen, 2009). Consequently, the increasing dependencies between different entities yield complex network structures that nowadays can be found on almost each level of economic collaboration. Whereas regarding a company's internal management the entities of such a network might be IT projects being dependent due to resource sharing, from an external interaction perspective they might be companies that depend on each other due to mutual supplier relations. Independent whether these network relations are considered from an internal management or an external interaction perspective, they all feature systemic risk as they enable an impact on a single entity to spread to the entire network. Therefore, Section III concentrates on the mitigation of systemic risk, based on an appropriate assessment and management of underlying dependencies.

Focusing on the increasing interdependence as challenge to a company's internal management, ***Section III.1*** investigates the coherence between dependencies and systemic risk in IT project portfolios. IT projects are not accomplished isolated or pairwise, but rather within portfolios of several IT projects. Therefore, they feature manifold dependencies in comparison (Graves et al., 2003). Some of them relate to a lower level of granularity as they refer to single IT assets or resources within one specific IT project. Others are located on a higher level of granularity, as they describe relations between different IT projects (Wehrmann et al., 2006; Zimmermann, 2008). Moreover, it has to be distinguished between direct and indirect dependencies. While some project management techniques at least qualitatively account for direct dependencies, indirect dependencies are most commonly not pictured adequately or even neglected completely. Thus, it has been recognized that classical techniques and methods for project management are not capable to account for the specific characteristics of IT projects in this context (Cho and Shaw, 2009). The fact that IT projects become increasingly interwoven represents, however, a major challenge for companies all over the world (Blumberg, 2012). Due to this development, a failure of a single IT project does no longer only influence the project itself, but can also spread to other assigned IT projects. This reflects the prevalence of systemic risk in IT portfolios. Therefore, dependencies do not only contribute to IT project complexity, but also directly increase the risk of IT projects that accordingly needs to be incorporated in the business case calculation of each individual IT project (Buhl, 2012). Moreover, a proper consideration of dependencies is not only crucial to the success of the corresponding IT projects, but also to the success of the whole IT portfolio and eventually even to a company's operational business. To mitigate the risk of IT project and related business failures, companies seek adequate means to face the challenging task of considering dependencies and associated risk more thoroughly. Thus, Section III.1 strives to provide means for an appropriate assessment of complex dependency structures in IT portfolios, likewise considering direct and indirect dependencies *[Objective III.1]*. Consequently, it addresses the following research question:

- *Can centrality measures be used to assess the criticality of a project to its corresponding IT portfolio, based on inherent project dependencies?*

Section III.1 of the doctoral thesis is an enhanced version of Wolf (2015) that is already published in the proceedings of the 12th International Conference on Wirtschaftsinformatik.

Focusing on the increasing external interaction of a company, ***Section III.2*** investigates the propagation and the extent of systemic risk in the subject area of value creation networks. Since exogenous shocks like earthquakes or floodings have shown the sensitivity of supply networks regarding systemic risk in recent years, Section III.2 specifically draws on these kinds of value creation networks. Although, entities in supply networks keep multiple relationships to other entities on preceding and succeeding supply stages of their network for reasons of diversification, these networks are not as resilient as they might appear. Globalization, specialization and, outsourcing lead to increasingly complexity (Wagner and Neshat, 2010). This development is reinforced by new kinds of outsourcing, enabled by the increasing digitalization of business services and processes (König et al., 2013). The resulting complexity and opacity of current supply networks hampers companies to determine the systemic risk arising from their established entanglements (Fridgen and Zare Garizy, 2015), i.e. they are not able to exactly quantify the consequences that an impact on their supply network might have to themselves. This also holds true for many other kinds of value creation networks. Determining the systemic risk a specific entity of a network is exposed to requires both, to quantify the extent of an occurring impact as well as its propagation through the network. With these information, an entity is able determine which of its various network relations is impacted to which extent. Thus, Section III.2 strives to consider systemic risk by providing means to assess the propagation of impacts in complex network structures *[Objective III.2]* and to quantify the impacts' extent to any assigned entity of the network *[Objective III.3]*. Since these objectives are exemplarily examined using supply networks as one instantiation of value creation networks, this section addresses the following research questions:

- *How to illustrate and assess the propagation of impacts in supply networks featuring systemic risk?*
- *How can impacts of systemic risk in supply networks be quantitatively assessed?*

Section III.2 of the doctoral thesis is a slightly modified version of Fridgen et al. (2015), which is an enhanced follow-up on Fridgen et al. (2012), and is already published in the International Journal of Production Research. Beyond the prior research (Fridgen et al., 2012) that is published in the Proceedings of the 20th European Conference on Information Systems, it includes detailed explanations, a detailed modelling description and an evaluation of the presented method by statistical means. Section III.2 also contains results of my diploma thesis "*Exogenous Shocks in Complex Supply Networks – Simulation-Based Evaluation with Modular Petri Nets*", which has been submitted to the Faculty of Business and Economics at the University of Augsburg in 2012.

I.4 Individual Contribution to the Included Research Papers

The six research papers included in this doctoral thesis were compiled in the following research settings. The research paper (Neumeier and Wolf, 2015), forming the basis for Section II.1, was mutually developed with another co-author. Although, I derived the basic idea of this research project, we jointly conceptualized and elaborated the paper's structure and content. Thus, the co-authors contributed equally to the paper's conception and elaboration. However, since I have been the more experienced researcher in this setting, I guided the entire paper process. By reviewing relevant literature in the context of IT project complexity I had a central role in sorting out inconsistent proceedings and in describing and delimitating existing theoretical foundations. Moreover, based on manifestations of IT project complexity reported in literature, I particularly was involved to derive antecedents and project areas as dimensions of the framework for assessment. I was also responsible for the evaluation based on the case-study. However, based on this examination, we jointly synthesized the central findings and the final framework. The research paper (Beer et al., 2013), forming the basis for Section II.2, was jointly developed in a research team of four researchers. Although the basic idea for the paper already existed, we jointly conceptualized and elaborated the paper's structure and content. Thus, I was involved in each part of the research paper. I strongly contributed to the written elaboration and the structuring of the whole research paper and in particular to the proposed model for monetary quantification of IT projects, including the assessment of single benefits and the aggregation of a risk-adjusted project value. Furthermore, I especially was involved in the delineation of the applied Action Design

Research methodology and the conceptualization of the application example. However, the co-authors in total contributed equally to the paper’s emergence. In contrast, the contributions to the research paper (Fridgen et al., 2014), forming the basis for Section II.3, were not equally distributed. This paper was also developed in a research team of four researchers, whereas the co-authors Gilbert Fridgen and Julia Heidemann were the more experienced ones, who had already presented the first idea of the paper (Fridgen and Heidemann, 2013) at the Dagstuhl-Seminar to the computer science community. Building upon this groundwork, we however jointly conceptualized and elaborated the paper’s structure and content. Hence, I was involved in each part of the research paper. I especially was involved in the conceptualizing and elaboration of the Project Success Measurement and the Project Controlling, which are means for a continuous project management. Furthermore, I had a core role by deriving and outlining the corresponding trigger points for the particular measures. Finally, we jointly synthesized the central findings in the beta cycle and the formalization of learning.

The research paper (Wolf, 2015), that forms the basis for Section III.1, was developed and written entirely on my own. Hence, I conceptualized the paper’s idea and delineated related foundations. Furthermore, I conducted the literature research and elaborated requirements to transfer centrality measures to IT project portfolios. Moreover, I simulated an exemplarily IT project portfolio and analyzed the criticality of the included IT projects. Based on the results, I derived implications for further research and practice. The research paper (Fridgen et al., 2015), forming the basis for Section III.2, as well as the predecessor research paper (Fridgen et al., 2012), were developed in the same research setting of three co-authors. Since the former one is a follow-up paper on the latter one, the following delimitations of contribution apply equally to both research papers. Based on the first idea of the paper that was provided by one of the co-authors, I thoroughly examined the existing literature. Furthermore, I examined the different specifications of Petri Nets with regard to the research objectives and developed, conceptualized, and elaborated the modeling language and procedure, used to investigate the research questions. I furthermore implemented a corresponding model in Java and simulated an example to evaluate the proposed modeling technique. Within the follow-up paper (Fridgen et al., 2015), I also detailed and enhanced the modeling procedure. I moreover conducted several simulation runs and tested the derived results by statistical means to indicate first implications for practice. As I however was the junior researcher within this research setting, the co-authors contributed central ideas, and provided guidance for the elaboration and the written formulation. Thus, overall the co-authors contributed equally to the paper’s development.

II Enhancing IT Project Evaluation to Cope with Emerging Risk

II.1 IT Project Complexity as a Major Risk for IT Project Success[1]

Research has shown that the substandard management of complexity is one of the common reasons for IT project failure. As such, companies need to strive to improve their management of complexity. However, doing so requires a clear and unambiguous understanding of what is meant by IT project complexity, which has not yet been addressed in existing literature. In this study, we therefore strive to provide conceptual clarity regarding the construct of IT project complexity, by considering the causalities of complexity aspects presented in extant literature. By doing so, we develop a two-dimensional framework based on generic complexity antecedents and context-specific project areas. We test the resulting framework against existing literature, by examining whether it is able to cover the manifestations presented therein. For a first step, we verify the framework against practice, drawing on an expert interview and a case study. We then enhance our framework based on the insights gained within the evaluation cycles. The resulting framework will help researchers and practitioners understand how complexity can occur in an IT project, as it provides insights into what causes complexity and where it is located within an IT project. Furthermore, it provides a basis for the further development of appropriate management strategies and quantification methods for complexity.

II.1.1 Introduction

Increasing market competition requires a high level of adaptability to rapidly-changing market conditions and customer expectations. This forces companies to continuously progress. Since projects enable change within a company, they are increasingly important (Watson, 2012). However, projects also face a high risk of failure (Matta and Ashkenas, 2003). Projects fail when they do not meet their objectives, concerning schedule, budget, or projected outputs. The failure of IT projects can cause devastating problems, and even total business failures, for companies (Flyvbjerg and Budzier, 2011). With this in mind, managers should aim to manage IT projects properly.

[1] This section is a slightly modified and improved version of Neumeier and Wolf (2015), like outlined in Section I.3 and I.4.

Although the exact relationship between IT project failure and IT project complexity has not yet been sufficiently investigated, it seems clear that complexity contributes to IT project failure (Parsons-Hann and Liu, 2005). For example, Vidal and Marle (2008) have found that while this relationship needs to be clarified, complexity seems to be one of the main reasons for IT project failure. Xia and Lee (2004) argue that one of the reasons for IT project failure can be a high level of complexity, as in such cases, there are many different factors that influence a project at the technological and organizational levels. Baccarini (1996) states that since complexity has an impact on cost, time, and quality, it can hamper the achievement of a project's objectives (Baccarini, 1996; Xia and Lee, 2004). Wallace et al. (2004) empirically confirm that complexity risk is one of six risk dimensions that influence the success or failure of software projects. A steady general increase in complexity, which has been regularly found in past research, reinforces the effects of this problem (Größler et al., 2006). IT projects are particularly affected by high levels of complexity, as they need to addresses various dependencies within a single project, or between different projects. The prevalence of IT project failure has been studied in depth, and has been found to be generally related to a lack of managerial approaches for coping with highly-complex projects, rather than to information technology per se (Jaafari, 2003). This indicates the need for appropriate means to successfully manage IT project complexity. However, IT project complexity is very difficult to understand, and there is no academic consensus about what is behind it or how it should be approached (Vidal et al., 2013). Therefore, most researchers have only addressed specific aspects that can be observed within complex IT projects, and which are thus assumed to somehow relate to IT project complexity (Tatikonda and Rosenthal, 2000; Novak and Eppinger, 2001; Größler et al., 2006). Accordingly, different categorizations of aspects have been proposed (Baccarini, 1996; Vidal and Marle, 2008; Vidal et al., 2013). In fact, the explanation of a phenomenon like IT project complexity, which is crucial to deriving solutions, often requires an investigation of underlying causes (Gregor, 2006), and so a comprehensive and structured assessment of IT project complexity, including causalities of observed aspects, is needed. Furthermore, the appropriate assessment of IT project complexity may empower companies to mitigate their overall risk of IT project failure (Latva-Koivisto, 2001; Größler et al., 2006).

With the above considerations in mind, we strive to provide conceptual clarity regarding the construct of IT project complexity, by considering the causalities of aspects of complexity described in existing literature. We thus aim to answer the following research question:

"How can complexity in IT projects be assessed with respect to its influencing factors?"

To do so, we develop a structured and elaborate framework for complexity assessment, which relates manifestations of complexity to generic causes and specific areas of occurrence. Following Gregor and Hevner (2013), we provide an overview of underlying theoretical knowledge. We then explain our research approach and the methodology used. Next, we develop our artifact, which is a framework for complexity assessment. We derive hypotheses about the causalities of complexity from existing literature, by structuring the aspects of complexity identified in literature within a framework. Following the design and evaluation cycle, we first evaluate the quality of the derived framework on the basis of manifestations of complexity stated in the literature. Based on the results of this evaluation, we then adjust the framework. In the next evaluation cycle, we conduct an expert interview with a leading strategy consultancy. To further validate the utility of the framework, we also test it through a real-world case study. Finally we discuss the framework's contributions and implications for practice and research, its existing limitations, and the outlook for future research.

II.1.2 Theoretical Background

Complexity is a topic that has been discussed in a variety of research fields, including philosophy, biology, mathematics, and informatics. Accordingly, understandings of complexity tend to vary greatly (Rosen, 1977). We assess the complexity of information system (IS) and information technology (IT) projects on a general level and thus rather refrain from existing specific definitions of computational complexity (Edmonds, 1995), software complexity (Wang and Shao, 2003), or any other complexity that only concentrates on a specific sub-area of IS/IT projects. It should also be pointed out that a common agreement on a definition of complexity does not exist (Schlindwein and Ison, 2004). Therefore, instead of adopting an existing definition of complexity or introducing a new one, we focus on assessing complexity in the context of managing IS/IT projects, which we hereafter simply refer to as complexity. In the following sections, we examine existing literature in order to clarify what is behind complexity and how it can be assessed in a structured and practical way. Thereby, we strive to discover causalities of IT project complexity in general.

II.1.2.1 Subjective vs. Objective Complexity

When people speak of something as being complex, they use "everyday language to express a feeling or impression that [they] dignify with the label complex" (Casti, 1995). Thus, when two people talk about complexity in the same case, they will not necessarily be talking about the same thing. This is because "like truth, beauty, good and evil, complexity resides […] in the eye of the beholder" (Casti, 1995). From a subjective point of view, complexity can be influenced by personal "knowledge, experience, or intelligence" (Größler et al., 2006, p. 255). This kind of complexity is the result of a particular perception of a situation by a subjective observer (Schlindwein and Ison, 2004), and is described as *subjective complexity* in this research. However, since subjective perceptions are unique to every individual, they do not allow for a generally valid independent assessment of complexity (Baccarini, 1996).

A different perspective is provided by Cilliers and Spurrett (1999), who state that "complex systems do have characteristics that are not merely determined by the point of view of the observer." Schlindwein and Ison (2004) also explain that complexity can be "understood as an intrinsic property of a certain kind of system, or as occurring in a certain kind of natural and social phenomena" (Schlindwein and Ison, 2004, p. 28). This understanding is based on the assumption that there is an objective reality that can be independently assessed and is not influenced by subjective perception (Schlindwein and Ison, 2004). Although it is probably impossible to separate the underlying objective reality from its subjective perception, it should be possible to make some conclusions regarding an objective situation by exploring similar properties that different subjective observations have in common. In this research, we assume that subjective perceptions follow from objectively observable properties. According to Casti (1995), complexity, like beauty, is in the eye of the beholder. An example can be used to clarify our related approach. In deciding whether to buy a new car, a customer must use subjective personal judgement, but that judgment is always based on objective properties, like design, features, and price, as well as their relationships to one another. In accordance with this perspective, we focus on properties of *objective complexity* as the basis of subjective perceptions.

II.1.2.2 Complexity Assessment

Complexity is determined by various circumstances, and is thus very difficult to grasp. Hence, related works in existing literature can be considered as assemblages of different observations within the context of complexity, rather than detailed and structured assessments or sharp definitions. The majority of articles on this topic address influence factors that are supposed to somehow relate to complexity, but which are derived from a narrow subjective perception of the topic. In adopting a more general perspective, we strive to provide conceptual clarity regarding the construct of complexity. Therefore, we introduce a uniform designation and distinguish between *aspects*, *characteristics*, and *manifestations* of complexity to facilitate comprehension:

- The vaguest category, *aspects* of complexity, refers to any kind of influencing factor that is supposed to somehow relate to complexity.
- *Characteristics* of complexity are considered to be aspects of complexity that exist independently of the specific area of occurrence (i.e., characteristics can be observed independently of a specific context).
- *Manifestations* of complexity are considered to be aspects that arise from a specific area of occurrence (i.e., manifestations can only be observed within a specific context).

Some approaches to complexity in existing literature focus on specific sub-areas of IS/IT projects, like computational complexity (Edmonds, 1995), software complexity (Wang and Shao, 2003), or even more specifically, the technological complexity of a source code (McCabe, 1976; Misra, 2006). They thus often describe different manifestations of complexity. Some attempts have also been made to determine the comprehensive characteristics of IT project complexity (Baccarini, 1996; Tatikonda and Rosenthal, 2000; Größler et al., 2006). However, the majority of studies address single aspects that are supposed to somehow relate to complexity (Baccarini, 1996; Tatikonda and Rosenthal, 2000; Größler et al., 2006). Moreover, most studies do not present a comprehensive and systematic structure or procedure, and the aspects mentioned are not treated consistently, or in some cases, are even contradictory. A few researchers have also proposed different categorizations for assessing complexity in a more structured way (Baccarini, 1996; Vidal et al., 2013). Vidal et al. (2013), for instance, divide complexity aspects "into four more intuitive groups […], which were cited in several of the references" that were examined for their study (Vidal et al., 2013, p. 255). Generally, categorizations and other research in the area lacks concrete delimitations between complexity aspects, and consequently lacks clarity regarding causalities. The hesitation of researchers to state causes for the phenomena that they investigate is a well-recognized issue in IS research (Bacharach, 1989; Avgerou, 2013). Yet doing so is crucial, since the explanation of an investigated phenomenon often requires an examination of the underlying causes (Gregor, 2006). Therefore, the contribution of existing research on complexity is to provide a list of possible aspects of complexity to be thought of when managing an IT project, rather than to provide structured and elaborate guidance on how to assess complexity or explain what is concealed within it. An approach that comprehensively assesses complexity from a managerial perspective, by providing insights into causalities for the genesis of complexity, does not yet exist, to the best of our knowledge.

II.1.3 Research Methodology

To develop an approach that is able to assess complexity, we follow a Design Science Research (DSR) approach, in accordance with Hevner et al. (2004) and Gregor and Hevner (2013). To address the *problem relevance*, we outline the need for an assessment of IT project complexity from the point of view of practice and research.

As discussed, the construct of complexity is still very vague. Although there are many publications that present *descriptive knowledge* of this field (Gregor and Hevner, 2013), there is no overall conceptual clarity to the construct of complexity. As few categorizations for the assessment of complexity exist, we develop an *artifact* that provides an improved solution to this problem (Gregor and Hevner, 2013). Even though recent research has criticized the concept of artifacts (Alter, 2015), we stick to the guidelines of Hevner et al. (2004), since theirs is an established procedure for DSR. The artifact is represented by a structured and elaborate framework that enables companies to assess IT project complexity, and therewith contributes to *prescriptive knowledge* in this field (Gregor and Hevner, 2013).

For the artifact's design, we use *design and evaluation cycles* to arrive at an improved framework for the assessment of complexity, which contributes to theoretical knowledge as well as practice. Thus, the final framework has been derived through several iteration steps. In the first design phase, we structure the aspects of complexity identified in existing literature within a framework, and thus derive hypotheses about the causalities of aspects of complexity. Within the first evaluation cycle, the derived framework is evaluated against extant literature to check whether it encompasses the manifestations of complexity that are mentioned by other researchers. This procedure is carried out in order to evaluate the *quality* of the concept, and to reveal possibilities for adjustment. It furthermore reflects the *design as a research process* principle (Gregor and Hevner, 2013). Based on the findings of the first evaluation cycle, the framework is adjusted in order to improve its quality. In the next evaluation cycle, business experts are consulted as a first step toward the evaluation of the *utility* of the framework. The feedback gained during interviews is then incorporated into our framework, after critical discussion with other researchers. Furthermore, the utility of the framework is tested in a real-world case study. This demonstrates the applicability of the framework in practice. Although we provide a modest first step for concept evaluation, the *validity* of the derived hypotheses about causalities of complexity still requires empirical evidence. As this is not within the scope of this elaboration, we encourage other researchers to empirically test and validate our hypotheses in their further research.

Nevertheless, as we do not only categorize different aspects of complexity, but derive hypotheses about related causalities and carry out initial tests on them, our framework contributes to prescriptive knowledge in the field of complexity research. It gives researchers a structured overview of the topic, and makes the theoretical comprehension of complexity possible. Furthermore, the framework enables practitioners to understand the characteristics of complexity, and thus facilitates detailed analysis of real-world IT projects.

II.1.4 Framework for the Assessment of Complexity

Based on common properties of findings from existing literature, we create our initial framework. As indicated, complexity generally depends on observation contexts and its areas of occurrence within an IT project. Thus, areas of occurrence are considered as the first dimension of our two-dimensional framework, and are henceforth referred to as project areas. A more detailed explanation of the included project areas is given in Section II.1.4.2. To indicate how complexity emerges within different project areas, we determine antecedents of complexity. Assuming that antecedents evoke manifestations within specific project areas, and considering them as our second dimension, we come up with a resulting framework, which is supposed to encompass all manifestations evoked by the derived antecedents within the included project areas. Hence, we set up a two-dimensional framework based on generic *antecedents* and context-specific *project areas*, with the former dimension describing what causes complexity and the latter describing where complexity is located. This approach is illustrated in Figure II.1-a.

To find the antecedents of complexity, as a first step, we focus on the characteristics of complexity that have been documented in existing literature and that are observable independently of the observation context. Therefore, Section II.1.4.1 examines the different characteristics listed in existing literature and whether they can be considered as antecedents of complexity.

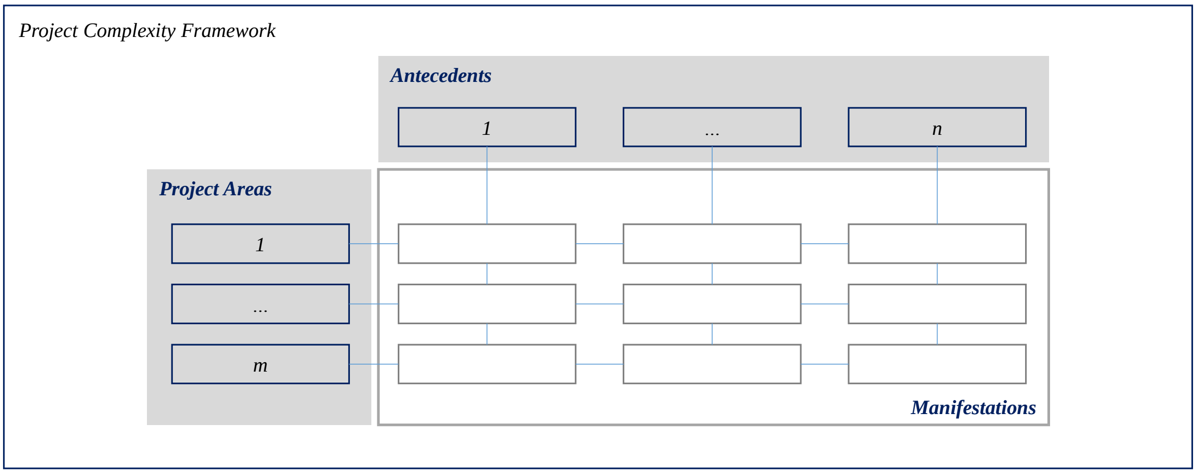

Figure II.1-a *- Framework for the assessment of project complexity, including dedicated key terms*

II.1.4.1 Determining Antecedents of Complexity

In existing literature, several aspects are mentioned that can be considered as characteristics of complexity, as they are observable independently of specific project areas. However, these characteristics mostly appear in studies with diverging and inconsistent definitions of complexity. Moreover, the fact that characteristics seem to be comprehensively observable is not sufficient to consider them antecedents of complexity. A complexity antecedent should influence complexity independently of a specific context, and the extent to which it can do so should be independent of the actual point of its assessment. Furthermore, it should be as independent as possible from subjective perceptions and should be distinct from other antecedents. With this in mind, we use the following criteria to decide whether a complexity characteristic within existing literature can be considered a complexity antecedent:

(a) Objectivity: As our focus is objective complexity, a complexity antecedent should not refer to subjective perceptions or cognition, which means it should not depend on human abilities like “knowledge, experience or intelligence” (Größler et al., 2006, p. 255).

(b) Time-independence: What an antecedent is able to influence, in terms of complexity, should not depend on the point in time at which it is actually assessed within a project’s lifecycle. Its extent of influence should be equal regardless of the phase of a project in which complexity is assessed.

(c) Distinctness: A complexity antecedent should be distinct and easily separable from other complexity antecedents, meaning that it is not listed among others (Bailey, 1994).

Prior literature mentions uncertainty, difficulty, multiplicity, interdependency, and diversity as characteristics of complexity. Below, we discuss these six characteristics derived from the literature, and examine whether and how they meet the criteria introduced above, and thus whether they can be considered as complexity antecedents in the sense defined by this research.

- Uncertainty is the extent to which a project is subject to potential future changes (Xia and Lee, 2004). The dynamics of projects can be described as their variability over time (Größler et al., 2006). The probability of varying over time represents the uncertainty of a project. Due to the similarity of the definitions of dynamics and uncertainty, we consider them as equals. Numerous researchers refer to uncertainty as a characteristic of complexity (e.g., Turner and Cochrane, 1993; Jones and Deckro, 1993; Frizelle, 1998; Suh, 1999; Williams, 1999; Sivadasan et al., 2002; Xia and Lee, 2004). Uncertainty can be examined objectively, as an absence of information exists regardless of the concrete abilities of individuals. Thus, uncertainty meets our criterion (a). However, it falls short of criterion (b). The uncertainty involved in a project also always declines with the project's progress (for a more detailed explanation, see Boehm's (1981) *cone of uncertainty* principle). As such, the extent to which uncertainty is able to influence complexity is strongly dependent on the point of its assessment within the project lifecycle. Furthermore, opinions vary as to whether uncertainty is a characteristic of complexity or should be considered separately. Whereas, for instance, Williams (1999) or Xia and Lee (2004) assert that uncertainty is a characteristic of complexity, Baccarini (1996), Laufer et al. (1996) and Lindemann et al. (2009) consider uncertainty to be a consequence of complexity, or even a separate concept. It also falls short of our criterion (c), as uncertainty is not only able to influence specific identified antecedents of complexity but is omnipresent in each and every planning activity. We hence consider uncertainty to directly influence projects themselves, rather than to represent a single aspect of complexity, and consequently suppose it to refer to a superior-level characteristic that has to be examined on its own. Furthermore, it is not clear that uncertainty determines complexity, as it only represents the possibility that an influence might occur in the future. Therefore, it is not considered as an antecedent of complexity in our research.

- Things that are "difficult" can be defined as hard to achieve, comprehend, handle, or express (Cardoso, 2005; Edmonds, 1995) and thus difficulty refers to something that is "complicated, involved or intricate" (Baccarini, 1996, p. 202). Various authors describe difficulty as a characteristic of complexity (e.g., Baccarini, 1996; Edmonds, 1995; Gidado, 1996; Cardoso, 2005; Closs et al., 2008). Since whether something is hard to comprehend strongly depends on subjective perceptions and underlying human abilities like knowledge, experience, or intelligence, difficulty does not fulfill our criterion (a). This is confirmed, for instance, by Baccarini (1996), who explains that difficulty, as an "interpretation of complexity is in the eyes of the observer" (Baccarini, 1996, p. 202). The extent to which difficulty influences complexity does not, however, depend on the time of its assessment, and hence difficulty fulfills criterion (b). With regard to the distinctness of difficulty from other complexity antecedents, different opinions exist in prior literature. Although some authors argue that difficulty is a characteristic of complexity, others claim that it is just the result of multiplicity and interrelatedness (Closs et al., 2008). Gove (1964) furthermore states that if a project includes many varied project elements, it is difficult to understand as a whole. Thus, difficulty cannot be observed distinctly from other complexity antecedents and falls short of criterion (c). With this in mind, we consider difficulty to be a subjective consequence of several other complexity antecedents, and not a separate antecedent in itself.

- We assume that multiplicity is equivalent to multitude and frequency, and refers to the number of project elements that a project involves (e.g., the number of subprojects that a project is split into or the number of employees that are involved in a project). Multiplicity is considered to be a characteristic of complexity by numerous authors (Williams, 1999; Gidado, 1996; Laufer et al., 1996; Milling, 2002; Cardoso, 2005; Größler et al., 2006; Closs et al., 2008; Lindemann et al., 2009). As the actual number of project elements is not influenced by human perception, multiplicity can be assessed objectively, and hence fulfills criterion (a). Furthermore, as quantity is a time-independent measure, the extent to which the number of elements is able to influence complexity is independent of the time of its assessment within a project's lifecycle. Therefore, it also fulfills criterion (b). Multiplicity can additionally be distinctly separated from other antecedents, and so fulfills criterion (c). Since multiplicity thus satisfies all criteria, we consider it to be an antecedent of complexity.

- Interdependency is assumed to be equivalent to connectivity and interrelatedness, and is characterized by the relationships and interactions within a project or between different projects (e.g., the interdependency of sub-projects or the interaction between the project's organizational elements). Various authors consider interdependency to be a characteristic of complexity (e.g., Jones and Deckro, 1993; Baccarini, 1996; Laufer et al., 1996; Gidado, 1996; Williams, 1999; Milling, 2002; Größler et al., 2006; Closs et al., 2008; Lindemann et al., 2009). Interdependencies can be considered objectively, since relations between technologies, departments, products, or other elements can be assessed without the influence of human abilities. Hence, interdependency fulfills criterion (a). Furthermore, the extent to which interdependency is able to influence complexity does not change over time. Therefore, it also fulfills criterion (b). Moreover, interdependency can be considered distinctly from other antecedents, and thus also fulfills criterion (c). Consequently, since interdependency fulfills all criteria, we consider it to be an antecedent of complexity in this research.

- Diversity can be defined as the variety within a project. This implies that a project can have different variants of the elements that define it (e.g., differences between subprojects, the diversity of the knowledge or cultures of team members). A large number of authors regard diversity as a characteristic of complexity (e.g., Jones and Deckro, 1993; Baccarini, 1996; Laufer et al., 1996; Gidado, 1996; Frizelle, 1998; Sivadasan et al., 2002; Lindemann et al., 2009). As the diversity of project elements is quantitatively assessable and therefore independent from the perceptions of the observer, it fulfills criterion (a). Moreover, the extent to which diversity - whether qualitatively or quantitatively assessed - is able to influence a corresponding complexity measure does not depend on the point in time at which it is assessed during a project's lifecycle. Hence, it also fulfills criterion (b). In terms of distinctness from other antecedents, it is clear that diversity is related to multiplicity. However, diversity addresses a separate issue, and can thus be considered distinctly from other antecedents. Consequently, as diversity fulfills criterion (c), we consider it to be an antecedent of complexity.

In conclusion to our investigation of the characteristics and antecedents of complexity, Table II.1-a summarizes our results regarding all characteristics derived from existing literature, in terms of their adherence to the defined criteria for complexity antecedents.

Table II.1-a - *Complexity characteristics in terms of criteria for complexity antecedents*

Characteristics of complexity	**Criteria**		
	Objectivity	Time-independence	Distinctness
Uncertainty	✓	–	–
Difficulty	–	✓	–
Multiplicity	✓	✓	✓
Interdependency	✓	✓	✓
Diversity	✓	✓	✓

Table II.1-a makes it clear that of the complexity characteristics commonly presented in extant literature, only multiplicity, interdependency, and diversity fulfill all criteria for complexity antecedents in this research. As shown in Figure II.1-b, they consequently form the horizontal axis of our initial framework.

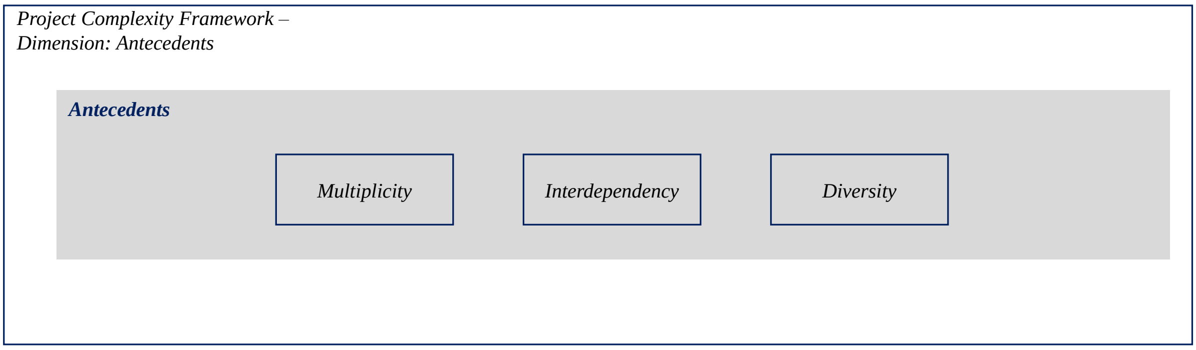

Figure II.1-b *- Horizontal axis of the initial framework: Identified antecedents of complexity*

II.1.4.2 Identification of Project Areas

To understand the project areas in which manifestations of complexity can arise, and to enable the structured allocation of complexity within a project, we divide project organization into different project areas, based on existing project management literature. We base our delineation of project areas on the work of Westerveld (2003), who proposes an "overall framework for the management of projects" (Westerveld, 2003, p. 411) based on the European Foundation for Quality Management (EFQM) Excellence Model. The EFQM Excellence Model was originally developed in 1989, to recognize organizational excellence in European companies. As the EFQM was developed for "traditional, functionally organized, permanent organizations" (Westerveld, 2003, p. 411) it cannot be directly used for project-focused organizations without adjustments. Thus, Westerveld (2003) introduces six organizational areas that represent the areas that project managers can work on to "increase the likelihood of achieving a successful outcome of their project" (Westerveld, 2003, p. 412). With this categorization, Westerveld (2003) makes it possible to clearly and unambiguously structure projects. We adhere to this categorization in setting out the following project areas:

- Contracting: This area includes the contractual relationships involved in a project. The partners within contracts can be, for example, suppliers, subcontractors, customers, or external service providers (Belassi and Tukel, 1996). Complexity can arise as a result of contractual relationships with any such partners, but also through the interactions of different contracting partners.

- Leadership and team: This area covers the skills and characteristics of the project managers and project teams (Belassi and Tukel, 1996). We include all aspects that affect the way that a project is led by the project manager, leadership style, and the way tasks and responsibilities are segregated and distributed within a team. We also consider staff constellation, working habits, communication skills, and team technical and managerial competence, as these play important roles in this area (Belassi and Tukel, 1996).

- Project management: This area involves the operational control and execution of a project. It includes organizational structure, process configurations, and other project-specific procedures. Furthermore, it covers all planning and scheduling aspects within a project (Belassi and Tukel, 1996), as well as the monitoring of project progress and adjustment of possible deviations from a plan (Munns and Bjeirmi, 1996).
- Resources: This area includes materials and means that are used as sources for a project. Since the availability of resources is critical to the success of a project (Belassi and Tukel, 1996), complexity within this area needs to be properly assessed.
- Stakeholder management: This area concerns a project's stakeholders, including top management and external parties. The support of top management and the involvement of external parties can greatly influence a project and its outcomes (Belassi and Tukel, 1996; Munns and Bjeirmi, 1996).
- Policy and strategy: This area involves project goals, the overall benefits of a project, and the means of achieving them. It is long-term-oriented and considers the whole lifecycle of a project (Munns and Bjeirmi, 1996).

Figure II.1-c presents an overview of the project areas that are used as the vertical axis of the developed framework.

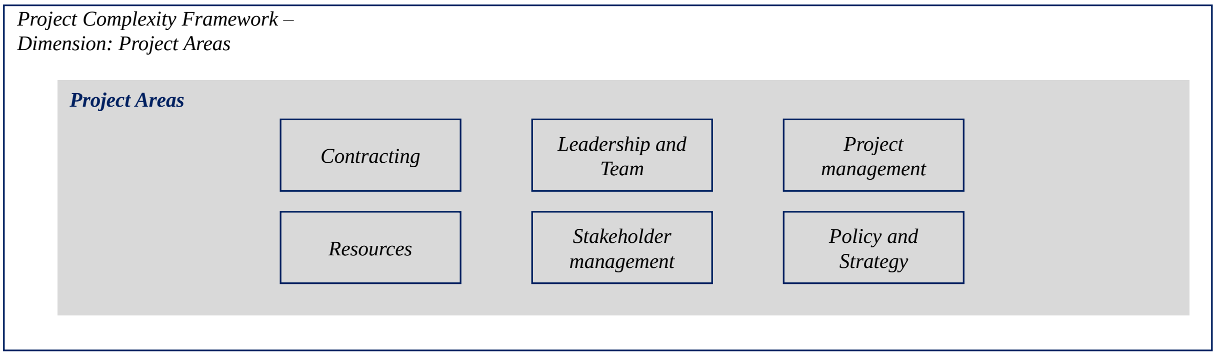

Figure II.1-c - *Vertical axis of the initial framework: Project areas*

II.1.5 Evaluation

After determining our two dimensions and designing our framework, we test the designed artifact through several evaluation cycles, in accordance with Gregor and Hevner (2013). First, the framework is evaluated against existing literature, to check the quality of the artifact and determine possible areas of adjustment. Based on the resulting findings, the framework is adjusted in order to improve its quality. To evaluate the utility of the framework, we also consult business experts through an interview. The feedback that we gain is then also incorporated into our framework. To demonstrate the applicability of the framework in practice, we apply it to a real-world case conducted by a leading business consultancy. Although this is a modest first step toward validating our hypothesis regarding complexity causalities, we do not provide empirical evidence in this research. Instead, our goal is to encourage other researchers to test and validate the causalities within our framework through further empirical studies.

II.1.5.1 Framework Evaluation against Existing Literature

In the first step, we evaluate the framework against existing literature, and assess whether all of the manifestations of complexity described in literature are covered by the framework. Table II.1-b provides an overview of all of the manifestations that can be assigned to the framework that we have developed. A detailed overview of all manifestation and its sources, which are referenced by the values in brackets, can be found in Table VI.1-a in the appendix. Our evaluation showed that only 41 of 62 manifestations could be assigned to the derived framework (66%), as the other 21 either did not fit one of the three antecedents or could not be sorted into a specific project area or even both. Thus, the framework in its initial state covers only about two-thirds of the manifestations of complexity mentioned in the context of IT project complexity in existing literature.

Table II.1-b - Overview of the framework with all assigned drivers

Project area		Complexity Determinant: Multiplicity	Complexity Determinant: Interdependency	Complexity Determinant: Diversity
Project area	*Contracting*	• number of customers (42) • number of specialties involved (subcontractor, trades) (52)	• interdependency between outsourcing partners (3)	• diversity of customers (8)
	Leadership & team	• number of employees (44)	• interdependency between teams (27) • team cooperation and communication (56)	• diversity of team (locations) (16) • diversity of team (specialist fields) (17) • diversity of team (time) (18)
	Project management	• quantity of organizational subtasks (5) • length of feedback loops (32) • number of communication paths (41) • number of work flow parts (49) • number of tasks /actions (38)	• interrelationships between the activities in schedule (4) • extent of interactions of components (19) • interdependency in a network (tasks) (21) • interdependency between operations (23) • interdependency in the work flow (24) • interdependency between tasks (26) • interdependency of work packages (29)	• diversity of parts of the work flow (11) • diversity of tasks (technology) (13) • diversity of tasks (territory) (14) • diversity of tasks (time) (15) • nature of subtask interactions (39) • number of process types (50)
	Resources	• number of different technologies (43) • number of inputs (46) • number of technological elements (36)	• interdependency of inputs (22) • interdependency of technologies (28) • interdependency of technological elements (30)	• diversity of technologies (7) • diversity of inputs (9)
	Stakeholder management	• number of stakeholders (53)		• geographic location of stakeholders (54) • variety of interests of stakeholders (55)
	Policy & strategy	• number of hierarchical levels (45)	• interaction between project's organizational elements (20)	

In line with the design search process proposed by Hevner et al. (2004) we have aimed to improve the framework based on the executed test. Therefore, we analyze whether an extension of the dimensions could possibly increase the framework's coverage of context-specific manifestations. We examine the manifestations that could not be assigned to the framework, in order to determine whether they exhibit the same properties.

We find that 12 manifestations cannot be assigned to one of the derived complexity antecedents. However, the only similarity that could be obtained between these manifestations is that four of them address the degree of novelty within a project (objective novelty (1), product novelty (34), new products/novelty (40), modifications to existing products (37)). Thus, we investigate whether novelty could reasonably be considered a further complexity antecedent. Whether an element in a project is novel to a company or not can be determined without being influenced by human abilities. Furthermore, the extent to which novelty is able to influence complexity does not depend on the point in time of its assessment. Therefore, novelty can be evaluated both objectively and time-independently. It is also distinct from other identified antecedents of complexity, and hence satisfies our last criterion. We therefore extend our initial framework by considering novelty as a separate antecedent of complexity.

In addition to the manifestations that cannot be assigned to an antecedent of the framework, there are 15 manifestations that cannot be assigned to any specific project area. However, 13 of these have a common property, in that they refer to a resulting product or elements that determine the project's scope. Those aspects could theoretically be assigned to the policy and strategy project area, since a project's output represents its main objective, or at least is strongly connected to that objective.

Since policy and strategy are carried out at the conceptual level and project output involves the operative level, it seems reasonable to further break down this project area. Therefore, to facilitate the assignment of manifestations to the framework, we divide this project area into project scope, which refers to all manifestations that can be assigned to the scope of a project, and project objective, which includes the policy and strategy of a project. This not only enables a more intuitive assignment of manifestations but also increases the coverage of the framework. Table II.1-c gives an overview of the manifestations that can be assigned to the framework, after the adjustment of the strategy and policy project area.

Table II.1-c *- Split of the project area Strategy & Policy*

		Complexity Determinant			
		Multiplicity	**Interdependency**	**Diversity**	**Novelty**
Project area	***Project objective***	• number of hierarchical levels (45)			• objective novelty (1)
	Project scope	• length of product lifecycle (33) • number of organizational units (47) • number of outputs (48) • number of product components (51)	• breadth of product program (2) • interaction between the project’s organizational elements (20) • interdependency between subprojects (25) • specification interdependence (31)	• diversity of outputs (10) • diversity of products (12)	• product novelty (34) • new products/ novelty (40) • modifications to existing products (37)

Figure II.1-d depicts the final dimensions of the adjusted framework, providing an overview of the final framework, including adjustments based on the evaluation against existing literature.

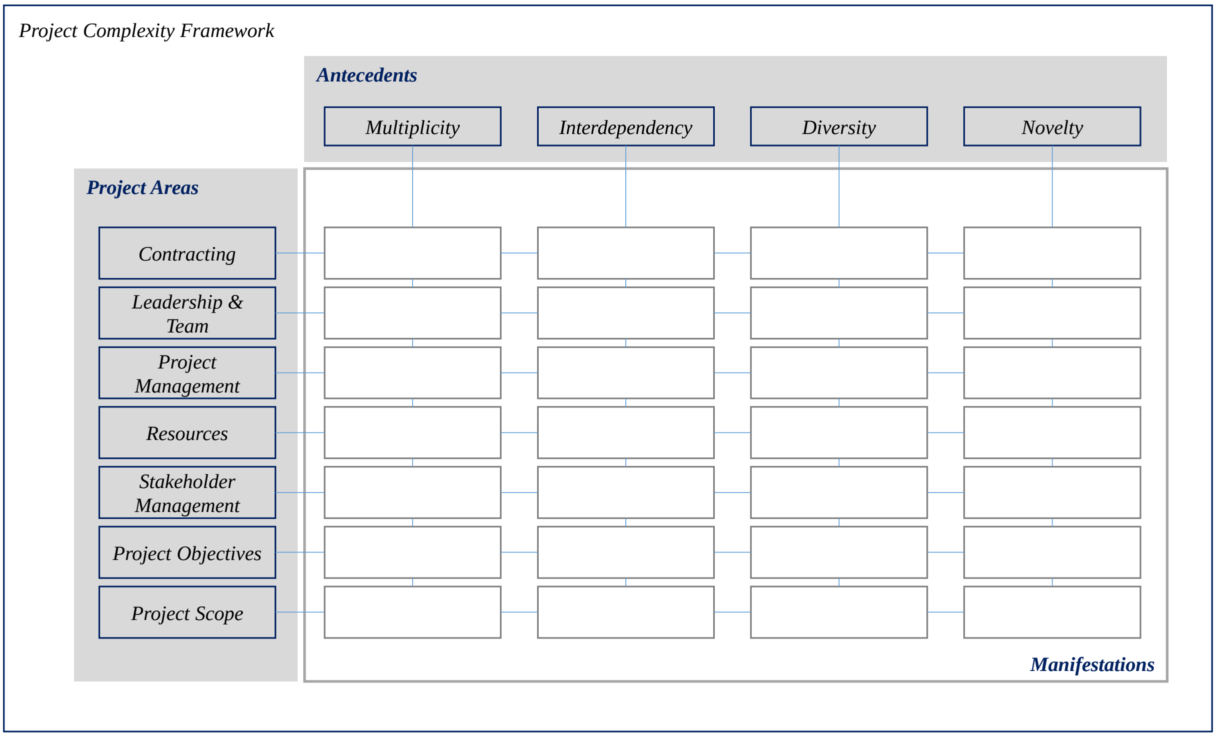

Figure II.1-d *- Adjusted framework for the assessment of IT project complexity*

Despite the adjustments, some manifestations that were identified in literature still cannot be adequately assigned to the framework. Six manifestations could be assigned to a project area but could not be assigned to a complexity antecedent (bargaining power of customers (60) – Contracting; nature of organizational subtasks (58), magnitude of organizational subtasks (35), overlap of design and construction (61) – Project Management; building type of technology (57) – Resources; difficulty of project objectives (6) – Project Objective). Only two manifestations that were identified in the literature could not be assigned to an antecedent or a project area (level of scientific and technological knowledge required (62), difficulty of location for technology (59)). Nevertheless, 87% of the manifestations mentioned in literature can be assigned to the revised framework.

II.1.5.2 Expert Interview

The purpose of the evaluation in this section is to gather information about the practical applicability and utility of our revised framework. In line with Hevner et al. (2004), we have developed our framework for the assessment of complexity as an artifact on the basis of existing literature concerning IT project complexity and other related fields. After evaluating the framework against literature and improving it (Gregor and Hevner, 2013), we conduct another design and evaluation cycle together with business experts. In doing so, we strive to verify whether the concept is practically useful for the assessment of IT project complexity. The focus of this evaluation is on the adequacy and comprehensibility of the complexity antecedents, the applicability of the project areas as holistic and reasonable structures for projects, and the practicability and utility of the framework as a whole.

Therefore, we gather feedback from one of the leading strategy consultancy (referred to in this research as SC), which has widespread experience in the field of IS/IT projects within the financial sector. Although, we have only consulted one company, we have been able to gain valuable insights into the benefits and obstacles involved in our concept, from a practical point of view. After the interview we critically discussed all of the feedback received from the business expert with other researchers before adjusting the presented framework accordingly. Table II.1-d presents an overview of the feedback received on our concept from the interview partner:

***Table II.1-d** - Observed obstacles and suggested improvements*

Observed benefits of the concept	• Problem relevance: SC confirmed that there is currently a lack of structured methods for the analysis of project complexity in practice. Thus, from SC's point of view, it is necessary to find a structure for the assessment of IT project complexity, as this is a relevant aspect of daily business.
	• General concept: According to SC, the assessment of complexity with a two-dimensional framework is a reasonable and useful approach, as it is easily applicable in practice. Furthermore, SC noted that the most important complexity antecedents from a practical point of view (interdependency and multiplicity) are included in our framework. Moreover, SC confirmed that diversity is usually not considered in project planning, which often leads to problems during the implementation of a project. SC also confirmed that the introduced project areas are appropriate for dividing a project into different segments. Within this context, SC emphasized that the importance of project areas can differ for specific projects, which makes it necessary to specify project areas according to the characteristics of the particular project. Since the project areas within the presented framework are formulated in a general manner, this is made possible, according to SC.
	• Application and utility: SC made it clear that there are two fields of application for the framework in practice. While SC confirmed that possible reasons for problems within a project are currently only examined after they occur, our framework could be used for an ex ante assessment of complexity. Consequently, possible causes of failure could be identified before a project starts and mitigating actions could be taken in advance. Furthermore, the framework could be used as a steering instrument during the lifecycle of a project or as a continuous controlling measure that detects reasons for failure, like exceeding time or budget. This reflects a valuable contribution for practice.
Observed obstacles and suggested improvements	• Complexity antecedents: In general, the complexity antecedents correspond to reality, according to SC, especially with regard to dependency and multiplicity, and also diversity. These represent important factors affecting complexity in SC's daily business. Moreover, SC made it clear that an unambiguous distinction between multiplicity and diversity should be maintained. SC confirmed that it is possible to understand these distinctions clearly in our framework, due to our definitions of complexity antecedents. However, SC suggested including examples in the descriptions of every complexity antecedent, in order to increase the precision and comprehensibility of the concepts. To follow this advice, we integrated explanatory examples into the definitions for each complexity antecedent, describing how the aspect in question causes complexity in IT projects.

II.1.5.3 Deployment through a Real-World Case Study

In addition to our expert interview, we have conducted a case study to further evaluate the utility of our developed framework. Through it, we apply our framework to a real-world case, in order to grasp its complexity and arrive at some initial insights regarding complexity reduction possibilities. The case is that of a financial service provider (FSP) for one of the world's leading automotive manufacturers, which launched a program involving projects to increase its resilience and efficiency after being hard hit by the financial crisis of 2009/2010. Overall, the program comprised eight projects. Two of these were aligned to the business model, three to operations, and another three to regulatory processes. After the program was initiated, the increasing complexity of the projects involved induced the FSP to set up a separate project for quality assurance. Based on an assessment of the projects' complexities, the quality assurance objectives included ensuring the quality of project deliverables, adhering to project schedules, and avoiding project delay and project failures.

In addressing this situation, we assess the complexity of one of the projects, which was aligned with the company's business model. The project in question was an integration project for the pan-European merger of two large fleet management companies, which involved five countries and was scheduled for a period of two years. To highlight critical management areas and in order to indicate starting points for complexity reduction, we have used our framework to carry out a high-level assessment of the complexity of the post-merger integration project. In it, we assess the relevance of each complexity antecedent within each project area and depict it in a complexity "heat map", as shown in Figure II.1-e. Relevance is determined based on expert judgements of involved project management, using a three-step scale of gradations.

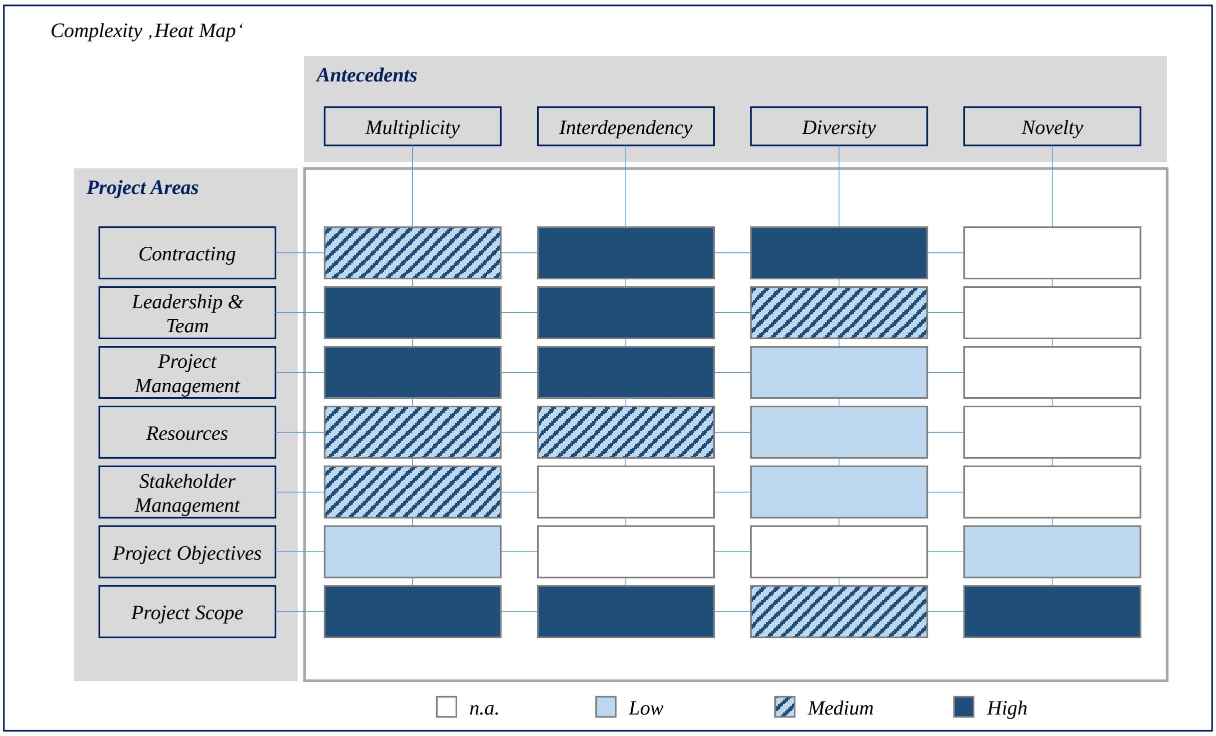

Figure II.1-e *- Heat map of IT project complexity*

This structured complexity assessment of the post-merger integration project shows that in terms of complexity reduction, the project scope area has a great deal of potential, as do the areas of leadership & team, contracting, and project management. Moreover, the assessment indicates courses of action for management, as, for instance, complexity induced by a high level of diversity in the contracting area could easily be avoided or reduced. Therefore, based on evaluation cycles regarding utility (Gregor and Hevner, 2013), represented by an expert interview and a case study deployment, we consider the proposed framework to be a useful tool.

II.1.6 Implications, Limitations, and Future Research

As complexity can be one reason for the failure of IS/IT projects, companies should strive for a clear and unambiguous understanding of IT project complexity. With this in mind, we introduce a concept for the structured assessment of project complexity that is specific to the IS/IT project context, with respect to its influencing factors. In line with the research guidelines provided by Hevner et al. (2004), we have followed the DSR approach to develop our concept as an artifact. We have also improved the artifact by putting it through two design and evaluation cycles (Gregor and Hevner, 2013). Thereby, we provide a first step towards the design evaluation by evaluating the framework against literature and practice. We initially created the framework based on existing literature in the field of IT project complexity. Our two defined dimensions address questions of complexity antecedents and areas where complexity can occur within an IT project. We assign manifestations of project complexity to those dimensions. Based on our first evaluation cycle against extant literature, our initial framework has been adjusted to subsequently account for 87% of all identified manifestations. The second evaluation cycle takes into account feedback on practice, concerning the usability and applicability of the framework, by drawing on an interview with experienced business consultancy and a real-world case study.

Our framework can be equally beneficial for research and practice, as it facilitates comprehension of the concealed aspects of complexity. On one hand, the framework can contribute to future research by analyzing and structuring existing literature to arrive at hypotheses about the causalities of complexity. On the other hand, it can help practitioners understand how complexity can occur within an IT project, as the matrix provides insights into the antecedents of complexity and where it is located within the different areas of an IT project. Additionally, the identification of manifestations from literature can help practitioners to understand the complexity within their IT projects, as the manifestations represent a reference list of aspects that might influence the complexity of a specific application case. Therefore, the framework can be used as an ex ante evaluation tool, to help practitioners identify problems and take adequate mitigating actions prior to a project’s implementation. Furthermore, it can be used as a project steering instrument, to help determine appropriate strategies for the better management of complexity during a project, and to counteract the risk of IT project failure.

However, the framework is not without limitations. By evaluating the framework against literature and real situations, we have ensured its quality and utility in practice. However, the validity of the derived hypotheses concerning the causalities of complexity still need to be empirically tested. Since this is not within the scope of this elaboration, we encourage other researchers to empirically test and validate our hypotheses in further research.

Overall, our approach provides a framework for assessing project complexity with respect to influencing factors, and thus clarifies the construct of IT project complexity. The introduced framework sets a foundation for the development of methods for analyzing and managing project complexity. As the quantification of complexity antecedents could support project complexity management, it might be interesting to examine the complexity antecedents described in this elaboration in more detail, in order to find out if and how they can be quantified. Furthermore, future research should examine what level of complexity is most advantageous.

Despite its limitations, our study contributes to the current body of prescriptive knowledge regarding complexity assessment by offering a clear and unambiguous structure for IT project complexity, and thus provides a first approach to the assessment of IT project complexity, which can be of help to practitioners as well as researchers. Furthermore, it provides a first glance at the causalities of complexity, which have not yet been explored in existing literature.

II.2 The Necessity for Integrated IT Project Quantification[2]

The probability of IT project failures can be mitigated more successfully when discovered early. To support an early detection, transparency regarding a project's cash flows shall be increased. Therefore, an appropriate analysis and calculation of a project's costs, benefits, risks, and interdependencies is inevitable. Until today, however, a method that appropriately considers these factors when estimating the ex ante project business case does not yet exist. Using the Action Design Research approach, we designed, applied, and tested a practicable and integrated method of determining the monetary value of IT projects, to generate generalized insights to benefits management. This method was conjointly developed by practice and academia, to ensure practical applicability while upholding scientific rigor. Furthermore, to support understandability of the method, we provide an application example.

II.2.1 Motivation

Companies continuously increased their IT investments over the last decades. According to Gartner (2012) this trend is about to continue. In this context, especially the number and complexity of large IT projects is growing. The complexity is intensified by dependencies within one or between different projects and processes and is boosted even further by the growing number of large projects. Another important influence is the rising uncertainty in an increasingly dynamic project management environment.

Flyvbjerg and Budzier (2011) found that one out of six IT projects causes budget deficits of 200% on average. In several cases this can even threaten the existence of the assigning company. Amongst others, reasons for the failure are IT specific risks concerning project evaluation, like for example misjudgment of user acceptance or changing security requirements of the new system. Another reason is the lack of recognition of different kinds of interdependencies (Wehrmann et al., 2006). However, according to Flyvbjerg and Budzier (2011), the continuous measurement and controlling of expected projects benefits seems to be positively related to IT project success. Whereas project costs are already measured elaborately by several practicable methods like the Constructive Cost Model of Boehm et al. (2000), corresponding methods concerning the management of an IT project's benefits just barely exist. Usually, that is because benefits of a project can oftentimes just hardly be quantified or transformed into monetary values. Moreover, in most cases benefits are not realized until a project has been completed. Therefore, the quantification of benefits in practice

[2] This section is equivalent to Beer et al. (2013), like outlined in Section I.3 and I.4.

is mostly conducted using qualitative and rarely quantitative but especially no monetary procedures. In this challenging context, practice demands for an approach incorporating costs, benefits, risks, and interdependencies. The use of such an integrated approach, which can be embedded in a continuous project controlling to compare the monetary results over time, enables a company to detect relevant deviations from target goals. Based on that, corresponding control measures can be taken, which reveal the need and allow for corrective actions to reduce the probability of IT project failure.

Therefore, the objective of this research is to introduce an integrated method, which considers costs, benefits, risks, and interdependencies and is, beyond that, easily applicable in practice. For the development of this method, we decided to use an Action Design Research (ADR) approach (Sein et al., 2011). Specific for this research approach is the simultaneous development and the evaluation of an (IT) artifact, which is done in mutual cooperation between practitioners and researchers. Due to the need of companies to evaluate IT projects more holistically and the lack of methods being available and applicable in practice, one of the world’s leading strategy consulting companies (in the following referred to as CC) pointed out their need for a methodically sound as well as easy to use method of benefit quantification for IT projects. Therefore, the Research Center Finance & Information Management (FIM), developed an approach to benefits management collaboratively, gathering feedback from practice regarding efficacy and applicability of the method on a regular basis and upholding scientific rigor. Furthermore, we tested the developed method at an industrial client, namely a multinational manufacturing company (in the following referred to as MC), who used the method to evaluate benefits of multiple mobile app development projects. The valuable feedback of both business partners, CC as well as MC, gave us the opportunity to satisfy the criteria of an Action Design Research process and to develop an artifact which fulfills the requirements of all stakeholders from business practice and science.

Figure II.2-a shows the ADR approach based on the depiction in Sein et al. (2011), adjusted to our specific project setting.

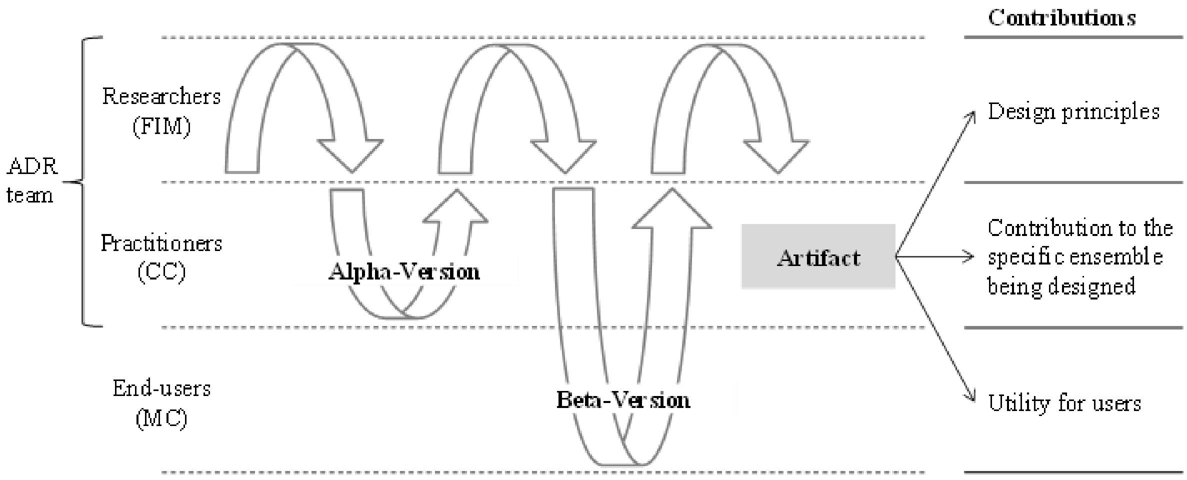

Figure II.2-a *- Building, intervention and evaluation scheme in ADR (cf. Sein et al. (2011))*

Since the objective of ADR is to generate prescriptive design knowledge by developing and evaluating an artifact[3] in cooperation with business partners, it seems to be the most suitable research method for this topic. The ADR approach is divided into four stages: at the first stage, which is called *Problem Formulation* (cf. Section II.2.2), the research problem is motivated by input from science and practice, i.e. the need for benefits management as indicated by our business partners, combined with the lack of corresponding approaches in science. At the second stage *Building, Intervention and Evaluation* (cf. Section II.2.2), the initial artifact is designed, evaluated and improved at the same time by its application through practitioners (Alpha-Version loop) and end-users (Beta-Version loop). *Reflection and Learning* representing stage three of the ADR approach matches the first two stages and has the objective to reflect and increase the understanding of the artifact. In our case, learning and reflection are represented by the feedback of the practitioner and end-user, and can be found in Section II.2.3 and in the application example given in Section II.2.4. In the last stage *Formalization of Learning* (cf. Section II.2.5) the artifact should be further improved for more generalized concepts, called *design principles*.

II.2.2 Problem Formulation

As described above, existing approaches to benefits management oftentimes account for qualitative factors, only. Some models establish quantification of benefits and sometimes also risks, but not on a monetary basis. In the following, we shortly present existing approaches to benefits management like they can be found via a thorough analysis of IT project management

[3] According to Sein et al. (2011), the artifact is a piece of hardware and/or software and hence is referred to as *IT artifact*. Although, we also implemented an IT driven tool for the management of benefits, we focus on the methodical approach which has been developed in this paper.

literature. Since the scope of this research is specifically on quantitative methods for IT project valuation, we focused on these kinds of approaches, although we are aware that lots of publications are heading in the direction of benefits management more generally.

The scoring model (Zangemeister, 1976) firstly identifies all relevant evaluation criteria of a specific project. These criteria are weighted by assigning specific scores. The scores indicate different levels of importance for decision-makers. Subsequently, a user value is calculated by multiplying the criteria by the corresponding weighting and aggregating them to an overall value. This allows for a comparison of the different alternatives. In the WARS-Model[4] (Ott, 1993) estimated benefits and costs are subdivided into three categories according to their tangibility. Each category is allocated with three levels of realization probabilities resulting in separate matrices for benefits and costs. Uncertainty is pictured via the classification into risk stages, representing the optimism or pessimism of a decision-maker. To evaluate projects more quantitatively, Schumann (1993) introduces a method based on functional chains, taking benefits up to the level of monetary values by focusing on the consequences of their effects. In this process, benefits are consolidated to categories or allocated to different company levels. Andresen et al. (2000) developed a framework to categorize benefits by efficiency, effectiveness and performance. In this context 'efficiency' is calculated as risk-weighted monetary, 'effectiveness' as risk-weighted quantitative but non-monetary, and 'performance' just as a qualitative value with a specific probability of occurrence. Another approach to evaluate IT investments, which is described by van Grembergen and De Haes (2005), is the Balanced Scorecard. In this approach the relations of cause and effect of qualitative and quantitative key figures are described. Two general types of key figures are distinguished: performance drivers and output figures. To evaluate a project, the degree of target achievement is measured for each key figure. For an ex ante evaluation of IT investments Walter and Spitta (2004) use the SMART-Model[5]. Though, the course of action of this model is in analogy to other scoring models, it additionally gives instructions for the application.

All approaches illustrated above consider benefits and risks to a different extent. However, to the best of our knowledge there exists no integrated approach, fulfilling all of the following requirements:

- Benefits of an IT project have to be considered monetarily.

[4] Economic Efficiency Analysis with Risk Categories (original term in German: Wirtschaftlichkeitsanalyse mit Risikostufen)
[5] Simple Multi-Attribute Rating Technique

- The risk associated with a project's benefits has to be considered monetarily.
- When assessing risk, dependencies between benefits have to be considered.
- The approach has to be practically applicable requiring a low level of additional overhead.

The requirement of practical applicability leads us to the adoption of several measures concerning the operationalization of our approach. We developed these measures on the basis of the feedback of our two collaborating business partners, CC and MC. In the following we outline these measures as we derive our model.

II.2.3 Model: Monetary Quantification of IT Projects

As mentioned earlier, in today's IT projects a wide range of project evaluation methods are already implemented successfully. Some of them have a strong emphasis on costs, like for example the Constructive Cost Model or Function Point Method (Mukhopadhyay et al., 1992). To provide a more integrated evaluation method, as a first step, we focus on benefits of IT projects considering costs but without examining them in detail. In accordance with our business partners, we consequently agreed to the following simplifying assumption:

Assumption 1: A project's costs C are deterministic and known in advance.

Hence, we focus on the accurate identification and evaluation of all relevant benefits of an IT project. In this context a benefit is considered to be either based on a direct or indirect reduction of payouts or on increased revenues. The consideration of non-deterministic costs within our model is subject to further research. Before we are able to derive an overall integrated project value, we first assess each benefit separately regarding monetary contribution and risks.

II.2.3.1 Assessment of a Single Benefit

There are quantitative and qualitative benefits of IT projects. Quantitative benefits can directly be measured whereas qualitative benefits are difficult to transform into monetary units (Walter and Spitta, 2004). To overcome these difficulties and to ensure the mathematical rigor of our method, we chose a cash-flow-based approach considering deterministic costs and including benefits as random variables. For a rigor application of our model, benefits need to be assigned without overlaps. In coordination with our business partner CC in the Alpha-Version-loop of the ADR approach, we first assign each benefit to an area in which it occurs, like for example the area of customers or employees, in order to grasp the benefits more holistically and identify possible overlaps.

To estimate the approximate monetary value of the respective benefit, we assume that each benefit can be assessed by a monetarization rule. These monetarization rules can finally be transferred into equations. Exemplarily, the benefit "cost savings through reduction of training times", is assigned to the area employees. The monetarization rule states increased productivity through shortened training times. Finally the equation $c_T \cdot \Delta n_T + c_E \cdot \Delta n_E$ can be derived, whereas c_T represents the hourly rate of a trainer T, Δn_T the number of overall saved trainer-hours, c_E the hourly rate of an employee E and Δn_E the number of overall saved training-hours for employees. However, this monetarization rule is just a means of support to raise the decision-maker`s awareness for the variables influencing the specific benefit. The indicated exactness of the calculated value is misleading, as benefits bear uncertainty and risk which has not yet been considered in the quantification.

At this point we received feedback from our collaborative business partner CC, that the estimation of exact parameters for a specific benefit is hardly possible for project staff. However, market-driven parameters indicate that benefits mostly are normally distributed. Based on this input we made the following assumption:

Assumption 2: The monetary values of benefits are uncertain and can be considered as normally distributed random variables $\tilde{b}_i \sim N(\mu_i, \sigma_i)$.

The simplifying assumption of a normal distribution for benefits is justifiable, since benefits depend on market risks and others, which can cause positive and negative deviations. At the same time, a normal distribution is mathematically easy to use and allows for an analytical calculation of our objective function as can be seen in Section II.2.3.3.

In a first attempt, we tried to directly retrieve the distributional parameters from the decision-makers. Though, CC argued that this approach is not feasible in practice, since these parameters are difficult to comprehend. To simplify the estimation of uncertain benefits, we hence draw back on an acknowledged procedure of behavioral finance, by using an interval-based scheme for the evaluation of each benefit, similar to Tversky and Kahneman (1974). The practical operationalization of estimating a lower bound u_i and upper bound o_i of the interval can be done by answering the question: "In which range will the value of the benefit be at a specific probability like for example 80%?" (cf. Figure II.2-b). We chose an 80% interval according to our business partner's suggestion. CC argued that an 80% probability is easily graspable by project staff members since it is commonly used in practice.

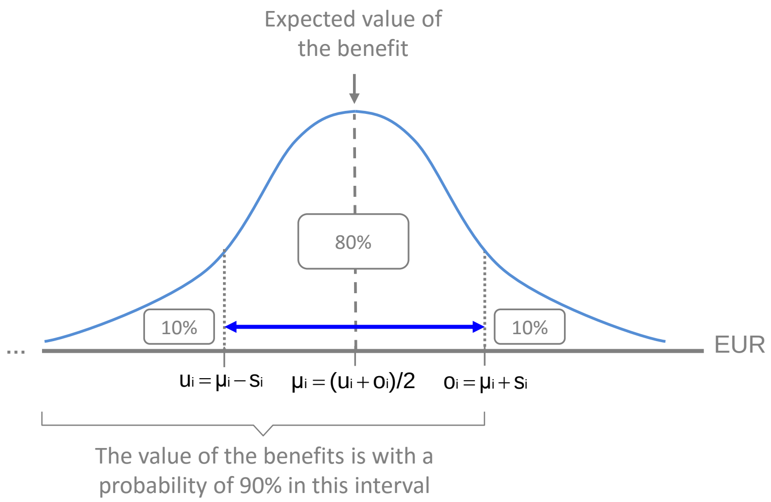

***Figure II.2-b** - Realization-interval of an expected value of a benefit*

Based on assumption 2 we are able to derive the expected value μ_i and the standard deviation σ_i of a benefit $\tilde{b}_i$. In accordance to Tversky and Kahneman (1974), we assume μ_i to be the mean between u_i and o_i, thus $\mu_i = \frac{(u_i+o_i)}{2}$. We calculate $s_i = o_i - \frac{(u_i+o_i)}{2}$ as the spread between μ_i and the upper and lower bounds respectively. With $F_{0,1}(x)$ as distribution function for the standard-normal distribution and $F(x)$ as the wanted distribution function with $\tilde{b}_i \sim N(\mu_i, \sigma_i)$ we know:

$$F(x) = F_{0,1}\left(\frac{x_i - \mu_i}{\sigma_i}\right) \qquad \text{II.2.(1)}$$

Since it is also known that $F_{0,1}(1{,}28) \approx 90\%$, and in this case $x_i = \mu_i + s_i$ we can constitute: $\frac{x_i-\mu_i}{\sigma_i} = 1{,}28 \Longrightarrow \sigma_i = \frac{x_i-\mu_i}{1{,}28} \Longrightarrow \sigma_i = \frac{s_i}{1{,}28}$. In order to obtain mathematical rigor, we therefore derive the parameters μ_i and σ_i for each benefit $\tilde{b}_i$ from the estimated realization interval of the decision-maker. This coherence is also shown in Figure II.2-b.

After identifying all benefits and calculating their expected values and standard deviations, we are now able to aggregate these, in order to derive a distribution of the overall benefits of an IT project.

II.2.3.2 Aggregation of a Risk-Adjusted Project Value

We determine the overall expected benefit of an IT project B by aggregating the expected values of each single benefit $\tilde{b}_i \sim N(\mu_i, \sigma_i)$.

$$B = \sum \mu_i \qquad \text{II.2.(2)}$$

To calculate the overall standard deviation of an IT project S, we have to account for dependencies between benefits which, sometimes react similar e.g. to external influences. For example in case of technological innovation multiple benefits might be affected simultaneously. To picture this effect, we constitute the following again simplifying assumption:

Assumption 3: Dependencies between benefits are linear.

Linear dependencies between two benefits $\tilde{b}_i$ and $\tilde{b}_j$ with $i, j = 1 \dots n$ can be measured by the Bravais-Pearson correlation coefficient p_{ij}. We can calculate the overall standard deviation of an IT project S by aggregating the standard deviation of the single benefits and their respective correlation coefficients.

$$S = \sqrt{\sum \sum \sigma_i \sigma_j p_{ij}} \qquad \text{II.2.(3)}$$

The identification of the correlation coefficients between every pair of benefits is a complex task, since a high number of parameters are involved and the context is hard to understand by project staff. As the involved practitioners (CC) suggested, we developed an easier approach for a gradually and guidelined determination of interdependencies. Firstly, we specified a default value, saying all benefits shall be moderately positive correlated. This pre-allocation is intelligible because all benefits occur within one project, wherefore they are at least subject to some kind of dependencies. In case of exceptions, in which the default setting needs to be adapted, corresponding pairs of benefits are identified and alternative correlation values are entered. To facilitate this adjustment, the decision-maker is able to select one of five options outlined in natural language instead of numerical values for the corresponding correlation of two benefits. For example an absolute positive correlation $p_{ij} = 1$, is described by “a high value of benefit $\tilde{b}_i$ always corresponds with a high value of benefit $\tilde{b}_j$”. For $i = j$ the correlation coefficient $p_{ij} = 1$.

Given these values, we can obtain a risk-adjusted project value considering costs, benefits, risk, and correlations monetarily. Therefore, we use a preference function which is in line with the Bernoulli principle and developed according to established methods of decision theory (Bernoulli, 1738; Bernoulli, 1954; von Neumann and Morgenstern, 1947; Markowitz, 1959). Similar formal approaches and assumptions for risk-adjusted economic value analysis have been derived by (Longley-Cook, 1998) and have been applied in the context of IT numerous times (e.g. Hanink, 1985; Bardhan et al., 2004; Zimmermann et al., 2008; Fogelström et al., 2010; Fridgen and Mueller, 2011). Therefore we postulate the following assumption:

Assumption 4: The calculation of the risk-adjusted project value follows the general structure $\phi(\mu, \sigma) = \mu - \alpha\sigma^2$. We define α as the parameter of risk aversion and assume that the decision-maker is risk-averse ($\alpha > 0$).

The risk-adjusted project value can be interpreted as the certainty equivalent for normally distributed random variables and an exponential utility function, and thus as an amount of money. The parameter $\alpha > 0$ is a linear transformation of the Arrow-Pratt characterization of absolute risk aversion (Arrow, 1971). The higher the value of α, the more risk-averse is the decision-maker. For practitioners the concept of risk aversion is fairly abstract. Therefore, a precise determination thereof is very difficult. Again, we considered the input of CC and MC and designed a survey to determine a company's parameter of risk aversion at the executive level. Such an approach can also be found in behavioral finance (Sautner et al., 2007). Thereby the relevant decision makers are asked multiple questions about their maximum willingness to pay for different fictive project settings to determine the risk class, which is afterwards assigned to a corresponding value of risk aversion. Since the outline of every question of this survey would go beyond the scope of this contribution, we refrain from a detailed description and provide an example in Section II.2.3.3.

For the calculation of the project's risk-adjusted value we compare deterministic cash outflows $-C$ with the aggregated expected benefits $\sum \mu_i$, adjusted by a risk discount $\alpha \sum \sum \sigma_i \sigma_j p_{ij}$, consisting of the overall standard deviation of an IT project squared and weighted by the parameter of risk aversion α. Hence, we are able to aggregate the risk-adjusted project value according to the following equation:

$$\phi(\mu, \sigma) = -C + \sum \mu_i - \alpha \sum \sum \sigma_i \sigma_j p_{ij} \qquad \text{II.2.(4)}$$

II.2.3.3 Application Example

As mentioned earlier, we applied this benefits management approach by using a specifically designed IT tool in a multinational manufacturing company (MC). The following example illustrates this application in a simplified way with altered and anonymized data. This step corresponds to the Beta-Version loop in the ADR approach.

MC operates primarily in the construction industry and has a sales force, which is distributing the company's products directly at the customers' sites. Furthermore, the dynamic pricing system of the company arranges different discounts for different customers. When necessary, sales representatives request current, customer specific prices through the company´s call center directly at the customers' sites. The company is about to launch a mobile app project to facilitate such pricing requests on mobile devices. Therefore, MC wants to calculate the project value under the following premises:

- The observation period is 1 year
- The risk aversion parameter of the decision-maker was determined to be 0.000031
- The total costs of the project are 78,300 € for in-house, external, back-end development, and support
- The identified benefits are:
  - Increased customer satisfaction and loyalty
  - Reduced customer call losses
  - Reduced number of false pricing proceedings
- The correlations between the benefits are all moderately positive

The risk aversion parameter was determined at the executive level, since this parameter is valid not just for this single project but for the whole enterprise. We investigated the risk aversion parameter, as stated in Section II.2.3.2, by a survey. The following question is part of this survey and exemplarily illustrates the kind of questions the decision-makers were asked:

Please state your maximum willingness to pay for a risk-mitigating measure in the context of a project with the following characteristics (cf. Figure II.2-c):

- The project has an expected value of 100,000 €
- The expected value deviates with 80% probability by 30,000 €
- The execution of the measure reduces the deviation to 20,000 €

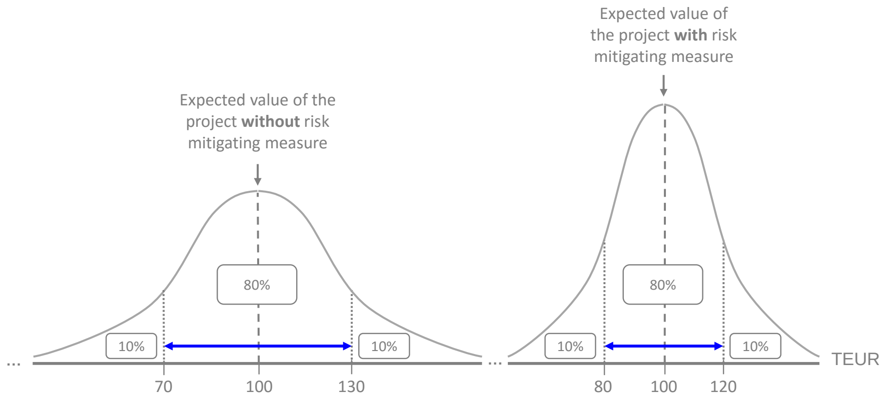

Figure II.2-c *- Reducing the deviation of an expected project value by risk mitigation*

Based on the maximum willingness to pay z_{max} as outcome of the survey, and the variance before and after (σ^2_{prior} and σ^2_{after}) the risk-mitigating measure, the parameter α can be derived:

$$\alpha = \left(\frac{z_{max}}{\sigma^2_{prior} - \sigma^2_{after}}\right) \qquad \text{II.2.(5)}$$

After the general parameters of the project setting like observation period, deterministic costs and risk attitude have been determined and all benefits have been identified, we were able to estimate an interval for each single benefit.

Benefit 1 is about increased customer satisfaction and loyalty and describes reduced customer losses due to the new mobile app. If a sales representative of MC is on the spot at a customer`s and needs to make a quick customized price enquiry, he or she can directly use the mobile app instead of conferring to the call center. Hence, without the app a longer process for pricing requests and longer waiting times would be necessary, which leads to customer dissatisfaction and can even result in customer losses. This coherence can be depicted through the equation $l_c \cdot v_c$ with l_c representing the expected number of customer losses prevented per year, and v_c the average customer value. Based on this monetarization rule, the responsible decision-maker estimated the 80%-interval for the expected value of benefit 1 to be (210,000;375,000) [€].

Benefit 2 is about reduced customer call losses. It represents the revenue that is generated through the capability to answer more or even all customer calls. The support center answers calls from customers as well as sales representatives. Due to the use of the mobile app, fewer sales representatives need to confer regarding pricing request and therefore less capacity is tied up at the support center. Consequently, capacity is freed for customer support and therefore fewer calls are missed and a higher number of enquiries can be answered. The corresponding monetarization rule is $c_l \cdot v_{cc} \cdot \Delta c_l$, whereas c_l is the number of customer calls lost due to higher capacity utilization of the support center in case of pricing requests, v_{cc} is the average value of a customer's call and Δc_l the expected reduction of lost customer calls as a percentage. For benefit 2 the 80%-interval is (25,000;50,000) [€].

The third benefit is the reduced number of false pricing proceedings. When a sales representative is at a customer's site, it is possible that the customer has short-term product enquiries. If in that case the representative is not able to confer with the call center, he has no current information about the customer specific product prices and is just able to either estimate the actual price or make an offer based on outdated information. Consequently, if the offered price is lower than the actual one, it comes to revenue losses. Since the mobile app enables real-time price enquiries, these revenue losses can be avoided. In this case, we can derive $p_o \cdot v_o \cdot \Delta p_o$ as monetarization rule for benefit 3, whereas p_o is the average number of price overwrites per year, v_o the average monetary value of a wrong price, and Δp_o the error reduction as a percentage. The resulting 80%-interval for the expected value of benefit 3 is (110,000;280,000) [€].

The expected values μ_i are determined by the mean of the corresponding estimated intervals. Therefore, μ_1 = 292,500 €, μ_2 = 37,500 €, and μ_3 = 195,000 €. The corresponding standard deviations are σ_1 = 64,453 €, σ_2 = 9,766 €, and σ_3 = 66,406 €. Aggregating the expected values of the single benefits leads to an expected project value $B = \sum \mu_i$ of 525,000 € (cf. Equation II.2.(2)). Taking the risk measures and a slightly positive correlation of 0.5 between all benefits, we calculated a risk discount (cf. Equation II.2.(4)) of 220,369 €. Considering overall deterministic costs C of 78,300 € we finally got an expected risk-adjusted project value $\phi(\mu, \sigma)$ of 226,331 € (cf. Equation II.2.(4)) for the mobile app project. Since the risk-adjusted project value is greater than zero, it increases the business value of MC. Therefore, the mobile app project should be launched.

II.2.4 Conclusion, Limitations, and Outlook

Unlike existing methods, which do not consider costs, benefits (especially benefits that are hard to quantify), risks and interdependencies between benefits, we introduce an integrated and novel method for benefits quantification in IT projects. According to the ADR cycle, we designed, applied and tested this method in collaboration with practice using real world data for development and constant improvement. Our objective is to generate generalized insights to benefits management by means of our artifact. In the context of our collaborative project, we identified methods, which can measure different project parameters and meet academic standards and preserve practical applicability. Since these methods can be assigned to different kinds of problems, we outline them in the following.

According to our business partners, the estimation of an accurate value for a benefit is difficult in practice. We found that an interval-based scheme according to Tversky and Kahneman (1974), which is a method from behavioral science, is a practicable and rigor means to assess the value of a project's benefits.

Another difficulty in practice is the determination of dependencies between benefits. Hence, we developed a simplified procedure, which assumes moderately positive correlations between benefits within the same project and provides an intuitive gradual adaption in exceptional cases in which there are higher or lower correlations between benefits. This procedure therefore meets practical requirements and is compatible with academic concepts.

Decision-makers in practice are oftentimes incapable of assessing their risk aversion. Therefore, we draw on an approach of behavioral finance, by developing a survey incorporating different questions inquiring the decision-makers willingness to pay in different project settings. This approach enables to derive the value of the decision-makers risk aversion by rigor means.

Finally, the presented method for benefits management constitutes an overall risk-adjusted project value of an IT project, which can be used as an important management control figure for decisions about and within IT projects and therefore is substantial for an overall value-based management.

Besides the introduced ex ante valuation of benefits in a business case, the implementation of this method in a continuous IT project controlling can help to identify deviations between the ex ante business case and the current project value during the course of a project and can therefore indicate needs for actions and support the early detection of IT project failure. The development of a continuous project steering and controlling by the means of the proposed method is our current work in progress. Moreover, the introduced method for benefits management should be further applied and tested in practice with more real world data for constant improvement. The application in practice also assists by setting up a knowledge base in the field of benefits management. This repetitive course of action leads to further improvement and adaptions of our benefits management method.

Our model, however, required several simplifying assumptions. We assumed the costs of an IT project to be deterministic since we focused on the quantification of the benefits. Thus, a more detailed examination of stochastic costs of IT projects is subject to further research. For the calculation of the risk-adjusted project value we consider the standard deviation as measure of risk. This two-sided risk measure scales risk as symmetric deviation of the expected value. Likewise, it is conceivable that the model might be adapted to include different risk measures like *Lower Partial Moments* or *Value at Risk* (VaR). In cooperation with our business partners we noticed that especially the VaR is easy to interpret for responsible decision-makers. Moreover, we consider linear dependencies between benefits only, as we picture them by a Bravais-Pearson correlation coefficient. Yet realistically, dependencies between benefits in some cases may also be non-linear. But since this is a complex subject and not satisfactorily solved by academia or practice, it is justifiable to work with this simplifying assumption of linear dependencies in order to derive first results. Furthermore, we assume a moderately positive correlation of benefits by standard, which may not realistically reflect the specific dependencies of all benefits, but at least is feasible due to the fact that these benefits occur within one and the same project. Also the gradual adaption of these dependencies may imply potential for inaccuracy, but is the most appropriate procedure in practice according to our business partners.

Besides the several simplifying assumptions, there are additional limitations of our model. We applied the developed approach to a mobile app project and derived valuable results. However, since it not yet has been applied to different IT projects, varying in scope and size, we cannot consider the approach to be appropriate for miscellaneous IT projects. As this is an important issue to practitioners, it is topic to further research and evaluation. Furthermore, we assume that it is possible to derive a monetarization rule for each benefit. This is also a limitation, as it might be conceivable that there are benefits, which are hard to or even cannot be assessed by monetarization rules.

With the method presented in this research, we are able to derive generalized insights regarding the interval-based estimation of benefits, the inquiry of the correlations between benefits, and the determination of the risk-aversion parameter. They provide a reliable basis for further development. It shall be analyzed for which kind and size of IT projects the presented method is suitable. It is conceivable that there are different requirements to the application of the method and therefore different results for small, middle or large IT projects as well as there might be differences for ERP-, CRM-, or BI-projects. This might be of great significance to practitioners as well as to researchers, who should feel encouraged to investigate for example the integration of non-deterministic cost, non-linear correlations and different kinds of risk measures.

II.3 Continuous IT Project Assessment for Value Assurance[6]

The probability of IT project failures can be mitigated more successfully when discovered early. To support a more insightful management of IT projects, which may also facilitate an early detection of IT project failures, transparency regarding a project's cash flows shall be increased. Therefore, an appropriate analysis of a project's benefits, costs, requirements, their respective risks and interdependencies is inevitable. However, to date, in requirements engineering only few methods exist that appropriately consider these factors when estimating the ex ante project business case. Furthermore, empirical studies reveal that a lot of risk factors emerge during the runtime of projects why the ex ante valuation of IT projects even with respect to requirements seems insufficient. Therefore, using the Action Design Research approach, we design, apply, and evaluate a practicable method for value-based continuous IT project steering especially for large-scale IT projects.

II.3.1 Introduction

Companies continuously increased their IT investments over the last decades. Especially the number and complexity of large IT projects is growing. The complexity itself is intensified by dependencies within one or between different projects and processes and is boosted even further by the growing number of large IT projects. Another important influence is the rising uncertainty in an increasingly dynamic project management environment. These developments have implications for IT projects success. To cope with these challenges, requirements engineering (RE) concentrates on design decisions and interventions by capturing, sharing, representing, analyzing, negotiating, and prioritizing requirements in recent years (Zave, 1997; van Lamsweerde, 2000; Cheng and Atlee, 2009; Jarke et al., 2010). Based on the evolution of IT, new opportunities and challenges in the field of RE emerge. Jarke et al. (2010) for example state that "the environment in which RE is practiced has changed dramatically" and therefore reveal demand for new ways to manage requirements (Jarke et al., 2010, p. 470). In that context, modern software development processes and especially methods of agile software developments allow for the ongoing verification and update of these requirements.

[6] This section is an editorially improved version of Fridgen et al. (2014), which is a follow-up on Beer et al. (2013) [cf. Section II.2]. Like outlined in Section I.3, it extends the integrated IT project assessment of Beer et al. (2013) by introducing a dynamic cash flow perspective and developing a method for continuous project evaluation and steering.

However, despite the scientific achievements in the context of RE, there is still a significant portion of IT projects that fail in the way that they run out of time, budget, or do not generate the planned value. According to a recent study by the IT Governance Institute about one out of five investments into IT is terminated before implementation (ITGI, 2011). A study by the Project Management Institute found that despite the fact that organizations increasingly applied a variety of means to manage their projects, still 36% of projects did not successfully meet their initial objectives or business intent in 2011 (PMI, 2012). Flyvbjerg and Budzier (2011) find that on average IT projects overrun their budgets by 27%. The question is why companies still fail to achieve the successes initially expected from these IT projects.

Amongst other reasons, unexpected economic risk factors that emerge during the runtime of projects cause budget and time overruns and consequently those high termination rates. Those risk factors lead to the late conclusion that – in contrast to prior expectations – anticipated results cannot be achieved (ITGI, 2011). In that context, Flyvbjerg and Budzier (2011) found for example that the continuous measurement and controlling of expected projects benefits (beyond costs) seems to be positively related to IT project success. However, this insight is often not considered in practice to date: If requirements are reconsidered during the runtime of a project, then typically because of technical or cost reasons (e.g. “which features are feasible with the limited budget?”). Financial dependencies between different project parts as well as the measurement of expected projects benefits are mostly neglected so far. Moreover, there is a lack of methods to compare the current financial project status with the ex ante valuation of the IT project (for example regarding the realized benefits). In many situations, if companies have decided to make a project once, they continue the project even if financial environments have changed.

While scientific literature on RE and project management methods primarily focuses on technical aspects (Jarke et al., 2010) or on the financial ex ante valuation of IT projects (Walter and Spitta, 2004; Wehrmann and Zimmermann, 2005), the continuous value-based management of IT projects (also with respect to requirements) is mostly neglected so far. In order to be able to identify emerging risks during the runtime of projects early and to counteract reasonably, processes and methods for a continuous value-based IT project steering are necessary, which as of today to the best of our knowledge are missing within scientific literature. Thus, based on the first idea presented by Fridgen and Heidemann (2013), the aim of this research is to develop a method for a continuous value-based IT project steering especially for large-scale systematically assessable IT projects. This approach extends the integrated IT project assessment that has been developed in our preceding research project

(Beer et al., 2013), by introducing a dynamic cash flow perspective and developing a method for continuous project evaluation and steering.

Our approach helps companies in their strive to measure the current success of an IT project during its lifecycle, allows them to provide a control mechanism, and to make future-oriented decisions.

II.3.2 Method

II.3.2.1 Action Design Research

For the development of a method for continuous value-based IT project steering, we decided to draw on Action Design Research (ADR), a design research method that has been developed by Sein et al. (2011). The ADR method is based on different stages as well as corresponding principles that guide the research process (Sein et al., 2011). In contrast to other design research methods (e.g. March and Smith, 1995; Peffers et al., 2007), ADR does not separate and sequence the design of an artifact and its evaluation in a “build and then evaluate” cycle (Sein et al., 2011). ADR rather supports ensemble artifacts that “emerge from the contexts of both their initial design and continual redesign via organizational use” (Sein et al., 2011, p. 52). Thus, the simultaneous development and evaluation of an artifact, which is done in mutual cooperation between practitioners and researchers, is a specific characteristic of this research method. Since the actual perception of a method for continuous value-based IT project steering by decision makers and its acceptance in business practice cannot be investigated solely driven by theories without actively engaging organizations (Beer et al., 2013), we believe that ADR is especially well-suited to our problem because of three reasons. First, ADR supports research driven by design theories and inspired by problems from practice (stage 1: *Problem Formulation*) that allows for an organization dominant building, intervention, and evaluation of artifacts (stage 2: *Building, Intervention, and Evaluation*) (Sein et al., 2011). Therefore, ADR helps us to structure and guide the initial development of a novel method for continuous value-based IT project steering, driven by the need of our business partners and the lack of suitable approaches in theory. It furthermore supports the method’s improvement by “reciprocal shaping” and “mutually influential roles”, using the expertise of researchers and practitioners, and its concurrent evaluation by the promptly use of the new method by practitioners (alpha version) and end-users (beta version) within an organizational context. Second, as we create a completely novel method, ADR helps to reflect on the design of the artifact (“guided emergence”) and to “generate and evolve design principles” that partly might have been already derived in stage 1 (stage 3: *Reflection and Learning*) (Sein et al., 2011).

Third, ADR asks for a generalization of outcomes from the “specific-and-unique to generic-and-abstract” (stage 4: *Formalization of Learning*) (Sein et al., 2011). Thus, we believe that ADR allows us to derive general recommendations that help to further improve project-steering methods in general.

II.3.2.2 Research Setting

In order to avoid IT failures and due to the lack of scientific rigor methods being available and especially easy applicable in practice, there is a need of companies for IT project-steering. Therefore, we design, apply, and evaluate a practicable method for continuous value-based IT project steering in collaboration with one of the world’s leading strategy consulting companies (in the following referred to as CC). We were gathering feedback from practice regarding efficacy and applicability of the method on a regular basis. Besides the feedback from practice, we also continuously took scientific literature into account when designing the method to uphold the scientific rigor. In addition, we tested the developed method at an industrial client, namely a multinational manufacturing company (in the following referred to as MC), who used the method to IT project steering of multiple mobile app development projects. Although mobile app projects are rarely large-scale IT projects, we were able to apply and evaluate our artifact in this IT project context too. Furthermore, with respect to the evaluation, we were able to gather additional qualitative feedback from the CC that applied our method (at least in parts) in three more IT projects. It may be argued, that our case study gives back just qualitative feedback and insights on our method in a first step. However, according to common literature (e.g. Dubé and Paré, 2003) qualitative feedback in case studies (e.g. gathered by interviews) is a validated approach, which also brings rigor and flexibility to case studies concerning the complex field of IS (Dubé and Paré, 2003). We therefore draw on this approach for a first, but indispensable step towards the evaluation of our method.

In sum, the valuable feedback in different evaluation cycles of both business partners – CC (alpha cycle and beta cycle) as well as MC (beta cycle) – gave us the opportunity to satisfy the criteria of ADR and to develop an artifact, which fulfills the requirements of all stakeholders from business practice and science. Figure II.3-a shows the ADR approach based on the depiction in Sein et al. (2011), adjusted to our specific research setting.

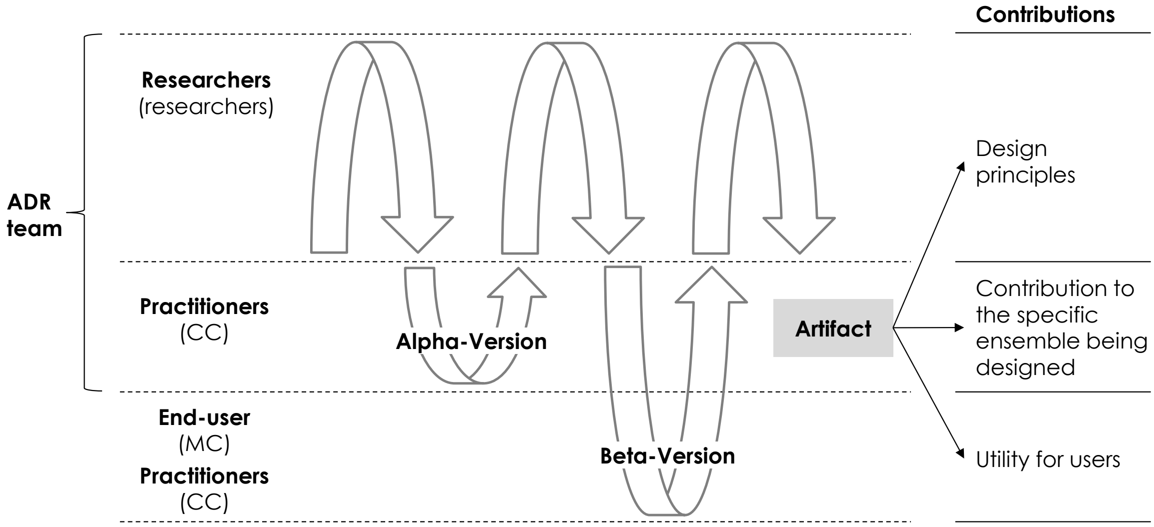

Figure II.3-a *- Building, intervention and evaluation scheme in ADR (cf. Sein et al. 2011)*

The remainder of Section II.3 is organized in accordance with the above mentioned stages. We first outline the theoretical foundations and the specific practical need of our research (stage 1). Subsequently, we describe the building, intervention, and evaluation that finally led to our method for continuous value-based IT project steering (stage 2). Afterwards, we reflect on our findings (stage 3) and generalize by deriving design principles for a continuous value-based IT project steering for decision makers in the context of project management (stage 4). Finally, we summarize our results, point out limitations, and suggest areas for further research.

II.3.3 Problem Formulation

The management of large scale IT projects in an increasingly dynamic and complex project environment is a challenging task for decision makers in companies [Denne and Huang 2003]. Although IT management processes, methods and techniques have improved significantly over the last couple of years – in the context of RE methods for agile software development allow for example for easily changeable requirements associated with the evaluation of potential changes (Ernst et al., 2012) – there are still a high number of "out-of-control tech projects" that fail in the way that they run out of time, budget, or do not generate the planned value (Flyvbjerg and Budzier, 2011). Flyvbjerg and Budzier (2011) analyzed 1,471 projects and found that on average they overrun their budget by 27% – and one out of six projects even by 200%. Recognizing this risk, there is a specific practical need of companies for techniques in order to avoid these IT failures. During different interviews with CC, they specified this need for a methodically sound as well as easy to use and practical applicable method of a continuous value-based IT project steering for especially large IT projects. Our method may be more influencing on large-scale IT projects as in this context complexity and risks are usually higher. Nevertheless, it can be applied to different kinds and sizes of IT projects since we draw on a generic approach. But the type and extent of application is subject to further research.

In theory, RE is an acknowledged phase within every IT project's lifecycle (Pohl, 1994) and an important factor for the success of an IT project (Cheng and Atlee, 2009). Thereby RE can be seen as a process to identify the purpose, a certain IT project has to fulfill (Nuseibeh and Easterbrook, 2000). It is realized by the analysis, documentation, communication, and implementation of the IT projects` stakeholders needs, also known as requirements (Nuseibeh and Easterbrook, 2000). One of the obstacles of RE is the fact that some of a project's requirements may change during the project's lifecycle and therefore are hard to manage and may lead to increased pay-offs (Nuseibeh and Easterbrook, 2000; Cheng and Atlee, 2009). To address changing requirements in the context of software development, Denne and Huang (2003) for instance develop an incremental funding methodology that values timely and incremental sub-functionalities. Another challenge of RE is to create a strong alignment between science and practice, which has become more and more important due to the changing economics of RE (Jarke and Lyytinen, 2010). These changing economics of RE can be seen in the increasing number of large business and technical systems, which need a more rigorous analysis of Return-on-Investment (ROI) (Jarke and Lyytinen, 2010).

II.3.4 Building, Intervention, and Evaluation (BIE)

II.3.4.1 Alpha Cycle

Based on the results of the problem formulation stage, the ADR team aimed to develop a method for a continuous value-based IT project steering. In this context, the objective of this research is to derive insights for the quantification and management of a specific project, which possibly can be generalized and transferred to other project settings afterwards. The BIE stage was initiated by the design of a process for value assurance in IT projects over their lifecycle by considering different steps. The initial process is depicted in Figure II.3-b.

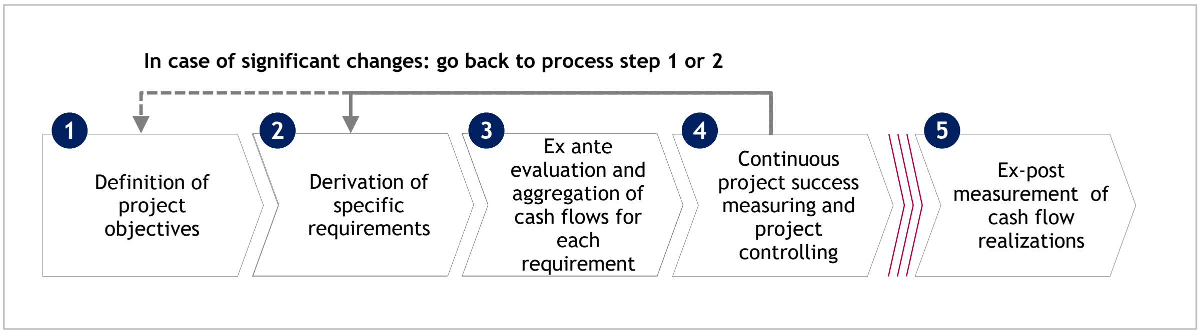

Figure II.3-b *- Value assurance in requirements engineering process*

We assume the general project objectives to be defined in step 1. In step 2, requirements r_i with $i = 1 \ldots n$ are derived from these objectives using established methods of RE. Requirements can be defined on different levels of granularity. For instance, there may be projects in which one requirement`s cash flow and risk, which should be estimated, might be on a very fine, detailed and technical level (e.g., two variables need to have a technical connection for exchanging integer-type data) or in extreme contrast, there may also be other projects, in which the level of requirement might be very functional, abstract and coarse (e.g., a new CRM system is needed). When developing our method, we primarily had requirements on this coarse level in mind that presumably can be measured by monetary values. However, we made sure through input by our business partners and literature (Feather and Cornford, 2003), that there are ways to handle different levels of granularity. Depending on the difficulties to estimate cash flows and risks of requirements of a specific level, it is common in practice to subsume few, fine requirements to one coarser requirement and estimate its cash flow and risk. There may be some requirements for which the estimation of cash flows and requirements may not be possible. But the application of our method and estimation of as many project-relevant cash flows and risks of requirements as possible is still better than making decisions concerning project steering just based on gut feelings.

Yet, this research focuses on steps 3 to 5 that basically apply the same quantitative method set in different phases of the project. This allows for intertemporal comparability and thus for a quantitative analysis of the project course.

Ex ante Evaluation and Aggregation of Cash Flows (Step 3)

On the one hand, there are quantitative aspects of each requirement that can be directly transformed into cash flows. On the other hand, there are qualitative aspects, which are difficult to transform into monetary units (Walter and Spitta, 2004). According to the feedback from CC, many approaches applied in business today refrain from quantifying these qualitative aspects as no decision maker dares to name exact numbers for parameters difficult to estimate.

However, our method requires that in step 3 cash flows cf_{it} are initially evaluated for each one of the requirements i in each period t with $t = 0 \ldots T$. Note, that we assume that cash flows can also be determined for requirements that must be implemented (e.g. due to legal requirements). This can be achieved by comparing the IT project to its alternatives (e.g. doing a task manually). As stated above, the granularity of requirements can vary. To facilitate the quantification it therefore may be easier in some situations to subsume some requirements to estimate the respective cash flow on a coarser level, even if a finer level may be more accurate. The evaluation of cash flows is then repeated multiple times in step 4 and finally in step 5. In the following, we describe how to accomplish this initial evaluation for benefits of requirements and describe the adaptations for step 4 and 5.

Assumption 1: The cash flows are normally distributed random variables $\widetilde{cf}_{it} \sim N(\mu_{it}, \sigma_{it})$. The cash flows are stochastically independent between different periods.

Normally distributed project cash flows are a common assumption in IT portfolio management (Wehrmann and Zimmermann, 2005; Wehrmann et al., 2006; Zimmermann et al., 2008; Fridgen and Mueller, 2011). Although our assumption might not picture reality in every case, especially projects' benefits cash flows are often market driven and thus a normal distribution seems applicable. Furthermore, the more cash flows or requirements are aggregated, the better the central limit theorem and variations thereof will apply. Assuming the cash flows to be independent is obviously simplifying means, too. However, as the model could easily be adapted to picture intertemporal dependencies between cash flows, this is subject to further research.

Treating cash flows as random variables clearly eases their estimation, as no decision maker has to commit to exact values. Their deviation then contributes to the project's risk, i.e. cash flows that are hard to estimate increase the project risk more than cash flows that are easy to estimate. In a first attempt, we designed our method so that the distributional parameters μ_{it}, σ_{it} and the correlation ρ_{ij} would be directly obtained from the decision-makers. Within the loops of the alpha cycle, we got the feedback from CC that this approach is hardly feasible in practice as (a) decision makers may not have the relevant statistical knowledge available and as (b) absolute values of many these parameters (e.g. correlations) are hard to interpret even for trained people. To simplify the estimation of these parameters, we hence draw back on a basic but acknowledged procedures, which we adapted for our problem setting and which we strive to in further ADR cycles. For instance, in the case of cash flows we draw on behavioral economics by using an interval-based scheme for the evaluation of each cash flow (please refer to Tversky and Kahneman (1974) for a critical discussion on these estimation methods, or for some kind of similar approach refer to Feather and Cornford (2003), who estimate for each requirement different criteria in ranges). For a more detailed and elaborate description of the following approach for deriving a risk-adjusted project value, please refer to Beer et al. (2013). Assuming normally distributed cash flows, we are able to derive expected values μ_{it} and standard deviations σ_{it} for each requirement r_i in each period t from this interval.

Having identified all cash flows $\widetilde{cf}_{it}$ and their distribution parameters, and assuming stochastical independence between periods (assumption 1), we can then calculate the distribution parameters of the net present value $\widetilde{npv}_i \sim N(\mu_i, \sigma_i)$ for each individual requirement based on the interest rate p:

$$\mu_i = \sum_{t=0}^{T} \frac{\mu_{it}}{(1+p)^t} \qquad \text{II.3.(1)}$$

$$\sigma_i = \sqrt{\sum_{t=0}^{T} \left(\frac{\sigma_{it}}{(1+p)^t}\right)^2} \qquad \text{II.3.(2)}$$

Aggregation of a Project Value Considering Risk and Dependencies

To determine the overall value (business case) of an IT project, we need to aggregate the $\widetilde{npv}_i$ of each requirement r_i to the project's $\widetilde{NPV} \sim N(\mu, \sigma)$. The project's overall expected value then is depicted by μ.

$$\mu = \sum_{i=1}^{n} \mu_i \qquad \text{II.3.(3)}$$

To calculate the overall standard deviation σ of the IT project, we have to account for dependencies between requirements, which sometimes react similar for instance to external influences. For example in case of technological innovation multiple requirements and therefore cash flows might be affected simultaneously.

Assumption 2: The net present values $\widetilde{npv}_i$ of the requirements r_i are linearly dependent. Their Bravais-Pearson correlation coefficient ρ_{ij} describes the dependencies between requirements i, j.

The identification of the correlation coefficients between every pair of requirements is a complex task, since a high number of elements are involved and the context is hard to understand by project staff. As the CC suggested, we developed an easier approach for a gradually and guided determination of interdependencies (cf. Beer et al., 2013). We can calculate the overall standard deviation σ of an IT project by aggregating the standard deviation of the single requirements and their respective correlation coefficients:

$$\sigma = \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n}\sigma_i\sigma_j\rho_{ij}} \qquad \text{II.3.(4)}$$

Using these parameters, firms can apply various methods of an integrated risk/return management (e.g. (*Conditional*) *Value at Risk*). Synchronized with the CC, we decided to use a risk-adjusted project value as our means for project evaluation, which is in line with the Bernoulli principle and developed according to established methods of decision theory (Bernoulli, 1738; Bernoulli, 1954; von Neumann and Morgenstern, 1947; Markowitz, 1959). Similar formal approaches and assumptions for risk-adjusted economic value analysis have been derived by Longley-Cook (1998) and have been applied in the context of IT numerous times, for example in Hanink (1985), Bardhan et al. (2004), Zimmermann et al. (2008), Fogelström (2010), and Fridgen and Müller (2011).

Assumption 3: We define α as the parameter of risk aversion and assume that the decision-maker is risk-averse ($\alpha > 0$).

The risk-adjusted project value then is depicted by ϕ.

$$\phi_{EA} = \mu - \alpha\sigma^2 \qquad \text{II.3.(5)}$$

The risk-adjusted project value can be interpreted as the certainty equivalent for normally distributed random variables and an exponential utility function and thus as an amount of money. The parameter α is a linear transformation of the Arrow-Pratt characterization of absolute risk aversion (Arrow, 1971). The higher the value of α, the more risk-averse is the decision-maker. For practitioners the concept of risk aversion is fairly abstract. Therefore, a precise determination thereof is very difficult. Again, we considered the input of the CC and designed a survey to determine a company's parameter of risk aversion at the executive level. Such an approach can also be found in behavioral finance (Sautner et al., 2007). Thereby the relevant decision makers are asked multiple questions about their maximum willingness to pay for different fictive project settings to determine the risk class, which is afterwards assigned to a corresponding value of risk aversion.

Continuous Business Case (Step 4)

So far we described the first three steps of the process for value assurance in IT projects depicted in Figure II.3-b. Since projects usually endure over a period of time T, a continuous project and business case management is essential for a lasting value assurance. Therefore, the main contribution of this research is the design, application and evaluation of a continuous IT project steering indicated by step 4 of the described process in Figure II.3-b.

In step 4, we are at the point in time $0 < \check{t} < T$. In $\check{t}$, some requirements $0 \dots \check{\imath} - 1$ might already have been fully implemented and generate certain and non-influenceable returns. Therefore, their associated cash flows cf_{it} are no more random variables for all t. For all other requirements $\check{\imath} \dots n$, the past cash flows cf_{it} are realized and thus no more random variables for $t < \check{t}$. However, for $t \geq \check{t}$, the $\widetilde{cf}_{it}$ are still prone to risk and thus random variables. All $\widetilde{cf}_{it}$ need to be reevaluated, as their values or distribution parameters, respectively, might have changed.

We identify two possible means to enable and support the continuous IT project steering: the *Project Success Measuring* measure and the *Project Controlling* measure. The objective of the project success measuring is a comparison of the ex ante business case target value and the corresponding actually realized project value. In contrast the project controlling enables to validate the ex ante estimated future cash flows from today's point of view considering current information. In the following we will examine these two measures in detail.

Project Success Measuring

Project Success Measuring (PSM) can be used in the course of the project lifecycle or as an ex-post means to investigate value deviations from the ex ante business case. To ensure comparability with the ex ante business case, all cash flows need to be discounted to $t = 0$. The project's expected value is then:

$$\mu = \sum_{i=0}^{\check{\iota}-1}\sum_{t=0}^{T}\frac{cf_{it}}{(1+p)^t} + \sum_{i=\check{\iota}}^{n}\left(\sum_{t=0}^{\check{t}-1}\frac{cf_{it}}{(1+p)^t} + \sum_{t=\check{t}}^{T}\frac{\mu_{it}}{(1+p)^t}\right) \qquad \text{II.3.(6)}$$

As only future cash flows of unfinished requirements are risky, the project's standard deviation is then:

$$\sigma = \sqrt{\sum_{i=\check{\iota}}^{n}\sum_{j=\check{\iota}}^{n}\sigma_i\sigma_j\rho_{ij}} \; with\; \sigma_i = \sqrt{\sum_{t=\check{t}}^{T}\left(\frac{\sigma_{it}}{(1+p)^t}\right)^2} \; for\; i \geq \check{\iota} \qquad \text{II.3.(7)}$$

We can then calculate $\phi_{PSM}(\check{t})$ using Equation II.3.(5). Figure II.3-c illustrates the formally described coherences for a better understanding.

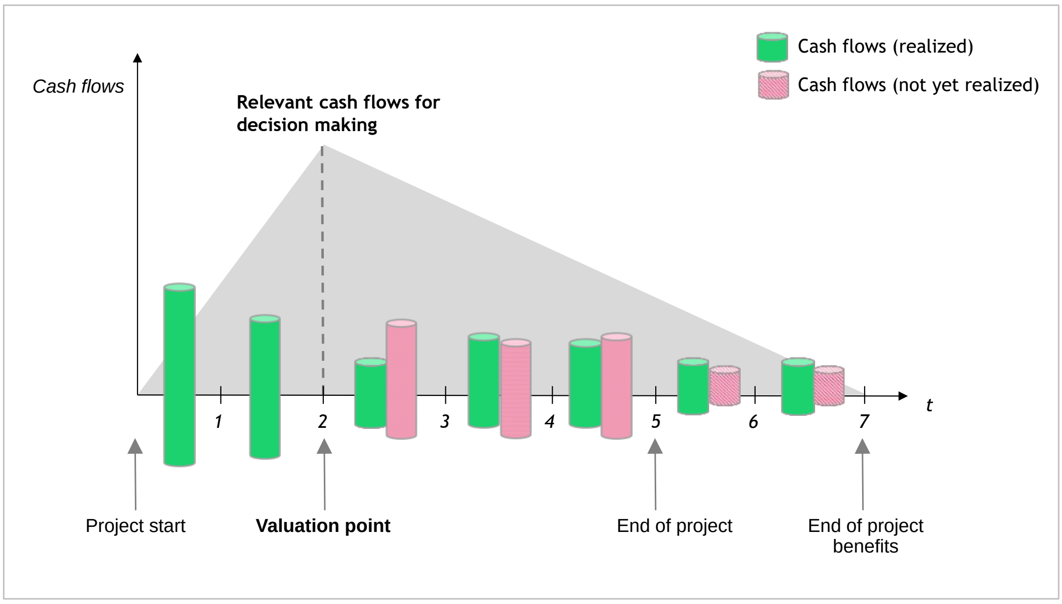

***Figure II.3-c** - Project Success Measuring*

Using PSM within the projects lifespan may enable the identification of deviations between planed and actual progression in an early stage of the project. To ease the recognition of critical deviations, specific kinds of triggers can be defined in reality. Such triggers include for example planed project or benchmark values at specific points in time or any combination of these. However, for reasons of simplicity we just examine some of them in the following. Additional triggers can be easily defined, though. A natural lower bound for a trigger is the ex ante business case ϕ_{EA}, as one would assume that not all anticipated risks actually occur during the project and thus $\phi_{PSM}(t) > \phi_{EA}$. This coherence is described in Figure II.3-d.

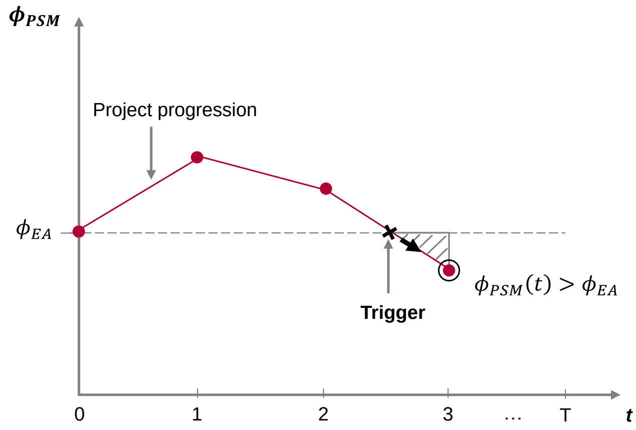

Figure II.3-d - *Project Success Measuring: Trigger 1*

As this trigger might give a warning too late, an earlier warning would be triggered when $\phi_{PSM}(t) < \phi_{PSM}(t-1)$. This trigger, illustrated in Figure II.3-e, consequently indicates a slowdown of the project progression and may sensitize the decision maker for the current project situation.

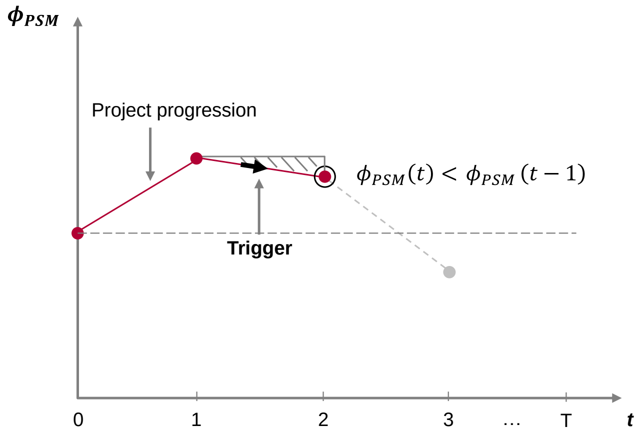

Figure II.3-e - *Project Success Measuring: Trigger 2*

In accordance with the CC, we furthermore identified the necessity of a triggering system that monitors if a project makes steady progress in terms of realizing value and avoiding risk. Similar to the lower part of the cone of uncertainty (Boehm, 1981; Armour, 2008), one would expect the project to reach its ex ante expected value at the end of the project. We use a linear benchmark that runs between ϕ_{EA} and the ex ante expected value μ, shown in Figure II.3-f. The question if differently shaped (e.g. convex) benchmarks are more suitable in a project setting is subject to further research.

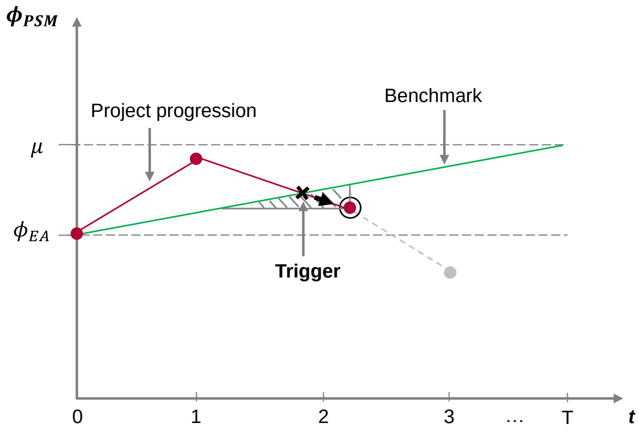

Figure II.3-f *- Project Success Measuring: Trigger 3*

The information about the current project value, the linear approximation and the respective triggers can be used for a continuous management of IT projects. It enables responsible decision makers to initiate adequate actions like a reallocation of resources in time and therefore mitigates the risk of project failure.

Project Controlling

For a rational project steering, PSM is not enough. In fact, it can still make sense to continue a project that has a negative project success $\phi_{PSM}(t)$. That is because the past cash flows and even the non-influenceable future cash flows that are considered in $\phi_{PSM}(t)$ need to be treated as "sunk" to make the decision on continuing a project. If influenceable future cash flows show a positive risk-adjusted net present value, then it is rational to continue the project. As in IT projects benefits usually occur late (Buhl, 2012) while big parts of the costs are already sunk, oftentimes finishing an unsuccessful project is favorable.

The Project Controlling (PC) supports the decision maker by deciding whether to continue a project or not. It is a future oriented project management measure and can be calculated during the projects lifecycle at different points in time. In $\check{t}$, it includes current information about already accomplished requirements (seen as sunk costs and requirements) and considers only the cash flows that can still be influenced. The net present value (for reasons of simplicity still discounted to 0) used for PC then has the following expected value:

$$\mu = \sum_{i=\check{\imath}}^{n} \sum_{t=\check{t}}^{T} \frac{\mu_{it}}{(1+p)^t} \qquad \text{II.3.(8)}$$

Its standard deviation equals the one used in PSM. We can then calculate the risk-adjusted residual project value $\phi_{PCM}(\check{t})$ using Equation II.3.(5). To ease the understandability of the formally described coherences, they are illustrated in Figure II.3-g.

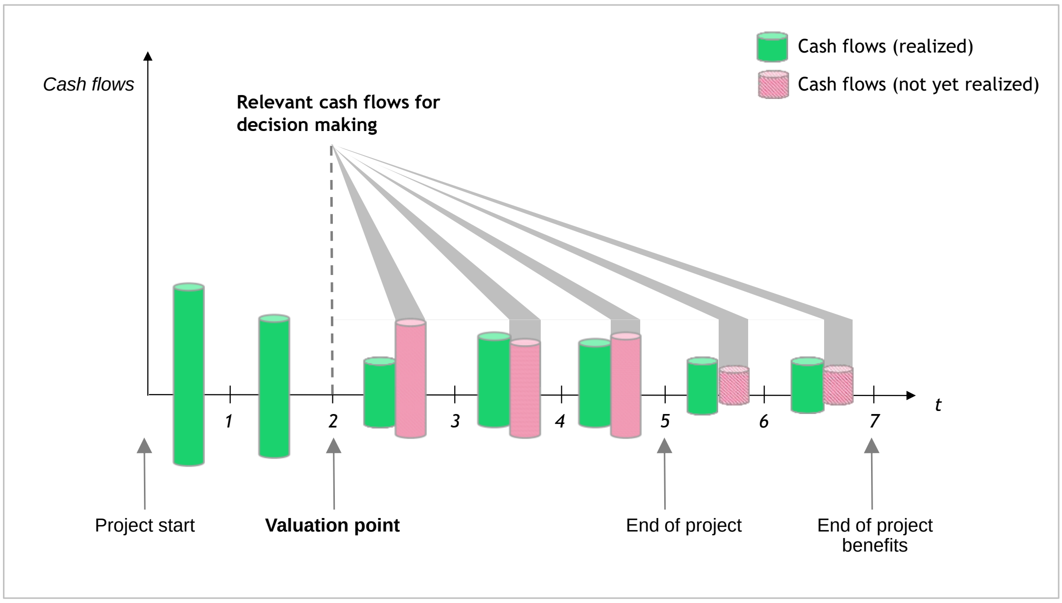

Figure II.3-g *- Project Controlling*

As already realized cash flows are not considered in the calculation, it is hardly possible to compare the risk-adjusted residual project value of different evaluation points. Hence, the objective of the PC is to indicate the necessity for project termination or at least safeguarding measures, rather than to compare the overall cash flow situation of the project at different points in time. This can avoid expensive project failure at the end of the implementation phase. Analogous to the PSM, specific triggers in the PC context can ease the recognition of critical project situations. However, the following triggers are also in this case just examples and additional triggers can easily be defined. A natural lower bound for the trigger in this case is a negative risk-adjusted residual project value $\phi_{PCM}(\check{t}) < 0$, illustrated in Figure II.3-h.

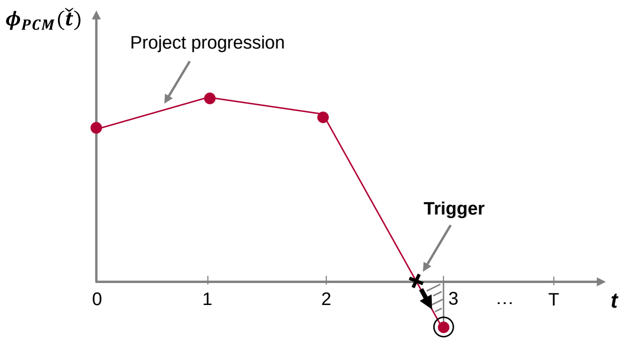

Figure II.3-h *- Project Controlling: Trigger 1*

In terms of value realization and risk avoidance, we again developed a triggering system together with the CC that monitors the actual project progress compared to the initial estimation. This enables to give earlier warnings than in the case of $\phi_{PCM}(\check{t}) < 0$. Therefore, we calculate the risk-adjusted residual project value based on the initial assessments of the ex ante business case and use it as a benchmark, like depicted in Figure II.3-i.

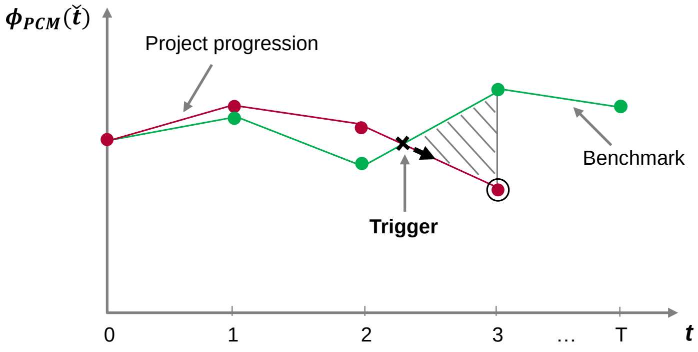

Figure II.3-i *- Project Controlling: Trigger 2*

Similar to the PSM it enables responsible decision makers to initiate adequate actions in time and therefore mitigates the risk of project failure. Furthermore, it indicates whether it is more reasonable to continue or to terminate the project at a specific point in time. However, it is important to understand, that a negative PC not necessarily indicates a project failure: If all value-adding requirements have already been implemented and the residual requirements provide negative business value, it makes sense to not finish the project.

Ex-post Measurement of Cash Flow Realizations (Step 5)

The ex post measurement is necessary to compare the ex ante estimated project values with the actual realized ones after the projects lifecycle and to gain valuable insights for upcoming projects. To achieve this, the results of the PSM are calculated at the end of the project and compared to the ex ante anticipated project value. Furthermore, it allows to associate critical environmental incidents occurred during the projects lifecycle to deviations between actual and estimated project cash flows. Analyzing this information enables to initiate a process of learning to improve the quality of ex ante business case estimations. Furthermore, it enables to build up a knowledge base that can support the prediction of a projects progression in the context of specific environmental influences.

II.3.4.2 Beta Cycle

During the beta cycle, we identified possible improvements for our method for a continuous value-based project steering on the basis of experiences in implementing it at the MC and on feedback by CC, which was implementing it at several of its clients.

The MC applied the method in several small projects with a project volume between 0.3 million € and 2.0 million €. Thereby, we received two major insights. First, while our presented risk-adjusted project value incorporates all relevant information including the decision maker's risk attitude and can be interpreted as a security equivalent, there might still be settings where other statistical measures might be more suitable. In the concrete case, the decision makers preferred a *Value at Risk* approach, measuring which project value will be exceeded with 80% probability, as this measure could be more easily interpreted and was more compatible with existing decision procedures. However, as risk attitude is not part of this measure, the comparability of projects and between different points in time is not given in general. While this was not conceived to be problematic by MC, as their projects were comparatively small, it poses opportunities for further research on how interpretability can be improved while ensuring rationality using decision theory. Second, applying the method to several small projects revealed a problem of incentives when doing the interval-based estimation of values: While costs were estimated in MCs IT department that was also held responsible for a realistic estimation, the estimation of the projects' benefits required the involvement of several business units. However, in the given project setting, those units were not held responsible for the results and therefore did only put little effort in the estimation resulting in very vague answers like "the benefit of this feature will be between 0 and 20,000 € with 80% probability", merely ensuring that they cannot be blamed for project failures afterwards. This reinforced existing and opens up areas for further research in incentivizing realistic project value and risk estimation.

In addition, to enhance our beta cycle, we draw on additional qualitative feedback from the CC. They adopted different elements of the developed method in three IT projects at a bank, insurance company and at an industrial client with an IT project volume sizing from 5 million to 150 million €. One of the IT projects used parts of the method to assure and steer an entire IT portfolio. Although, the approach has not yet been implemented as a whole at one client, we were able to gather valuable feedback from the practitioners with regard to the benefits as well as the obstacles of our method. In three independent feedback cycles our business partners validated the used principles and proceedings. In that context, we conducted three in-depth interviews with the project leaders of the three IT projects in September 2013. As already stated by Sein et al. (2011) "ADR is useful for open-ended IS research problems that require repeated intervention in organizations to establish the in-depth understanding of the artifact–context relationship" (Sein et al., 2011, p. 52). To date, we got the following feedback regarding our method (cf. Table II.3-a):

***Table II.3-a** - Further feedback from CC projects*

Observed benefits of the method	• General proceeding: All interviewed business partners appreciate the general proceeding (especially with respect to the ex ante evaluation of the IT project requirements and the continuous IT project success measuring and controlling) and value the ex ante monetary assessment of cash flows and risks with respect to the project requirements. • Estimation of the parameters: In most cases they were able to monetize the costs and with respect to the benefits the expected savings (one procedure is to ask different experts and to average the estimations in order to reduce the mistakes); we learned that they (bank and insurance) consider the interval based estimation as practicable procedure. • Continuous update: They stated that the continuous update of PSM and PC supported the management of their projects.
Observed obstacles and improvement ideas of the method	• Mathematical approach: They consider the method in parts still too mathematically challenging and too hard to interpret for average top management purposes. To simplify the interpretation, they propose an initial estimation of cash flows on a higher granularity (e.g., estimating net present values of whole project parts instead of cash flows of individual requirements), which is then refined during the project while still staying within the same theoretical framework. Another solution would be to have specialized employees who are trained in applying the method. • Visualization: They suggest an easier visualization of the PSM and PC in form of a simple management cockpit. • Context of the IT project: According to the CC, the willingness to implement a monetary project steering like the proposed one depends on the context of the IT project. To give one example, the risk department of a large financial institution may be more open to apply it than the manufacturing department of a small industrial corporation.

II.3.5 Formalization of Learning

Based on our research results and in meaning of ADR, we are able to derive generalized insights that can be assigned to different kinds of problems in the context of value assurance in IT projects. The first three steps of the process for value assurance in RE (cf. Figure II.3-b) focus on identifying and considering all project requirements and their transformation in a practicable method for an integrated quantification of IT projects. The challenge of maintaining applicability while upholding scientific rigor turned out to be a recurring topic throughout the action design research project. The estimation of accurate values for cash flows, risk aversion and, dependency parameters, which are necessary for a holistic calculation of the overall project value, is according to both our business partners a difficult task for project staff in practice. In this context we are able to state following generalizable findings: First, The interval-based scheme, a method from behavioral economics being discussed by Tversky and Kahneman (1974), is a practicable and rigor means to assess the value of a project's requirements and cash flows. Second, in order to assess a value for the risk aversion of decision-makers, an approach of behavioral finance (cf. Sautner et al., 2007) doing a survey containing questions about the decision-makers' willingness to pay in different project settings is advisable. Beyond that, the acceptance of monetary IT project management methods seems to depend on various parameters that need to be further examined, e.g. in empirical studies. Within our project we identified the following parameters: the complexity of the method itself, the company's size and industry, the projects' size, the responsible division, the involved divisions and top-management support, and the decision makers' analytical education and skills.

II.3.6 Conclusion and Limitations

We introduce a novel integrated approach for a continuous value-based IT project steering for large IT projects, which – unlike existing methods – considers costs, cash flows of requirements, risks, and interdependencies between requirements comprehensively. Therefore, this approach complements existing scientific literature in the context of RE and project management methods for the financial ex ante valuation of IT projects. The approach was designed, applied and evaluated according to the ADR cycle in collaboration with two business partners from practice. In addition, we were able to gather additional qualitative feedback from the CC that applied our method (at least in parts) in three more IT projects. In the context of our collaborative project, methods were identified, which can measure different project parameters and meet academic standards while at the same time preserve practical applicability. Furthermore, these methods have to be embedded in a project management process to enable the value assurance over the lifecycle of IT projects. As stated in section II.3.2, the case study gives back qualitative feedback and insights on our method. Even though this is a validate approach in the complex field of IS (Dubé and Paré, 2003) according to common literature (e.g. Dubé and Paré, 2003), we hope to draw on quantitative feedback in further evaluations in real-life IT projects. In this context, we develop two means to ensure a continuous value-based IT project steering: First, the PSM ratio, enabling a comparison of the overall cash flow situation of the project at different points in time and therefore an early detection of deviations from the ex ante business case. Second, in the context of PC we develop the risk-adjusted residual project value, indicating the necessity for project termination or at least safeguarding measures. Therefore, our approach supports practitioners to measure the success of an IT project during its lifecycle, enables a control mechanism for the project progression and eases future-oriented decisions regarding the projects continuation, which may also reduce the overall risk of IT project failure.

Nevertheless, since our model is based on several assumptions it is not without limitations that are described in the following. First, although normally distributed cash flows are a common assumption in IT portfolio management (Wehrmann and Zimmermann, 2005; Wehrmann et al., 2006; Zimmermann et al., 2008; Fridgen and Mueller, 2011) and can also be braced by practical observations, they nevertheless are a restriction to the applicability of the model. Second, for the calculation of the risk-adjusted project value, we consider the standard deviation as measure of risk. This two-sided risk measure scales risk as symmetric deviation of the expected value. Likewise, it is conceivable that the model might be adapted to include different risk measures like *Lower Partial Moments* or *Value at Risk* (VaR). In cooperation with our business partners we noticed that especially the VaR might be easier to interpret for decision-makers. Third, we consider linear dependencies between requirements only, as we picture them by a Bravais-Pearson correlation coefficient. Yet realistically, dependencies between requirements in some cases may also be non-linear or there may be n-ary dependencies between requirements. But since this is a complex subject and not satisfactorily solved by academia or practice, it is justifiable to work with this simplifying assumption of linear dependencies in order to derive first results. Beyond these assumptions our model has further limitations as follows. Since the developed approach has only been applied in depth to mobile app development projects and only in parts to three other large scale IT projects, we are yet not able to draw general conclusions about miscellaneous IT projects, varying in context, scope, and size. However, the first results derived from application in practice indicate that for specific kinds of projects, the approach might have to be adjusted in order to reduce complexity of mathematical expense (cf. Beta Cycle). Since detailed calculations can be substituted by more vague estimations, this adjustment can be easily performed, though. In this case, the resulting lack of mathematical rigor might be overcompensated by the increase in practicability. Consequently, the results are worse compared to the mathematical rigor procedure but still better compared to isolated, non-mathematical procedures. As the applicability of this approach in different, varying IT projects obviously is an important issue to practitioners, it is topic to further research and evaluation. This may also be a helpful input for the desired knowledge base.

We presented an integrated approach, combining RE and IT project value quantification in a continuous value-based IT project steering process. This approach enables to derive generalized insights for interval-based estimation, the inquiry of the correlations between requirements, and the determination of the risk-aversion parameter. These insights provide a first basis for further development as it now shall be analyzed, for which kind and size of IT projects the approach is especially applicable. As already described by Sein et al. (2011), such consecutive and sustainable analyzes are parts of the ADR. In this case, they might be of great significance to practitioners as well as to researchers.

III Managing Dependencies to Mitigate Systemic Risk

III.1 Dependencies as Root Cause of Systemic Risk[7]

Recent technological developments associated with changes in customer expectations have required continuous innovation from companies all over the world, thereby driving these companies' IT portfolios towards increasing complexity and interdependency. Simultaneously, existing methods of IT portfolio management are not able to cope with this interconnectedness of IT projects, and too little research has been performed on appropriate risk assessments of dependency structures. By considering such dependency structures as IT project networks, we draw on centrality measures to assess the risk associated with inherent project dependencies. We examine different kinds of centrality measures, whether and to which extent they are able to depict characteristics specific to IT project networks. Based on the most appropriate measure, we derive criticality values indicating projects crucial to the IT portfolio's success. These criticality values should empower companies to successfully manage their IT portfolio.

III.1.1 Introduction

Information technology (IT) has become a critical success factor in many industries. However, despite various planning techniques, there is still a huge number of failed IT projects. In this context, the "chaos report" is often quoted, which states that 80% of all IT projects are only partly implemented or even fail completely (Standish Group, 2013). Moreover, Flyvberg and Budzier (2011) contend that around 16% of IT projects cause on average budget deficits of about 200%. A questionnaire by the Radar Group (2012), surveying 560 IT decision makers in Scandinavia, concludes that one reason for IT project failure is a lack of transparency regarding dependencies. Since IT projects usually are not accomplished in isolation or pairwise but rather within an aggregated portfolio of several IT projects, they incorporate higher-order dependencies (Graves et al., 2003). This becomes even more relevant, as recent technological developments and associated changes in customer expectations force companies to continuously come up with innovations (Nguyen and Mutum, 2012). Consequently, IT projects which previously would have been developed as one coherent solution, are now split into several standalone but interrelated IT services with customer impact, to satisfy the continuous demand for innovation. Therefore, IT project portfolios, henceforth simply

[7] This section is an enhanced version of Wolf (2015), like outlined in Section I.3 and I.4.

referred to as IT portfolios, tend to comprise many small projects rather than a few big ones. This further heightens the need from praxis for a more detailed assessment of risk due to related dependencies.

In addition, literature considers the appropriate assessment of dependencies as a crucial risk during the project-planning phase (Buhl, 2012). Although Kundisch and Meier (2011[b]) assert that compared to the claimed importance of this topic, relatively little research can be found, there are at least some approaches of IT project and portfolio management that tried to incorporate dependencies to some extent (Lee and Kim, 2001; Wehrmann et al., 2006; Kundisch and Meier, 2011[a]; Beer et al., 2013). However, existing methods based on classical portfolio theory are not sufficient to cope with characteristics specific to IT portfolios (Cho and Shaw, 2009). Since the structure of dependencies between projects in an IT portfolio is important for the success of each single IT project (Zimmermann, 2008), each single project can also be crucial to the overall success of the portfolio. This is known as systemic risk and is characteristically based on direct and indirect dependencies within network structures. Therefore, we consider IT portfolios as IT project networks, and present a novel approach drawing on concepts from sociological research instead of classical portfolio theory. By considering projects of an IT portfolio as nodes and dependencies amongst them as arcs, we can analyze the corresponding network based on centrality measures, derived from the mathematical field of graph theory, and strive to identify the most important node of the network (Wasserman and Faust, 1994). Projecting this onto IT portfolios we consequently aim to identify the most critical project of the IT project network. Therefore, we set forth the following research question:

"Can centrality measures be used to assess the criticality of a project to its corresponding IT portfolio, based on inherent project dependencies?"

To answer this question, we assess different kinds of common centrality measures and outline whether and to which extent they can depict characteristics specific to IT portfolios, in order to consider them appropriate. By determining which projects are crucial to the success of the overall IT portfolio, the results should empower companies to take appropriate actions (e.g. reallocation of dedicated resources) in order to successfully manage their IT portfolio. Meredith et al. (1989) proposed a three-stage research cycle for activities in the field of operations research. They cluster research into description, explanation and testing phase. Our research is located in the explanation stage of this cycle, which is supposed to yield first concepts and models from which causal relationships and testable hypotheses can be derived.

The remainder of Section III.1 is organized as follows: Section III.1.2 presents a literature review of different kinds of dependencies in IT portfolios and their current assessment. Section III.1.3 outlines the basic principles of the approach, including preliminary considerations and an application example to facilitate comprehensibility and verify applicability. Finally, Section III.1.4 summarizes, concludes, and depicts the limitations of the approach.

III.1.2 Literature Review

To develop a novel method that properly assesses dependencies and contributes to existing literature, it is necessary to know which kinds of dependencies exist in IT portfolios and how they are currently appraised. Therefore, a keyword (dependency, interdependency, interaction, project, portfolio, information technology, information systems, model, approach, quantification, assessment) based search of different data bases (AIS Electronic Library, EBSCOhost, EmeraldInsight, ProQuest, ScienceDirect, Wiley) was conducted. Since not each database supports the same and/or conjunction of search terms, in some cases the search term has been adapted. To account for different methods and approaches assessing dependencies in varying disciplines, the search term has to be kept at a generic level. Consequently, the resulting set of articles is too large to directly process it. To condense the number of articles we stick to the approach of Kundisch and Meier (2011[b]), including only articles being published in the top journals of the Information Systems, Production and Operations Management, and Project Management disciplines. Subsequently, the articles' titles were conducted to decide whether an article contributes to the research objective or not. If the title did not suffice to decide whether the article properly contributes to the topic, the abstract was examined. By analyzing the articles it became apparent, that some of them, despite the initial impression, did not properly contribute to the research objective and hence had to be excluded afterwards. To complete the search procedure, we did a forward and backward search of citations in the set of relevant articles, like recommended by Webster and Watson (2002).

Based on this investigation we can constitute that in existing IT portfolio literature there are different kinds of dependencies connecting two or more projects. While some articles just mention certain types of dependencies, others try to introduce whole frameworks, structuring different categories of dependencies based on specific characteristics. Like Santhanam and Kyparisis (1996), Lee and Kim (2001), Tillquist et al. (2002), or Zuluaga et al. (2007), most articles in literature present either some or all of the following dependencies: resource, technical, and benefit dependencies. Generally, resource dependencies refer to projects competing for any kind of resources. Technical dependencies most commonly refer to projects competing for technical systems or applications (Santhanam and Kyparisis, 1996). However, technical systems and applications can also be considered as input resources of a project. Therefore, Wehrmann et al. (2006) subdivide resource dependencies into personnel and technical dependencies. In contrast, Kundisch and Meier (2011[a]) introduce a framework subdividing resource dependencies into allocation, performance, and sourcing interactions. Benefit dependencies are also considered as synergies, and can be realized if the benefit of one or more projects increases while being simultaneously implemented with another project. One example could be the reuse of code fragments for two similar software development projects. For further explanations and differentiations of synergies, refer to Cho and Shaw (2009).

Structuring dependencies by characteristics, Wehrmann et al. (2006) and Zimmermann (2008) differentiate between inter-temporal and intra-temporal dependencies. Inter-temporal dependencies refer to projects taking place at different points in time; for example, if a project is based on a preceding one. Intra-temporal dependencies refer to different projects taking place at the same point in time; according to Wehrmann et al. (2006), they involve structural dependencies, which refer to projects that are based on the same processes, IT functionalities or data, and resource dependencies.

Determining how and to which extent dependencies between different projects exist is a topic most commonly left to expert judgment. For such evaluations, scoring systems are often the method of choice (Fischer, 2004; Maheswari and Varghese, 2005; Maheswari et al., 2006). However, the processing of resulting values, henceforth considered as dependencies, is handled differently. While most models in the context of IT portfolio management incorporate dependencies within the risk assessment, there are also some different approaches. Based on the differentiation between intra- and inter-temporal dependencies (Wehrmann et al., 2006), we therefore subsequently briefly depict how current methods of IT portfolio management consider dependencies.

To account for intra-temporal dependencies, Santhanam and Kyparisis (1996) propose a non-linear optimization model, considering resource and technical dependencies as auxiliary conditions to their objective function of selecting an optimized project portfolio based on fixed budgets. Further approaches considering dependencies as auxiliary conditions in an optimization model can be found in works by Lee and Kim (2001) and Kundisch and Meier (2011[a]). Considering dependencies in terms of risk, e.g. Butler et al. (1999), Wehrmann et al.

(2006), and Beer et al. (2013) refer to portfolio theory (Markowitz, 1952) to determine a risk and return optimized IT portfolio. They consider dependencies by correlation coefficients based on covariances of the corresponding IT projects. Verhoef (2002) introduced a modified discounted cash flow method, which evaluates dependencies implicitly while focusing on cost and time risks within the interest rate. Since many of the existing approaches incorporating intra-temporal dependencies consider only dependencies between two different projects or depict them predominantly by financial restrictions, they partially fall short (Zimmermann et al., 2012). Furthermore, some approaches are adopted from financial methods. Therefore, they would have to fulfill specific premises (e.g. portfolio theory), which are however not at all or only partially applicable in the context of IT portfolios. Other methods again feature a very high level of subjectivity (e.g. scoring methods) since they are almost purely based on expert estimations.

Inter-temporal dependencies are most commonly considered based on real option models. In this context, many approaches have been proposed (Dos Santos, 1991; Benaroch and Kauffman, 1999; Taudes et al., 2000; Bardhan et al., 2004) using either the Black-Scholes model or binomial trees. Since these methods are derived from financial option methods and have been adapted to real options, they are considered somewhat inappropriate for evaluation of inter-temporal dependencies in an IT project portfolio context, due to their underlying premises (Emery et al., 1978; Schwartz and Zozaya-Gorostiza, 2003). For a more detailed discussion on whether restrictive premises of financial option methods can be adapted to real options and whether the models can be appropriately used in this context, please refer to (Diepold et al., 2009; Ullrich, 2013).

Based on the previous examination of current methods for IT portfolio evaluation, we can conclude that existing approaches cannot be considered completely appropriate regarding incorporation of dependencies prevailing in IT project networks. Besides, the most important drawback is, to the best of our knowledge, none of the existent IT portfolio management techniques explicitly accounts for transitive dependencies between IT projects. However, an assessment of these transitive dependencies is crucial to an appropriate risk assessment in network-like structures.

III.1.3 Model

Concepts from the sociological research field of social network analysis have recently been applied to several other research areas, such as supply chain management, logistics, and IT landscape management, in order to assess risk originating from dependencies within these network structures (Carter et al., 2007; Kim et al., 2011; Simon and Fischbach, 2013). We interpret IT portfolios as IT project networks, by considering projects as nodes and dependencies amongst them as arcs. Consequently, we can evaluate the adaption of social network measures to the research area of IT portfolios by analyzing the appropriateness of different centrality measures, in order to assess the risk of the portfolio's corresponding IT project network. Centrality measures strive to identify the most important node of a network (Wasserman and Faust, 1994). For IT project networks, we henceforth assume that the centrality values of nodes represent criticality values of projects, indicating their importance to the success of the corresponding IT portfolio, based on the projects' dependencies. Furthermore, we define the success of an IT portfolio as its accomplishment, time- and budget-wise.

III.1.3.1 Modeling IT Portfolios as Networks

The mere assertion that two projects of an IT portfolio are somehow dependent is not sufficient for a company to allocate resources adequately. To do so, the company needs information on the direction of this dependency. Therefore, the IT project network of a corresponding IT portfolio can be visualized as based on directed arcs. An arc pointing from one project to another indicates a dependency of the initiating project (where the arc originates) on the project where the arc ends. To assess the criticality of a project, we consequently focus on incoming instead of outgoing arcs. Furthermore, dependencies between different projects are rarely equally weighted in reality. Ergo, to account for different strengths of dependencies, we presuppose the arcs of an IT project network to be weighted. However, the calculation of such bilateral dependency weightings does not fall under the scope of this research, as we rather focus on how to assess the coherence of these identified dependencies within a network environment. We therefore assume that it is possible to quantify any kind of dependencies for pairwise combinations of IT projects. The validity of this assumption is borne out in theory, as corresponding quantification techniques based on expert judgments and scoring models are already used in the field of IT portfolios (Fischer, 2004; Maheswari and Varghese, 2005; Maheswari et al., 2006).

Before we are able to identify crucial projects by deriving criticality values based on the projects' dependencies, we first need to examine whether and which centrality measures are appropriate to account for the specific characteristics of IT project networks.

III.1.3.2 Requirements to Centrality Measures in IT Project Networks

Since the only prerequisite for the application of centrality measures is the existence of a network composed of nodes and arcs, such measures nowadays are widely applied, although most of them were originally introduced in the social network context (Newman, 2010). However, like social (Landherr et al., 2010) or supply networks (Kim et al., 2011), IT project networks feature specific characteristics that must be considered in order to properly assess the projects' criticality. These characteristics are based on a common understanding of dependencies in IT portfolios. We subsequently outline the underlying logical consideration and derive some simple and generic requirements which a centrality measure must take into account, in order to be considered reasonably applicable in the IT portfolio context and in the context of this research. However, the derived requirements can rather be considered as minimum requirements than as a comprehensive list, and do not feature any kind of prioritization.

There are centrality measures that have been designed for either directed or undirected networks. However, with slight modifications, many of them can be applied to both, directed and undirected networks. As explained above, we can visualize IT project networks as composed of directed arcs. Consequently, an appropriate centrality measure should account for directed relations as stated in the following requirement:

Requirement (Req.) 1: The measurement accounts for directed relations between projects.

Furthermore, we consider four influential factors in order to determine the importance of an IT project to its corresponding portfolio: The strength of the dependencies (a), the number of directly dependent projects (b), the number of indirectly dependent projects (c), and the inherent importance of directly and indirectly dependent projects (d).

Regarding (a), we assume an IT project to be more important if it has strong dependencies to other projects, as opposed to the case where these dependencies are weak. By considering the arcs of an IT portfolio to represent corresponding dependencies, the strength of dependencies can be depicted by weighted arcs. Accordingly, the criticality value should increase with the weighting of arcs or rather the strength of dependencies, as stated in the following requirement:

Requirement (Req.) 2: The result of the measurement for a specific project increases with the strength of relations to dependent projects.

Regarding (b), we expect a project to be more important to its corresponding network if there are many other projects in the network that directly depend upon it. For example, a single project is more important to its corresponding portfolio if it has five other projects which directly depend on it, in contrast with the case where it has just three others directly dependent on it. Assuming arcs represent dependency relations, an appropriate measure should hence consider that the criticality value of a single project increases with the number of relations pointing directly from other projects of the network towards it. This is stated in the following requirement:

Requirement (Req.) 3: The result of the measurement for a specific project increases with the number of directly dependent projects.

Regarding (c), we expect a project to influence the criticality of another project, even though it does not directly but rather indirectly depend upon the other project. Extending the example from above, a single project that has only three directly dependent projects is not necessarily less important than the project which has five directly dependent projects. The importance does not solely depend on the number of directly dependent projects, but also on the number of indirectly dependent projects. Consequently, an appropriate measure should also consider that the criticality of a project increases with an increasing number of indirectly or transitive dependent projects, as stated in the following requirement:

Requirement (Req.) 4: The measurement accounts for transitive dependencies, as the result increases with the number of indirectly dependent projects.

Regarding (d), we additionally expect a project to further influence the importance of another project it depends on, if it has a high importance itself. This means that a project with a dependent project ranked as important has a higher importance to the network itself, as opposed to a project having a relatively unimportant dependent project. Consequently, an appropriate measure should also consider that the criticality of a node with a higher criticality on its own contributes more to the criticality of another node it is dependent on, rather than a node with a lower criticality. This is stated in the following requirement:

Requirement (Req.) 5: The result of the measurement of a specific project increases with the importance of directly and indirectly dependent projects.

Although there are many different centrality measures, we in a first step will only introduce some of the most common ones in the following. In particular we will examine, how and to which extent they account for Req. 1-5, and if they can reasonably be applied in the IT project network context.

III.1.3.3 Examination of Different Centrality Measures

Closeness centrality is a centrality measure that determines the importance or status of a node in a network based on how close a node is to the others in a network (Wasserman and Faust, 1994). The calculation therefore is based on the summed distances of one node e from all other $n-1$ nodes of the network. Considering $d(e,i)$ to represent the shortest path from node e to any other node i, the closeness centrality $C_C(e)$ can be calculated (Sabidussi, 1966). However, since $C_C(e)$ is dependent on the overall number n of nodes in the network, we can derive a corresponding standardized $\overline{C_C}(e)$ (Wasserman and Faust, 1994). Both $C_C(e)$ and $\overline{C_C}(e)$ are depicted in the following equation:

$$C_C(e) = \frac{1}{\sum_{i=1}^{n} d(e,i)}\,, \qquad \overline{C_C}(e) = \frac{n-1}{\sum_{i=1}^{n} d(e,i)} \quad with\ i \neq e \qquad \text{III.1.(1)}$$

This measure is applicable to directed and undirected networks and thus fulfills Req. 1. It also accounts for weighted arcs, which in this case represent distances between adjacent nodes. Since short distances are advantageous for the purpose of closeness centrality, the measurement increases for declining strength of weights and therefore does not fulfill Req. 2. Moreover, it falls short on Req. 3-5, since it neither increases with the number nor the criticality of directly or indirectly dependent projects.

Another measure of centrality, determining the status of a node by how often it is located on the shortest path between all other pairwise combinations of nodes, is *betweenness centrality*. Assuming p_{ij} to be the number of shortest paths connecting any node i and j, and $p_{ij}(e)$ the number of paths containing node e, the betweenness centrality $C_B(e)$ can be calculated (Freeman, 1979). Since also $C_B(e)$ is dependent on the overall number n of nodes in the network, we can derive a corresponding standardization $\overline{C_B}(e)$ as well (Wasserman and Faust, 1994):

$$C_B(e) = \sum_{i=1}^{n}\sum_{j=1}^{n} \frac{p_{ij}(e)}{p_{ij}}\,, \qquad \overline{C_B}(e) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{p_{ij}(e)}{p_{ij}}}{\frac{(n-1)\cdot(n-2)}{2}} \qquad \text{III.1.(2)}$$

$$with\ \ i \neq e, \qquad j \neq e, \qquad j < i$$

Although this measure has been developed specifically for undirected relations, Gould (1987) has shown that it can also be used for directed relations based on geodesics between pairs of entities. Therefore, it fulfills Req.1. However, this measure considers transitive dependencies and thus can be used to analyze which projects are connected over several stages of the IT project network, it does not fulfill Req. 3 and 4, as it does not increase with the number of transitive or directly dependent projects. It also falls short on Req. 2 and 5, since it does not increase for the strength of dependencies or the criticality of dependent projects.

Degree centrality can be calculated based on the number of arcs directly connecting one node of a network to the others. The existence of connections between nodes in the network is depicted in a so-called adjacency matrix, which consequently represents the network structure. This adjacency matrix $\boldsymbol{A}$ in the simplest case contains binary elements a_{ij} with $a_{ij} = 1$ if there is a relation between node $i = 1 \dots n$ and node $j = 1 \dots n$ and $a_{ij} = 0$ if not. By considering the number of nodes a specific node e is linked to, the degree centrality $C_D(e)$ can be calculated. To enable comparability for different network sizes, a standardized measure $\overline{C_D}(e)$ has been proposed similar to closeness and betweenness centrality (Wasserman and Faust, 1994; Newman, 2010):

$$C_D(e) = \sum_{i=1}^{n} a_{ie} \;, \qquad \overline{C_D}(e) = \frac{\sum_{i=1}^{n} a_{ie}}{n-1} \qquad \text{III.1.(3)}$$

By distinguishing between in- and out-degree centrality relating to incoming and outgoing arcs of a node, this measurement is applicable to directed networks and therefore fulfills for Req. 1. Since the measure also increases with the number of directly dependent projects and the strength of dependencies, it also fulfills Req. 2 and 3. However, degree centrality does not account for transitive dependencies and thus does not fulfill Req. 4. It also falls short on Req. 5 since it does not increase with the importance of dependent projects.

In order to account for the phenomenon that more interconnected nodes contribute more strongly to the status of nodes to which they are adjacent, other centrality measures such as the *eigenvector centrality* have been developed (Bonacich and Lloyd, 2001). Assuming $\boldsymbol{v} = (v_1, \dots, v_n)^T$ to be an eigenvector for the maximum eigenvalue $\lambda_{max}(\boldsymbol{A})$ of the adjacency matrix $\boldsymbol{A}$, the eigenvector centrality $C_E(e)$ for a node e is defined as follows (Bonacich and Lloyd, 2001):

$$C_E(e) = v_e = \frac{1}{\lambda_{max}(\boldsymbol{A})} \cdot \sum_{j=1}^{n} a_{je} \cdot v_j \qquad \text{III.1.(4)}$$

With $\boldsymbol{A}^T$ being the transposed matrix of the adjacency matrix $\boldsymbol{A}$, the respective matrix representation of Equation III.1.(4) can be derived:

$$\boldsymbol{A}^T\boldsymbol{x} = \boldsymbol{x} \qquad \text{III.1.(5)}$$

Eigenvector centrality quantifies to which extent nodes are related to others within the same network (Bonacich and Lloyd, 2001). For each node that depends upon another, it weights the corresponding binary value in the adjacency matrix $\boldsymbol{A}$ by the eigenvector centrality of the dependent one. When this concept is applied to IT project networks, the binary value, indicating whether a project i is dependent on another project j, is weighted by the criticality value of project j. Since this measure has been developed for directed networks, it fulfills Req. 1. It also fulfills Req. 2, since it increases with the strength of dependencies. By calculating eigenvector centrality for a specific node, the value theoretically also increases with the number of directly and indirectly dependent nodes, as well as with their criticality. However, as the status of a node is solely influenced by its relations to other nodes, this method has a major drawback: If a node has no incoming relations from others, its status equals 0 and it therefore does not contribute to the importance of other nodes (Bonacich and Lloyd, 2001). Therefore, this measure in fact fulfills Req. 5, but falls short on Req. 3-4.

To account for this drawback, eigenvector centrality has been further enhanced and some derivatives have evolved. One of these derivatives introduced by Bonacich and Lloyd (2001), is *alpha centrality*:

$$\boldsymbol{x} = (\boldsymbol{I} - \propto * \boldsymbol{A}^T)^{-1} * \boldsymbol{e} \qquad \text{III.1.(6)}$$

This centrality measure overcomes the mentioned drawback of eigenvector centrality by assigning an exogenous status to each node of the network. In Equation III.1.(6) this exogenous status is represented by the vector $\boldsymbol{e}$. This vector theoretically enables the ability to account for influences like project budged, which determine the exogenous status of different nodes to different extents. However, as the assessment of a project´s exogenous status is not in scope of this elaboration but rather a topic for further research, we stick to the work of Bonacich and Lloyd (2001), who exemplarily considered $\boldsymbol{e}$ as a vector of ones. Consequently, the initial (exogenous) status of each node of the network is set to 1, independent of its relations to other nodes. The remaining elements of the equation are the identity matrix $\boldsymbol{I}$, the transposed adjacency matrix $\boldsymbol{A}^T$ and the scalar $\propto > 0$, representing a ratio for the relative relations between the exogenous (assigned) and endogenous (inherent) status of the nodes. Consequently, if $\propto$ is close to its lower boundary 0, the corresponding centrality values are close to the exogenous status of the nodes. In contrast, if $\propto$ is close to its upper boundary $\frac{1}{\lambda_{max}(\boldsymbol{A})}$, where $\lambda_{max}(\boldsymbol{A})$ represents the maximum eigenvalue of $\boldsymbol{A}$, the corresponding centrality values are almost exclusively based on the endogenous status, or rather on the network or relation structure.

Since this measurement in contrast to eigenvector centrality indeed increases with the number of each directly and indirectly dependent node, it not only accounts for Req. 1, 2, and 5, but also for Req. 3 and 4. Moreover, it features the possibility of including exogenous influences like project size or volume. Therefore, we consider this measure as appropriate for the criticality assessment of projects in the sense of this research. Table III.1-a summarized the results regarding the appropriateness of the five requirements for all examined centrality measures in this section.

Table III.1-a - *Examination of centrality measures - Summary*

Centrality Measure	**Req. 1**	**Req. 2**	**Req. 3**	**Req. 4**	**Req. 5**
Closeness Centrality	✓	–	–	–	–
Betweenness Centrality	✓	–	–	–	–
Degree Centrality	✓	✓	✓	–	–
Eigenvector Centrality	✓	✓	–	–	✓
Alpha Centrality	✓	✓	✓	✓	✓

III.1.3.4 How to Assess Critical Projects based on Alpha Centrality

Presuming that dependencies between IT projects can be quantified, and considering these to equal network alike structures, alpha centrality allows the derivation of an interpretable criticality value indicating an individual project's importance to the overall success of the IT project network. In doing so, it not only accounts for direct dependencies, like the number of directly dependent projects, but also for indirect or transitive dependencies. To facilitate the comprehensibility and illustrate the suitability of alpha centrality in an IT portfolio context, this section briefly introduces the basic principles of the measurement using the three simple topology examples shown in Figure III.1-a.

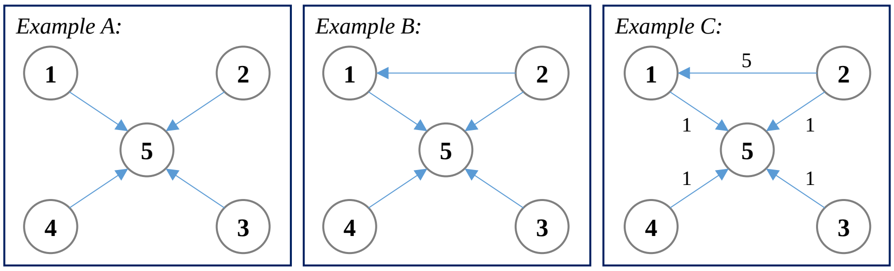

***Figure III.1-a** - Examples of simple IT project network topologies*

Alpha centrality uses an $n \times n$ adjacency matrix $\boldsymbol{A}$ whose elements a_{ij} with $i, j = 1 \dots n$ represent the connections of the network and consequently the projects' dependencies. Considering arcs as unweighted, each element a_{ij} represents a binary value indicating whether project i is directly dependent on project j or rather whether i contributes to the criticality of j. In the case of weighted arcs, each element a_{ij} represents the weight of the corresponding dependency relation between i and j.

In the following, the binary adjacency matrices of example A and B are depicted, as well as the weighted adjacency matrix of example C.

$$\boldsymbol{A}_A = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \boldsymbol{A}_B = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \boldsymbol{A}_C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 5 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

In example A, project 1, 2, 3, and 4 depend on project 5. Consequently, one would assume the latter as most important, or rather most critical to the success of the overall IT portfolio, and therefore to account for the highest alpha centrality value. Assuming $\boldsymbol{e} = [1, 1, 1, 1, 1]$ to be a vector of ones and based on the corresponding adjacency matrix $\boldsymbol{A}_A$, we can calculate the alpha centrality vector $\boldsymbol{x}^T = [1, 1, 1, 1, (1 + 4 \propto)]$ according to III.1.(6). This vector verifies the presumed result.

In contrast to example A, project 2 additionally is dependent on project 1 in example B. In this case, one would expect a direct increase in importance of project 1 and an indirect increase in importance of project 5, as the status of project 1 increases and therefore contributes more to the status of project 5. The corresponding alpha centrality vector $\boldsymbol{x}^T = [(1+\propto), 1, 1, 1, (1 + 4 \propto + \propto^2)]$ is in line with the expectations.

While examples A and B implicitly assume equal intensities of the existing dependencies, example 3 includes different intensities represented by weighted arcs. Representing the logical weighted extension of the one in example B, the alpha centrality vector of this example is $\boldsymbol{x}^T = [(1 + 5 \propto), 1, 1, 1, (1 + 4 \propto + 5 \propto^2)]$.

III.1.3.5 Application Example

To demonstrate how this procedure can be used in practice, we illustrate the application with an example. Since we were not yet able to gather corresponding data, the intensities of project dependencies are assumed in this example. However, the other circumstances are based on real world observations. In our case, the company incorporates an in-house IT provider that recently changed its software development process from the waterfall model to a release-oriented model. As a result, its current IT portfolio includes some projects that actually are sub-projects of an ensemble, which due to innovation pressure has been subdivided into several standalone projects. Hence, the portfolio features a high level of dependencies, and overall includes 15 projects, ranging from small infrastructure to big software development projects, all of which must be implemented within the next five years. In this context, the company faces the question of how to allocate its limited resources in order to accomplish the portfolio on time and under budget. Therefore, a risk analysis shall be conducted in order to identify the projects most critical to the IT portfolio, due to its inherent dependencies. To do so, the company first needs to identify and quantify the dependencies between the projects; this is usually accomplished based on interviews with the IT portfolio manager and other experts from the project management office (PMO). In this example, the resulting values have been normalized to range from 0 to 1, and the corresponding dependency structure of the portfolio is shown in Figure III.1-b.

Based on this dependency structure, we derived an adjacency matrix $\boldsymbol{A}$ denoting whether and to which extent the projects are related to each other. Each element $a_{ij} > 0$ of this $n \times n$ matrix indicates that project i is dependent on project j. For the calculation of an alpha centrality value based on III.1.(6), we assumed the vector $\boldsymbol{e}$ to be a vector of ones. Since we rather wanted to examine the criticality of projects based on their dependency structure than on their exogenous status, the scalar $\propto$ has been set to its upper boundary value $\frac{1}{\lambda_{max}(\boldsymbol{A})}$, with $\lambda_{max}(\boldsymbol{A}) = 0{,}8243$. Based on III.1.(6) we were able to derive criticality values for each project, listed in Table III.1-b.

Thus, the most critical projects in descending order are projects 4, 8, 3, 15, 14, 12, 11, 7. This is logical, since project 8 that at a first glance seems to be the most critical one, as it receives many relations from other also critical projects (3, 7, 11, 12, 14, 15), is dependent on project 4. Therefore, project 4 is even more critical than project 8. In this example project 4 is considered to be a small infrastructure project of low volume whereas project 8 represented a software platform project with a huge volume.

***Table III.1-b** - Example results*

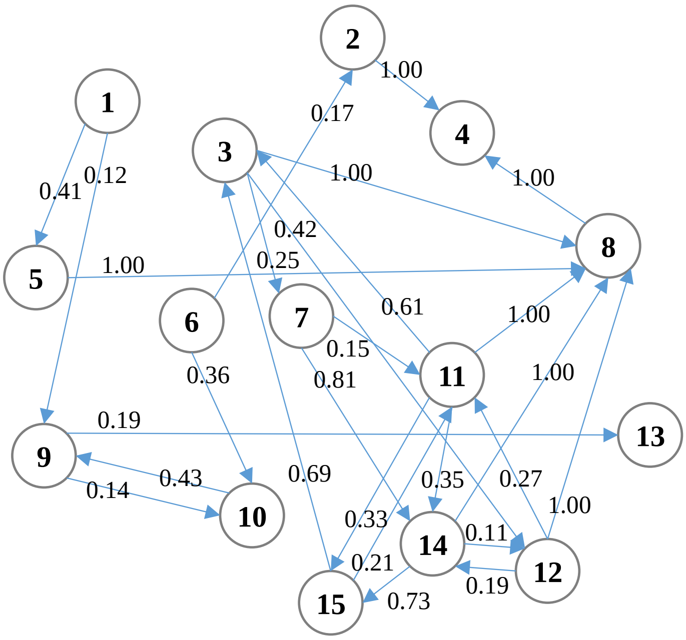

***Figure III.1-b** - Example: Dependencies of an IT portfolio*

Nr.	$\frac{1}{\lambda_{max}(\boldsymbol{A})}$
1	0.0000
2	0.0000
3	2.0381
4	8.4092
5	0.0000
6	0.0000
7	0.6285
8	6.8178
9	0.0000
10	0.0000
11	0.9340
12	1.2350
13	0.0000
14	1.3205
15	1.5691

Although this is just a very simple example, it illustrates the importance of dependency assessment quite well, as e.g. an allocation of resources based solely on project volume, as well as an inaccurate assessment of dependencies, would probably have led to a failure with regard to time or budget of the IT portfolio.

III.1.4 Summary, Conclusion, and Limitations

The increasing demand for continuous innovations forces companies all over the world to assemble IT portfolios containing a high level of dependencies, while lacking appropriate methods to manage these dependence structures, as traditional methods rather focus on cost and benefits than on the accurate assessment of direct and indirect dependencies. In order to empower companies to cope with the challenging task of successfully managing their IT portfolios, we explicitly focus on the assessment of the inherent dependency structure and derived a new procedure to assess the criticality of projects based on their dependencies. We therefore consider IT portfolios as IT project networks and draw on graph theory, as it is an approved means for the assessment of dependencies in network alike structures. In particular, we illustrate specific characteristics of IT project networks and evaluate different centrality measures regarding their appropriate applicability in this context. In doing so, alpha centrality was revealed as being a valuable approach in determining risk assessment of IT portfolios. It not only accounts for direct but also transitive dependencies, and shows that more critical projects contribute more strongly to the criticality of other projects they depend on. We depict the suitability of this measure based on its basic principles, and consequently propose an alpha centrality based assessment of dependencies to identify projects crucial to the success of the overall IT portfolio. To facilitate the comprehensibility and to verify the proposed procedure, we examine an exemplary IT project network based on its dependencies. The plausible results of the example application indicate that the proposed procedure is appropriate to analyze the dependencies between IT projects, and to assess their criticality to the overall portfolio's success. It furthermore highlights the practical implications of empowering companies to properly assess direct and indirect dependencies in their portfolio, as both common methods in practice as well as an inaccurate assessment of dependencies can lead to ill-considered decisions. Furthermore, the results especially emphasize that consideration of transitive dependencies is crucial for an appropriate risk analysis of IT project networks.

However, this approach is not without limitations and provides topics for further research. Referring to the three-stage cycle for research activities of Meredith et al. (1989), we were not yet able to proceed from the explanation to the testing stage based on a real-world example, despite various efforts to gather data. We are currently in communication with a large IT consulting company in order to get data for the evaluation of a real-world example, which will lead to further research. Moreover, we do not explicitly consider different kinds of dependencies; however, this is considered acceptable as a first step, and the differentiation between various kinds of dependencies is a topic for a follow-up research. Furthermore, this approach explicitly assumes that for a pairwise combination of IT projects, any kind of dependency can be quantified. Although, there are already some approaches quantifying different kinds of dependencies, further research should be encouraged to investigate appropriate measures in this respect. By assigning an initial status to each node of the network, independent of the networks dependency structure, this approach accounts for exogenous influences to the project's importance. Since determination of these exogenous influences is not in scope of this elaboration, they are assumed to be equally strong. However, exogenous influences, such as project budget or mandatory requirements, can determine a project's importance to different extent in the real world. Therefore, continuing research is required to include these kind of influences in a comprehensive risk assessment of IT project networks.

III.2 Assessing the Propagation and Impact of Systemic Risk[8]

Global supply networks that can be considered as interlaced supply chains are shaping existing economic structures. These supply networks are creating a high level of complexity. Simultaneously, the perceived number of exogenous shocks such as natural disasters is increasing. These exogenous shocks can directly or indirectly impact the participating companies of a supply network, which can also threaten the network as a whole. However, the complexity and opacity of today's supply networks inhibit an accurate prediction and quantification of such impacts. Therefore, companies are unable to develop adequate safeguards, while existing mechanisms are insufficient. The objective of this study is to model, analyze, and quantify the impacts of exogenous shocks on supply networks. Therefore, we use a Petri Net-based approach, which enables a simulation of different supply network constellations, to assess the vulnerability to exogenous shocks. Furthermore, we include a detailed description of modeling and evaluation of the presented method. For an exemplary supply network, we simulate different intensities of an exogenous shock combined with different safety stocks of the entities. Statistical tests are conducted to verify the results. We thereby illustrate the results that could be yielded from a real-world application.

III.2.1 Introduction

Global supply networks are shaping the economic structures today (Christopher and Lee, 2004). Such supply networks can be considered as interlaced supply chains (Harland, 1996; Lamming et al., 2000). These structures are building up a high level of complexity and inherit many advantages (e.g., more flexibility in supplier decisions) (Blackhurst et al., 2005) as well as risks for the participating companies. The emerging dynamic interdependencies not only increase one company's exposure to risk (Hallikas et al., 2004) but can also threaten the entire network (Rice and Caniato, 2003). This phenomenon is known as systemic risk. The financial crisis of 2008/2009, when the collapse of few financial institutions spread over the entire network of financial systems and the real economy, is only one example. Supply networks are also becoming increasingly vulnerable to the impacts of exogenous shocks (Wagner and Neshat, 2010). As of 14 November 2011, the Bangkok Post listed on its website that in the first half of 2011, Thailand accounted for about 45% of the worldwide hard disk drive (HDD) supply in the first half of 2011. The widespread flooding in Thailand in October/November 2011 directly impacted almost 30% of this capacity. Hence, as of 8 November 2011, iSuppli

[8] This section is a slightly modified version of Fridgen et al. (2015), like outlined in Section I.3 and I.4.

listed on its website that the affected companies all over the world experienced shortages in the HDD supply. Such natural disasters as well as other stochastic events like economic crises or resource shortages are considered as exogenous shocks in the context of this research. These incidents are able to affect the miscellaneous entities of a supply network in a positive or negative manner. An exogenous shock that directly impacts at least one entity, can indirectly influence other entities due to its propagation through the supply network. In case of competing entities, a direct negative impact on one entity can even lead to indirect positive influences on others. Hence, even if a company is not directly impacted by an exogenous shock, it may be threatened existentially due to the network structure.

In order to diversify the risk of disruptions as far as possible, many manufacturers keep contractual relationships with different suppliers (Babich et al., 2007). Suppliers in the context of this research are considered to be either resource suppliers or manufacturers of intermediate products in the different upstream stages of the supply network. Nevertheless, the complexity and complementing direct and indirect dependencies of these suppliers can lead to disruptions of the entire supply network even despite a perceived diversification in the preceding stages (Buldyrev et al., 2010; Friesz et al., 2011). Also from a geographical perspective, global supply networks are often not as diversified as they might seem. Some levels of supply networks, e.g. the production of specific components, can be very concentrated in several industrial sectors. For instance, as of 21 October 2011, ZEIT-online listed on its website that, for instance, manufacturers focusing on the same industry niches are usually located in the same area as the necessary infrastructure and know-how are in place. Besides the already mentioned examples of concentration, namely, HDD production in Thailand and high tech industry in Silicon Valley, ZEIT-online furthermore listed on its website that another example is the exclusive production of synthetic resin in the north of Japan, accounting for about 90% of the global supply. Also, geographical circumstances like the natural occurrence of resources can be a reason for the convergence, as for instance, 97% of the global supply of rare earth metals is mined from China (Lewis et al., 2011). A natural disaster in such an area could not only affect the supply networks of a specific industrial branch but also the entire economy. Indeed, the flooding of Thailand and the big earthquake in Japan in the March of 2011 showed how fragile global supply networks are to such disruptions. For instance, as of 12 November 2011, iSuppli listed on its website that after the earthquake in Japan, when many manufacturers recognized the need for missing machinery parts, they were not able to immediately identify the responsible company due to the lack of information on the upstream suppliers.

Meredith et al. (1989) proposed a three stage cycle for research activities in operations research. They cluster research into description, explanation, and testing phase. In this spirit our research is located in the explanation stage of this cycle. This stage is supposed to yield first concepts and models from which causal relationships and testable hypotheses can be derived. This research supports the information evaluation process in order to draw conclusions on the structure and condition of supply networks. We introduce a feasible approach that enables the simulation of different compositions of supply networks impacted by distinctive exogenous shocks. These compositions can be quantitatively evaluated to reduce weaknesses and bottlenecks. Furthermore, the approach visualizes different entities, their linkages, and the network structure. The results should empower companies to take adequate actions in order to stabilize their supply networks (not exclusively) against exogenous shocks. For simplification, we assume all necessary information to be available.

This work is a revised and enhanced follow up on Fridgen et al. (2012), which has been published at the 20th European Conference on Information Systems. Beyond the existing publication, it includes detailed explanations, a detailed modeling description, and an evaluation of the presented method by statistical means.

The remainder of Section III.2 is organized as follows. Section III.2.2 presents the literature review. Section III.2.3 specifies the language and characteristics of the model that form the basis for the analysis of supply networks. In Section III.2.4, we describe the modeling procedure. Section III.2.5 illustrates a simulation-based analysis of an exemplary supply network. Section III.2.6 summarizes and concludes the study.

III.2.2 Literature Review

Managers tend to handle the impacts of shocks on supply networks as one-time events rather than an inadequacy in the supply network structure (Levy, 1995). Even if shocks are one-time events, they nevertheless can threaten the existence of a company and are able to uncover the structural weaknesses of supply networks.

In the following literature review, we will first give a brief overview of the literature regarding shocks in general. Afterwards, we will focus on shocks, risk, and uncertainty in the context of supply networks. The modeling of shocks on supply networks leads us to the different application areas of Petri Net variants.

Regarding shocks in general, Dow (2000) emphasizes that besides the propagation mechanisms, the origin of shocks is also important as internal firm factors and other ascendancies can amplify the small shocks into bigger shocks, spreading over the entire system. Shocks on complex networks and systems with memory are discussed by Sornette et al. (2004) and Sornette and Helmstetter (2003), distinguishing between endogenous and exogenous shocks. Demirgüç-Kunt and Detragiache (2005), Claessens et al. (2010), Campello et al. (2010), and Cetorelli and Goldberg (2011) discuss exogenous shocks as a cause for systemic bank distress. Considering shocks in the context of systemic risk, Buldyrev et al. (2010) discuss shocks as a trigger for a cascade of failures in interdependent networks.

One exemplarily category for interdepend networks being exposed to shocks are supply networks. Since they inherit various uncertainties, Blackhurst et al. (2004) describe potential methodologies to model uncertainty in supply chains, and suggest a network-based approach to retain important information. Moreover, Prater (2005) provides a framework for different types of uncertainties that impact the supply networks. Vidal and Goetschalckx (2000) handle uncertainties in logistic systems by developing mixed integer models (MIP), which are also used by Tsiakis et al. (2001). Focusing on uncertainty as the root cause for disruption, Trkman and McCormack (2009) suggest a framework for the assessment of supplier risk. A methodology to assess operational and accidental risks in process industry projects is presented by Sharratt and Choong (2002). Blackhurst et al. (2008[b]) introduce a multi-criteria scoring procedure to assess and monitor supplier risk in the automotive industry. Hallikas et al. (2002) illustrate a risk analysis for production networks, whereas Harland et al. (2003) focus on the influence of complexity, globalization, and outsourcing on risk and its changing location in the supply network. Regarding disruption risk management in supply networks, Kleindorfer and Saad (2005) provide a conceptual framework reflecting the activities of risk assessment and mitigation. Lu et al. (2011) consider product substitution to mitigate disruptions in supply chains. Wagner and Bode (2008) classify disruptions by different sources based on the distinction between materialization inside or outside the supply chain. Nair et al. (2009) use cellular automata to simulate and examine cooperation and defection patterns in supply networks, as well as underlying decisions and incentive schemes. They highlight and prove the importance of managing interdependencies among firms in supply networks to reduce risk. Hallikas et al. (2004), furthermore, notice that the accumulation of dependencies between companies leads to an increased exposure to risk. Considering supply networks topologies as another root cause for disruption risk, Nair and Vidal (2011), Peng et al. (2011), and Zhao et al. (2011) use varying metrics to examine supply network topologies and their resilience regarding disruptions. Kim et al. (2011) apply key social network analysis metrics on supply networks in order to identify and evaluate central nodes. Mizgier et al.

(2013) propose and evaluate different centrality measures regarding advantages and disadvantages to identify bottlenecks in supply networks. In order to measure the impact of risk and disruptions on supply network performance, Mizgier et al. (2012) study the performance of supply chain networks based on their collective dynamics. Moreover, Friesz et al. (2011) explore a supply network based on a complex dynamic Nash game, considering disruptions and the related risk and uncertainty by variance. Cigolini et al. (2011) introduce a simulation meta-model as decision support system to improve supply chain performance. In order to quantify the propagation of disruptions in supply chains, Wu et al. (2007) were the first to develop a Disruption Analysis Network (DA_NET) approach based on Petri Nets, which enables the adherence of different attributes, like stock or cost, to state and event nodes. Based on these considerations, Zegordi and Davarzani (2012) proposed a colored Petri Net (CPN)-approach, extending the one of Wu et al. (2007) by considering dependencies between different disruptions.

Besides the numerous extensions and modifications of Petri Nets, there has been an extensive discussion on their application areas. In this regard, many articles have been published on the production and manufacturing processes of Petri Nets models. For example, Dubois and Stecke (1983) use Petri Nets to analyze control problems of production systems and Silva and Valette (1990) constitute the usage of Petri Nets to support the production area in general. In the last few years, Petri Nets have also been successfully applied to model and analyze supply chains. For example, Dong and Chen (2001) analyze manufacturing supply chains based on object-oriented Petri Nets. Using stochastic Petri Nets (SPN), Arns et al. (2002) propose a performance analysis for supply chain models. Desrochers et al. (2003) use complex-valued tokens to increase the descriptive abilities of ordinary Petri Nets to model supply chains. Fung et al. (2003) develop an XML-supported modular Petri Net-based approach to denote the workflow in supply chains. Blackhurst et al. (2004) reflect uncertainty in supply chains using a Petri Net-based model. Furthermore, Blackhurst et al. (2008[a]) use a hierarchical Petri Net extension to discover and predict supply chain conflicts. Considering a scattered supply network, Dotoli and Fanti (2005) suggest a generalized SPN approach to model the management of distributed manufacturing systems (DMS). .

To investigate in and derive insights from complex systems of interrelated entities in dynamic environments, many frameworks and theories with different labels have been published. One of these, is the principle of Complex Adaptive Systems that represent networks of multiple interacting entities exhibiting adaptive actions to endogenous and exogenous environmental changes (Choi et al., 2001). Since supply networks have increasingly developed to complex systems being shaped by dynamic interactions between autonomous entities over the last decades, the principles of Complex Adaptive Systems have been adopted on the context of complex dynamic supply networks (Pathak et al., 2007). Based upon this, many methodological enhancements like agent-based-modeling, cellular automata, or system dynamics have been derived (Pathak et al., 2007), of which especially agent-based-modeling has attracted a lot of attention in recent years. This approach aims to answer the question how the collective behavior of a system arises from interactions among autonomous agents (Mizgier et al., 2012) and therefore is considered as an appropriate methodology to model and simulate supply networks. Although there are many ways to investigate such questions regarding the behavior of dynamic systems and interactions, simulation has been successfully proofed in this context (Gupta, 1997; van der Zee and van der Vorst, 2005). Kleijnen and Smits (2003) distinguish four kinds of simulation methods: spreadsheet simulation, business games, system dynamics and discrete-event dynamic systems simulation. Since the objective of this research is to visualize and quantify the impacts and propagation of exogenous shocks, which are rather discrete events, we stick to the discrete-event dynamic system simulation. One possible method in this context is an approach based on Petri Nets. Due to its mathematical foundation and graphical visualization, Petri Net-based methodologies have been shown to be an appropriate tool for modeling dynamic systems (Wu et al., 2007). In this research we use a modified and enhanced Petri Net-based approach of Wu et al. (2007), introducing a modular Petri Net concept where each module represents one entity or agent of a supply network. Based on these modifications we again consider different interacting entities in a complex system, each being represented by its own underlying Petri Net. Therefore, in our opinion, the presented approach can be considered as an agent-based-modeling-approach in the sense of Bonabeau (2002).

Though different Petri Net variants and their application areas have been intensively discussed, there has been little research on using Petri Nets to analyze and simulate the impact of exogenous shocks on supply networks. This research field remains relatively untouched to the best of our knowledge. Therefore, we introduce an approach to visualize, simulate, and analyze the impact and propagation of exogenous shocks on supply networks. Our model extends the valuable DA_NET approach of Wu et al. (2007), which enables the quantification of disruptions on straightforward supply chains. Since the modeling of supply network characteristics, stochastic elements, and the dynamic simulation of multiple order cycles require some additional features, we need to modify DA_NET approach, though. Comparing the proposed method to other previously published models, Cigolini et al. (2011) for instance, provide an object-oriented simulation meta-model to improve supply chain performance. They consider single-product supply chains only, and materials and orders can only be exchanged between two actors belonging to adjacent supply chains. Our approach in contrast rather aims to visualize and quantify the impact and the propagation of exogenous shocks on the single entities of a complex supply network than supply chain performance. It furthermore enables the handling of various (upstream-)products and supports interactions among agents belonging to non-adjacent stages of the supply chain.

Rossi and Pero (2012) provide a timed attributed Petri Net-based approach, identifying and assessing risky events in supply chains on an operational level. They use Petri Nets to create a model of the supply chain. Afterwards, they use the coverability graph of this Petri Net to identify the transition sequences causing disruptions. Moreover, based on the number of disruptions caused by specific transition sequences, they assess the underlying risky events by statistical means and derive tested statements regarding their relative importance. In contrast, we examine the impact and propagation of specific exogenous shocks instead of investigating endogenous risky events based on transition sequences. Moreover, we do not focus just on the operational level but consider shocks taking place on different risk levels of logistic networks. In our experience, when facing an exogenous shocks like natural disasters on their supply network, the information of interest for a single company is to exactly quantify the consequential impact rather than to measure the overall network performance. Therefore, in contrast to previously published models, our method focuses on the quantification and propagation of shock impacts on any entity in a supply network, independently of the shocks' occurrence or the entities' position at the stream of the supply network. Moreover, the developed method provides the possibility to measure the impact of an exogenous shock in various terms like the number or length of disruptions or the change in prices. Furthermore, based on the proposed approach, simulations of various shocks on different supply network constellations can be performed to examine different supply network topologies regarding weaknesses and bottlenecks. However, to test and evaluate the method in a first step, we examine and simulate one exemplary supply network using statistical means to conclude about the plausibility of examination results.

III.2.3 Modeling Language

We assume that supply networks are characterized by flows of order and material between the participating companies. These companies are referred to as different entities of the network in the following study. Wu et al. (2007) contemplated an unidirectional flow of material and goods in a supply chain. In addition, we consider recurring bidirectional flows of materials and orders in a dynamic environment of miscellaneous entities. These flows can represent different supply chains. Therefore, we use the expression supply network. To establish a circular flow situation with Petri Net elements (a general description of Petri Nets can be found by Murata (1989)), the operation represented by a transition needs to transfer a specific number of units from its input to its output place. Wu et al. (2007) perform a one-time calculation of the supply chain output to get information on the effects of disruption on its outcome. Therefore, the DA_NET approach calculates values for the output places of a specific fired transition only. Thus, the result of one calculation step in DA_NET is a matrix denoting just the attributes of the output places. Consequently, for Wu et al. (2007) it was not necessary to save the information on the attributes of the input places after the adjacent transition was fired. Within our approach, this information becomes compulsory when simulating multiple order cycles, as each succeeding cycle needs the information on the modified input values after the preceding cycles. Besides, each place has to be considered for a general idea of the network condition.

Generally, Petri Nets enable the simulation of different states of a system by converting the network into a mathematical equation (van der Aalst et al., 2000). As the basic elements of classical Petri Nets (Petri, 1962) are not sufficient to model complex types of nets, we apply some existing extensions thereby fulfilling the following requirements:

(1) Contemplating specific characteristics of miscellaneous materials.
(2) Reflecting different input/output ratios for different production operations.
(3) Handling stochastic events.
(4) Featuring capacity restrictions.
(5) Including timing aspects.
(6) Involving modularization to tackle complexity.

As similar requirements have been aroused for different application areas, appropriate Petri Net enhancements have already been developed (Drees et al., 1987). Regarding requirement (1), a development of the last decades was the transformation to so called high-level Petri Nets, featuring several types of tokens, each able to carry complex information (Jensen, 1991). Genrich and Lautenbach (1979) introduce predicate/transition-nets (Pr/T-nets). In order to handle technical problems by applying the method of place-invariants to the Pr/T-nets, Jensen (1981) develops a Colored Petri Net (CPN) approach by introducing different colors for different kinds of tokens (Jensen, 1987). Extending CPN with time, van der Aalst (1993) presents the interval timed CPNs. In terms of practicality, Kristensen et al. (1998) present their practitioner's guide to CPN. Lakos (1995) enhances CPN in order to include object-oriented concepts. This approach is called Object Petri Nets. Another method is the DA_NET approach of Wu et al. (2007), wherein attributes are attached to place and transition nodes instead of moving colored tokens through the network. Regarding requirement (2) and (4), weights are added to the initial arcs and capacity constraints are added to the initial places (Murata, 1989). Regarding requirement (3), Molloy (1982) uses SPNs for the purpose of performance analysis whereas Marsan et al. (1984) present the general SPN approach in order to evaluate system performance. Furthermore, Marsan (1990) gives an introduction to SPNs in general. Regarding requirement (5), adding time features to the original Petri Net modeling language has been a major research area (Berthomieu and Diaz, 1991). In this regard, for example, Ramchandani (1974) develops a timed Petri Net approach by associating a lead-time with each transition. Merlin (1974) and Merlin and Farber (1976) present time Petri Nets, in which a lower time bound a and an upper time bound b is associated with each transition. Regarding requirement (6), Dotoli and Fanti (2005) consider a modular Petri Net approach to be an appropriate methodology to model DMS. Based on the concepts of the modular Petri Net markup language, Kindler and Petrucci (2009) formalize a minimal version of modular high-level Petri Nets.

Our approach uses weighted arcs to reflect the variety of material quantities and order volumes. It uses places with capacity constraints to depict limited capabilities and resources. Furthermore, transitions associated with firing conditions are used to govern the firing process. To fulfill the requirement of representing distinctive characteristics of order and material flows, we stick to the approach of Wu et al. (2007) by attaching attributes to place and transition nodes. Regarding time features, this elaboration sticks to the flexible approach of time Petri Nets. It considers stochastic elements by enabling a random distribution function for firing the transitions with $a \neq b$ and $b \neq 0$. Furthermore, it considers consumer demand to be stochastic.

An advantage of Petri Nets is the possibility of an intuitive graphical depiction. Furthermore, the scalability and flexibility offer a great area of application. The major advantage of Petri Nets, however, is their mathematical basis, which allows to break them down to specific subnets and analyze each subnet separately. The concrete mathematical system of the approach used in this research is outlined in the following.

III.2.3.1 Mathematical System

The following mathematical definitions enable the quantitative modeling of the supply network and are basic principles for the simulation results at the end of this research. The parameters used and corresponding descriptions are illustrated in Table VI.2-a in the appendix. Each Petri Net is composed of places, transitions, and arcs. Transitions are activities, which change the attributes of their adjacent places. There are n transitions t_j with $j = 1 \dots n$ and m places p_i with $i = 1 \dots m$, each having specific properties. Besides, there are arcs connecting the places and transitions. We consider every transition t_j and every place p_i to have defined attributes d_{lj} with $l = 1 \dots L$ and c_{ki} with $k = 1 \dots K$ respectively. Hence, each transition t_j has an attribute set $\boldsymbol{D}_j = [d_{1j}, d_{2j}, \dots, d_{Lj}]$. The attribute set $\boldsymbol{C}_k = [c_{k1}, c_{k2}, \dots, c_{km}]$ denotes the value of one specific attribute c_k for each place p_i. For multiple attributes c_k, this consequently leads to a $K \times m$ - matrix $\boldsymbol{C}$ where each column represents the attributes of one place.

$$\boldsymbol{C} = \begin{bmatrix} c_{11} & \cdots & c_{1m} \\ \vdots & \ddots & \vdots \\ c_{K1} & \cdots & c_{Km} \end{bmatrix}$$

Next, we derive a $m \times n$ - matrix $\boldsymbol{Z}_k$ for each attribute c_k, which depicts the modification of the underlying attribute caused by transition t_j for each place p_i. This modification is depicted as numeric value, which, for instance, can be derived from a function $f_j(c_{ki}, d_{lj})$ relating the attributes c_{ki} of the places with the attributes d_{lj} of the transitions.

$$\boldsymbol{Z}_k = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{m1} & \cdots & z_{mn} \end{bmatrix}$$

Each transition t_j has a decision logic E_j, which decides whether a transition is fired or not. It can be denoted as E_j = IF (constraint) THEN (consequence).

Arcs can be divided into two subsets. The subset consisting of arcs pointing from places P to transitions T is defined as $P \times T \rightarrow N$ and denoted by $Pre(p_i, t_j)$. The other subset, which consists of arcs pointing from transitions to places, is defined as $T \times P \rightarrow N$ and denoted as $Post(t_j, p_i)$. The binary variables $Pre(p_i, t_j)$ and $Post(t_j, p_i)$ equal 1, if there exists a specific arc between t_j and p_i, otherwise they equal 0. The input places of a transition t_j are identified by monitoring the values of $Pre(p_i, t_j)$ in an $m \times n$ - input matrix $\boldsymbol{I}$, while the output places are obtained in a $m \times n$ - output matrix $\boldsymbol{O}$ containing all $Post(t_j, p_i)$.

$$\boldsymbol{I} = \begin{bmatrix} Pre(p_1, t_1) & \cdots & Pre(p_1, t_n) \\ \vdots & \ddots & \vdots \\ Pre(p_m, t_1) & \cdots & Pre(p_m, t_n) \end{bmatrix} \qquad \boldsymbol{O} = \begin{bmatrix} Post(t_1, p_1) & \cdots & Post(t_n, p_1) \\ \vdots & \ddots & \vdots \\ Post(t_1, p_m) & \cdots & Post(t_n, p_m) \end{bmatrix}$$

The relations between places and transitions are already identified by the modifications of the matrices $\boldsymbol{Z}_k$. Hence, to identify input and output places, it would be sufficient to compose just the input matrix $\boldsymbol{I}$, as modified places which are not monitored in $\boldsymbol{I}$ can be considered as output places of the corresponding transition. However, for the sake of operationalization and completeness, we set up matrix $\boldsymbol{O}$.

As we consider a network of material and order flows, we contemplate places to be marked, if the quantity of their underlying (material/order) is larger than zero. In this case, places contain exactly one token. Hence, we obtain a binary marking vector $\boldsymbol{M}^h = [M^h(p_1), M^h(p_2), \dots, M^h(p_m)]$ with $h \in N^0$ that shows which place $p_{i=1,\dots,m}$ contains a token and which remains empty for each stage h of the marking process. It can be derived from the attribute matrix $\boldsymbol{C}$ or rather from the specific attribute set $\boldsymbol{C}_k = [c_{k1}, c_{k2}, \dots, c_{km}]$ representing the attribute quantity. Based on this attribute set, $M^h(p_i)$ is set to 1 if $c_{ki} > 0$ and to 0 if $c_{ki} = 0$. The firing vector $\boldsymbol{B}^h = [b_1^h, b_2^h, \dots, b_n^h]$ of binary variables $b_j^h \in \{0; 1\}$ indicates whether a transition t_j is fired at stage h of a marking process. To calculate the firing vector $\boldsymbol{B}^h$, firstly, we need to sum up the values of each column of the input matrix $\boldsymbol{I}$ and denote them into a separate sum row vector $\boldsymbol{Y}$. Secondly, a vector $\boldsymbol{V}^h$ for each stage h is derived according to the operation: $\boldsymbol{V}^h = \boldsymbol{M}^h \cdot \boldsymbol{I}$. Finally, each element of $\boldsymbol{Y}$ is compared with the equivalent element of $\boldsymbol{V}^h$ at the same point of the vector. If the element of $\boldsymbol{Y}$ equals the element of $\boldsymbol{V}^h$, the corresponding digit of $\boldsymbol{B}^h$ is set to 1, otherwise it is set to 0. However, whether and how a transition t_j is fired, additionally depends on the firing logic E_j.

The functional algorithm $F(\boldsymbol{C}_k, \boldsymbol{Z}_k, \boldsymbol{B})$ is a matrix operation, which defines how the firing of activated transitions affects the initial attribute sets of the different places. For each attribute, we calculate an update of the attribute set $\boldsymbol{C}_k$, which denotes the values of the attribute after the changeover from stage h to stage $h+1$ for each place, by using the following equation with $(\boldsymbol{C}_k^h)^T$ and $(\boldsymbol{B}^h)^T$ as the transposed vectors of $\boldsymbol{C}_k^h$ and $\boldsymbol{B}^h$:

$$(\boldsymbol{C}_k^{h+1})^T = F(\boldsymbol{C}_k, \boldsymbol{Z}_k, \boldsymbol{B}) = (\boldsymbol{C}_k^h)^T + \boldsymbol{Z}_k^h \cdot (\boldsymbol{B}^h)^T \qquad \text{III.2.(1)}$$

For each stage $h+1$, we can derive the updated marking vector $\boldsymbol{M}^{h+1}$ from the updated attribute set $\boldsymbol{C}_k^{h+1}$. Extending this coherence to a finite number of stages $H \in N^0$, we derive the equation:

$$(\boldsymbol{C}_k^H)^T = F(\boldsymbol{C}_k, \boldsymbol{Z}_k, \boldsymbol{B}) = (\boldsymbol{C}_k^0)^T + \sum_{h=0}^{H-1} \boldsymbol{Z}_k^h \cdot (\boldsymbol{B}^h)^T \qquad \text{III.2.(2)}$$

III.2.3.2 Modularization of Petri Nets

The major disadvantage, and hence, the reason for the rarity of Petri Nets in practical applications, is the rising complexity when trying to model large supply networks (Murata, 1989). To reduce this complexity and enable an intuitive modeling of supply networks, we consider them as a composition of different modules representing the distinctive entities of the real-world network. The use of a limited number of standardized modules neither constricts the applicability nor the performance of Petri Nets; however, it increases their transparency (Kindler and Petrucci, 2009). Therefore, we propose a modularization of the Petri Net in analogy to Dotoli and Fanti (2005), to facilitate the analysis of the overall network and theoretically enable the examination of each single module. We extend the modules identified by Dotoli and Fanti (2005), as we consider them to be connected through order and material flows of standardized goods via interfaces located on the modules' borderlines. Incoming and outgoing orders are depicted as interfaces on the top and the bottom, while interfaces on the left and right hand side, respectively, represent material inflow and material outflow. The interfaces are determined by their positioning on the borderlines or corners of the modules. Different interfaces on the same borderline can represent orders or material concerning different kinds of goods or different suppliers/customers. The plaid input interfaces in the left upper corner of the modules enable the impact of exogenous shocks. Figure III.2-a illustrates the structure of a module and its interfaces.

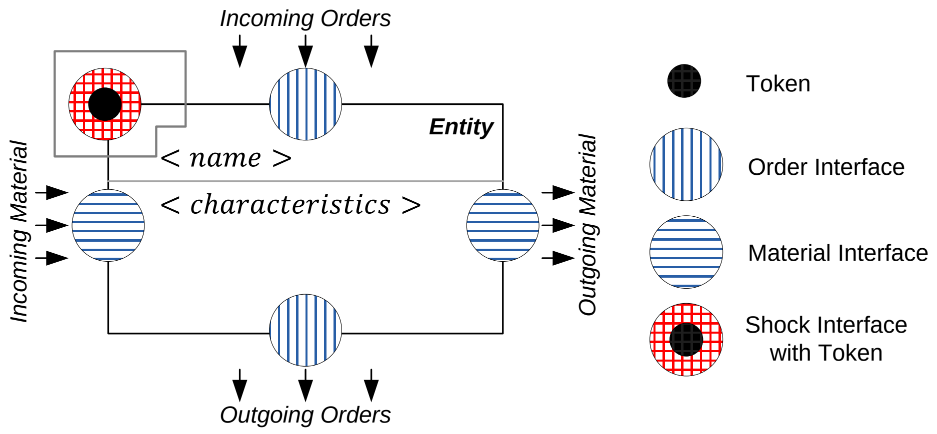

Figure III.2-a *- Structure of a module*

Modules can be aligned by connecting the output interface of one module with the corresponding input interface of another. This modularization is expandable to an arbitrary number of interfaces. However, this requires an adaption of the Petri Net structures inside the module.

Each module represents its own stand-alone Petri Net. Its conversion into a mathematical equation is based on the same mechanisms as described in Section III.2.3.1 above. Each input interface of module x has a corresponding output interface of an aligned module y, having the same attribute values. In an integrated modular Petri Net, these places have to be considered as one place p_i with $\boldsymbol{C}_i = [c_{1i}, c_{2i}, \dots, c_{Ki}]$.

III.2.4 Modeling Procedure

We assume that a supply network can be modeled using four kinds of modules representing the real-world entities, namely resource suppliers, manufacturers, retailers, and logistic service providers (LSPs) (cf. Dotoli and Fanti, 2005). In reality, different kinds of entities can be involved in a supply network, but for reasons of simplicity we stick to these four kinds of entities and the respective modules. Though, additional modules can be easily defined. Each module represents the complete Petri Net of its corresponding entity. The modules, their interfaces, and the Petri Net structures inside the modules can be modeled flexibly, according to the desired complexity level and requirements of the user. Figures III.2-b – III.2-e illustrate the four exemplary modules with their interfaces, although for reasons of simplicity, in a very ingenuous way.

Generally, we constitute that places are bearings of specific underlyings like orders or materials, and transitions are activities representing specific steps of the value creation process. Places and transitions have specific attributes. The presence of a token allocates the corresponding values of the attributes (the arrival of a delivery on a storage place is the assignment of values to its exemplary attributes, quantity and cost). In order to enable a transition, a token on the input place has to represent the availability of the underlying and therefore, a quantity larger than zero. The exact value of the underlying's quantity can be considered as an attribute (stock) of the accordant place. A transition is enabled if all input places store a token. The firing of an enabled transition additionally depends on the decision logic and can change the attributes of the aligned places. It reduces the stock of its input places and increases the stock of its output places. In contrast to classical Petri Nets, where the firing of a transition automatically removes tokens from input places, the respective token in our model is removed only if the stock of the corresponding place equals zero.

The resource supplier has a finite amount of available resources. After receiving an order, the resource supplier mines and processes an appropriate volume of resources according to the amount available. If required, additional restrictions like a specific capability of the mining machines can easily be added.

In Figure III.2-b, the transition inside the module is enabled by the presence of tokens on the three input places 1-3. Place 3 represents a natural repository and stores a token if resources are available. The order input interface (Place 2) stores a token if orders from customers are in place. The shock interface (Place 1) represents an arbitrary, compulsory input factor (e.g. mining facility) for the firing of the transition, which can be impacted by the shock. The firing of the transition creates a token on the material output interface (Place 4), which activates the attributes by assigning corresponding values. At the same time, the attributes of the input places are modified accordingly. If an aligned place of the transition already stores a token, the firing of the transition equals an update of the attributes, as the initial attribute set $\boldsymbol{C}_k^h$ of stage $h = 0$ is replaced by the new attribute set $\boldsymbol{C}_k^{h+1}$ of stage $h + 1 = 1$. The new values of these attributes are calculated by the functional algorithm, which aligns the initial attribute set $\boldsymbol{C}_k^h$ of the places with the modifications $\boldsymbol{Z}_k^h$ triggered by the transition. The values of the modification can be based on a corresponding function $f_j(c_{ki}, d_{lj})$, which depicts how the transition with its attribute set $\boldsymbol{D}_j$ modifies the initial attribute set $\boldsymbol{C}_k^h$ of the places. If the available resources are not sufficient to cope with the volume of incoming orders, the values of the output place are adjusted according to the availability of resources.

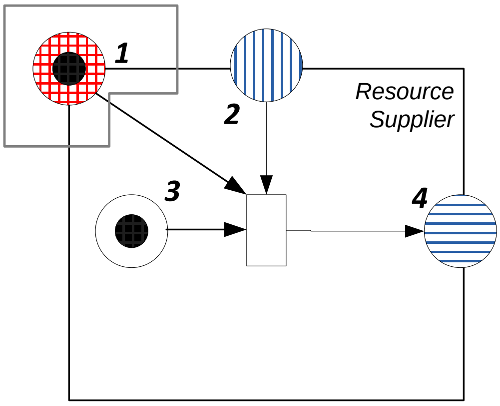

Figure III.2-b *- Module: Resource Supplier*

The manufacturer receives orders from its customers and orders the required amount of input material from its suppliers. After the required material is available, the manufacturer assembles and processes the products according to its customers' orders. Manufacturers can have specific stocks of input material.

In Figure III.2-c, transition I, representing the order handling, is enabled by the arrival of a token and the respective order on the order input interface (Place 2). The firing of this transition creates tokens, accordingly, on the order administration place (Place 3) and the order output interface (Place 6). Simultaneously, it accordingly modifies the attributes of place 2. Transition II is enabled by the presence of tokens on place 3, the shock interface (Place 1) and the material input interface (Place 4). As described above, the order administration place stores a token after the first transition is fired. The shock interface represents an arbitrary, compulsory input factor (e.g. production facility) for the firing of the second transition. Place 4 stores a token as soon as the upstream entity gets a token on its material output interface. The firing of the second transition, representing the manufacturing process, creates a token on the material output interface (Place 5). Accordingly, it modifies the attributes of places 5, 4, and 3. If the material on place 4 at one period is not sufficient to cope with the volume of orders on place 3, the transition sets the values according to the maximum available material under adherence of the transition's attributes.

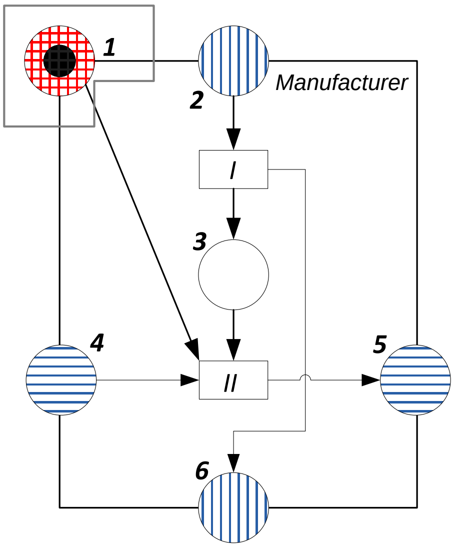

Figure III.2-c *- Module: Manufacturer*

The LSP is an intermediary that processes goods from one entity of the network to another. For the processing, we assume capacity as a representative restriction, for example, the availability of only a limited number of containers for the transport.

In Figure III.2-d, the transition inside the module is enabled by the presence of tokens at the three input places. Place 2, representing the capacity restriction, stores a token if transportation resources, like containers, are available. Assuming that the LSP has been assigned by a resource supplier or a manufacturer, the material input interface (Place 3) stores a token according to the material output interface of the prior company on the upstream. The shock interface (Place1) represents an arbitrary, compulsory input factor (e.g. means of transport) for the firing of the transition. The firing of the transition, representing the transportation process, creates a token on the material output interface (Place 4) and analogously reduces the values of place 3. If the LSP is not capable to deliver the entire amount of material at once, an amount according to the existing capabilities is delivered.

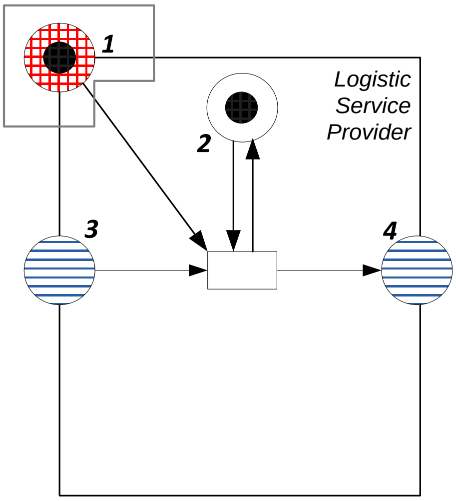

Figure III.2-d *- Module: LSP*

The retailer orders goods from its suppliers and sells them to its customers. The stock of goods is depleted each period. The order volumes are based on the customer demand and hence, the retailer is considered to be the end-user of our network.

In Figure III.2-e, the transition inside the module is enabled if the shock interface (Place 1) and the material input interface (Place 2) contain a token. The shock interface represents an arbitrary, compulsory input factor (e.g., selling equipment) for the firing of the transition. The place 2 stores a token as soon as the prior entity on the upstream gets a token on its material output interface. The firing of the transition creates a token on the order output interface (Place 3) whereas it modifies the attributes of the place 2 accordingly.

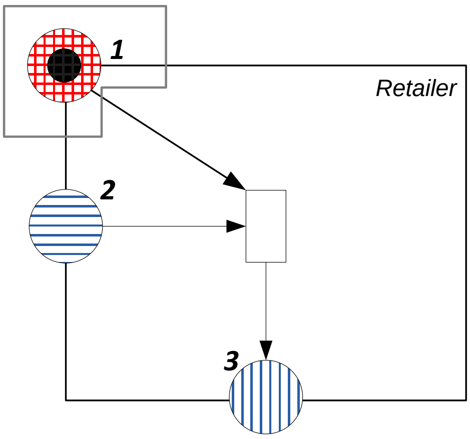

Figure III.2-e *- Module: Retailer*

Shocks generally have the ability to affect any transition inside the module. To indicate such an exogenous shock in a supply network, we define a fifth correspondent module.

The shock module shown in Figure III.2-f is characterized by a shock source (Place 1), which enables the transition inside to fire, and a shock output interface (Place 2), which is able to connect to the shock input interfaces of the other modules. Different output interfaces in the right upper corner of the module represent different shock impacts. In terms of tokens and attributes, firing the transition has the following effect: The initial values from place 2 and place 1 are modified. As place 2 stores a token initially, the firing of the transition updates the attributes of the shock output place and the respective shock input place of the affected (connected) module. This, consequently, changes the module's behavior. Firing another token, which relocates the places attributes to the initial values, can restore the original behavior to the pre-shock state.

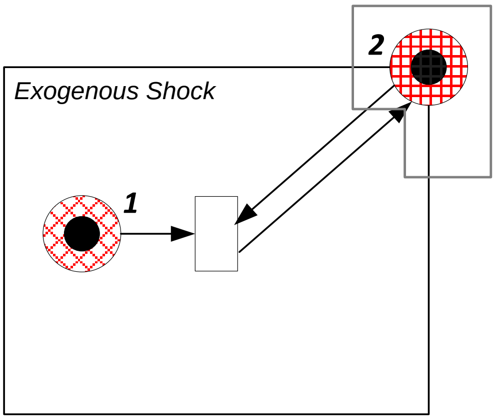

Figure III.2-f *- Module: Exogenous Shock*

III.2.5 Simulation-Based Analysis of Shock Impacts

Our modular Petri Net approach can be used for a wide range of possible applications. One possible application is the analysis of the stability of supply networks to the exogenous shocks, in the context of delivery dropouts. The exemplary supply network shown in Figure III.2-g consists of a manufacturer with three supply stages B, C, and D on the upstream, connected directly or through LSPs. Supplier C usually receives the ordered goods via ship (LSP1) from the resource supplier D. There is a more expensive possibility of an air freight delivery by another service provider (LSP2), which is activated only if LSP1 is disabled. In this initial setting an exogenous shock (e.g. prolonged stays in the harbor) occurs, impacting LSP1 by a delay in the delivery time of its shipment.

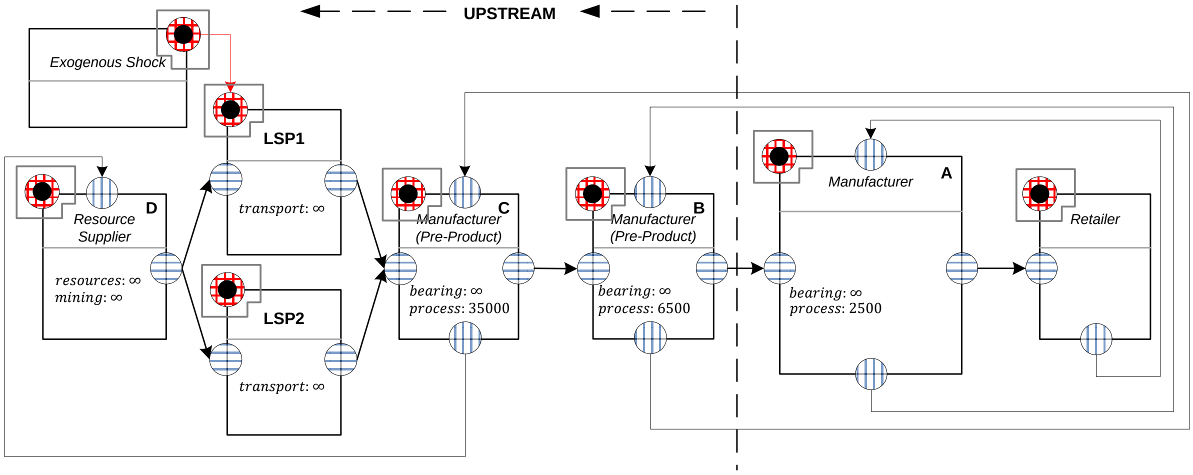

Figure III.2-g *- Supply network and shock, illustrated with a modular Petri Net*

Considering the quantity of material and orders as the only attribute of interest for this simple example, we simulated this network based on the following assumptions:

- The resource supplier has unlimited resources and unlimited mining capacity.
- LSPs have unlimited transportation capabilities.
- Manufacturers have unlimited storage capacities, but limited processing capabilities.
- Each Manufacturer has a predefined target safety stock based on the delivery time of its supplier.
- The volume of each order is linked to a specific lot size.
- The stochastic customer demand is represented by the outgoing order of the retailer.
- The retailer has no safety stock and thus, its bearing is depleted in each period.

Based on these assumptions and the chosen parameter setting, we did a sensitivity analysis and suggest that the model is robust. A description of the parameters we used for the simulation including justifications for the chosen parameter values and corresponding robustness checks are shown in Table VI.2-b in the appendix.

We are aware that this simple example does not inherit all the customs obtained in the area of supply chain and operations management. We are especially aware that existing batch or order size and safety stock calculation methods with their specific restrictions, like service levels (α, β, γ), are not considered. As the objective of this example is to verify the viability of the presented mathematical Petri Net approach rather than describing an accurate real world setting, we consider these facilitations as acceptable, as a first step.

Furthermore, we assume a Gaussian distribution for the retailers order. Since we provide a simulation based approach, other distributions can easily be assumed, though. Each of the defined Petri Net modules represents the logical behavior of a corresponding real world entity. Therefore, the presented approach can also be considered as a simulation meta-model, connecting the corresponding Petri Nets of various real world entities of a supply network. The numerous advantages of simulation based approaches in the context of real world systems have already been described by Cigolini and Rossi (2004).

In each period of the simulated supply network setting shown in Figure III.2-g, the retailer orders a stochastic amount of goods and material. Consequently, the manufacturers check one after the other if their stock of material is sufficient to cope with the incoming orders. They just order appropriate amounts of material from their suppliers if their own available stock drops below the defined safety stock. However, even if the stock drops below the safety stock, they keep the production on until their bearing is empty. Resource supplier and LSP, on the other hand, check if their resources and capacities are sufficient to process the volume of incoming orders. Each state of the Petri Net represents one period in time. Hence, in this example the time until ordered goods arrive in the bearing of the ordering entity is normally two periods. Consequently, the safety stock of the manufacturers depends on the time span between order and delivery, as well as on the average customer’s demand. The bearings of retailer and manufacturers, in the following referred to as bearing A, B and C, are represented by the interfaces on the left border of the modules.

Taken this initial setting, we simulated 1000 periods of transient and 19000 periods of shock phase within each simulation run. Simulation runs have been performed for different delays in delivery (shock intensities).

We can obtain different system characteristics using this method e.g. for the stock of material. Figure III.2-h shows the material stock of the manufacturers exemplarily for 1000 periods from period 800 to 1800. The exogenous shock (e.g. prolonged stays in the harbor) strikes once at period 1000 resulting in a continuous delay of delivery. We assumed a delay of 35 periods with the above-mentioned bearing and process capabilities of the manufacturers.

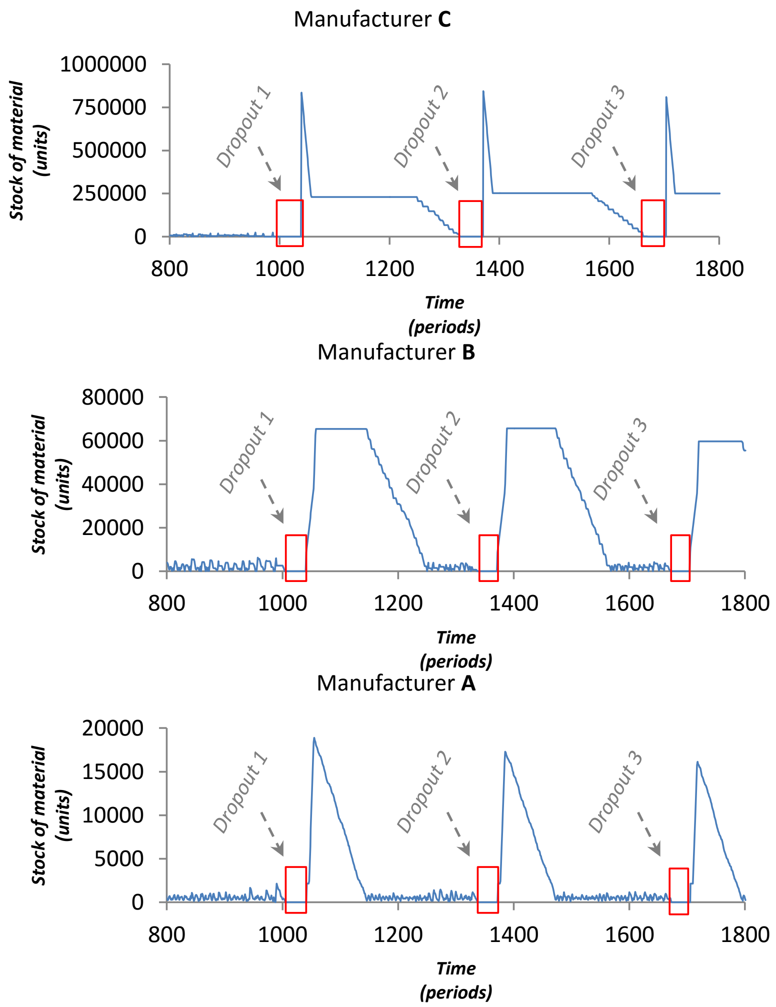

Figure III.2-h - Development of the material stock in case of shock impact

Looking at dropout 1, all manufacturers face periods without delivery, as their stock reserves were not capable to compensate the delayed shipment. We distinguish between disruption and dropouts as follows. Single periods without delivery are defined as disruptions. Dropouts on the other hand are considered to be intervals of more than two disruptions in a row. After some periods without delivery, the delayed ship with the outstanding material arrives, resulting in an instant replenishment of bearing C, as the ship has been loaded continuously during the layover in the harbor. According to the accumulated orders and capability restrictions, manufacturer C processes the received goods to manufacturer B and manufacturer B processes them to manufacturer A. Consequently, the replenishment of the bearings of manufacturers B and A is also delayed. Due to lot sizes, manufacturers order even more material than necessary to accomplish their customers' orders. Hence, each manufacturer is building up additional stock. After all outstanding orders have been delivered, the manufacturers (starting with A) process incoming orders by reducing their stock until it drops below the level of their safety stock. Then, they again start ordering goods from their suppliers. Therefore, the stock of manufacturer B will not be reduced until the stock of manufacturer A is below the safety stock level, and the stock of manufacturer C will not be reduced until the stock of manufacturer B is below the level of safety stock. If the stock of manufacturer C is again insufficient to compensate the amount of incoming orders during the continuing delay of shipment, it again results in periods without delivery, indicated by dropout 2.

Another characteristic that can be obtained from our exemplary supply network is the bullwhip effect, shown in Figure III.2-i. The bullwhip effect is a real-world phenomenon of supply networks, which describes the increasing volatility of orders as moving up the supply chain (Nikolic et al., 2004). Among others, one reason for the bullwhip effect is the variation in lot sizes in the different stages of the upstream. We take the relative standard deviation to account for the varying extent of μ, which is due to the different input ratios and lot sizes of the manufacturers on the upstream. For our exemplary network, we find a relative standard deviation σ/μ of 0.903 for manufacturer A, 1.492 for manufacturer B, and 1.830 for manufacturer C. We consider this as an indicator for the appropriateness of our methodology.

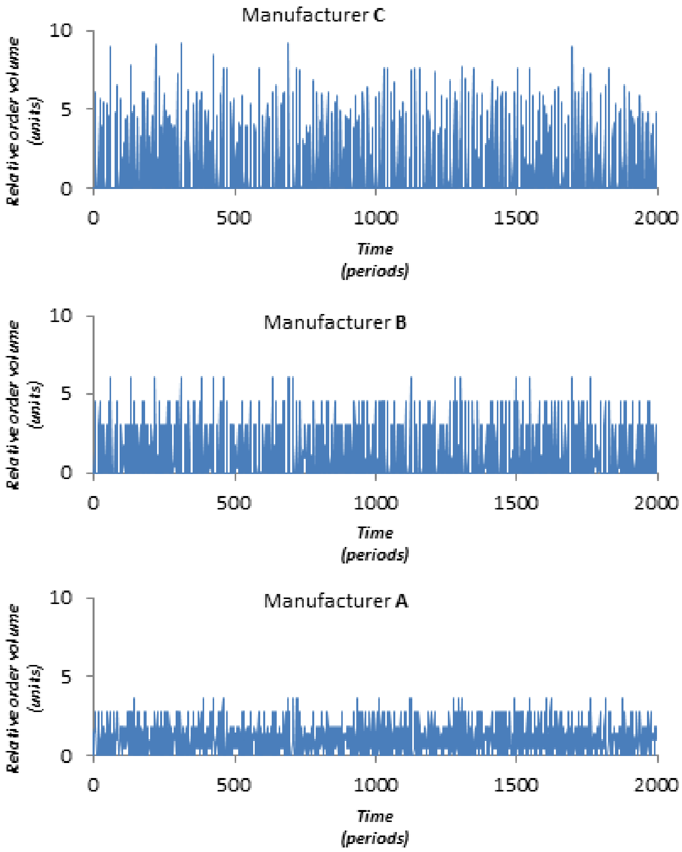

Figure III.2-i *- Illustration of the bullwhip effect: Order volumes relative to its mean values*

Monitoring the retailer's stock, we are able to draw further conclusions for our exemplary network. Figure III.2-j shows the coherence between delivery dropouts at the retailers end and different shock intensities.

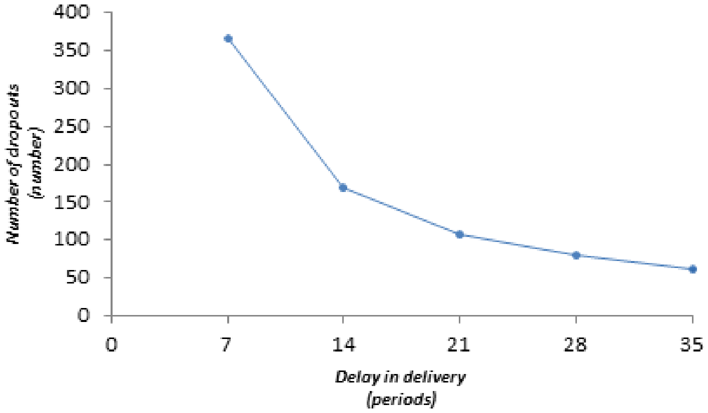

Figure III.2-j *- Number of dropouts*

The results indicate that based on the presence of a shock impact or rather, a delay in delivery, an increase in shock intensity leads to a decline in the number of dropouts. Intuitively, this seems implausible but it becomes clearer when we compare the permanence of such delivery dropouts. In this regard, Figure III.2-k shows the coherence between the permanence of delivery dropouts and shock intensities.

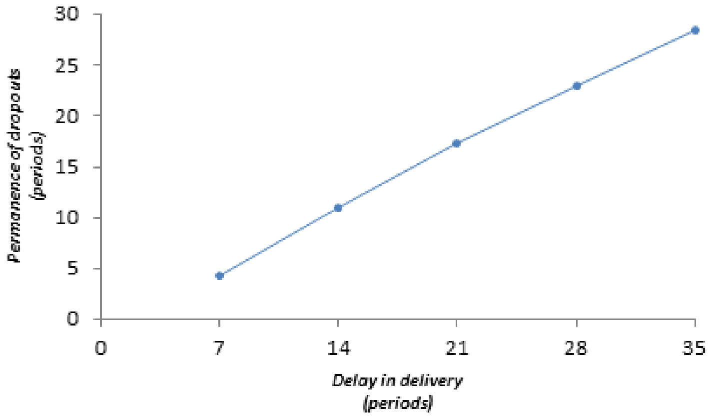

Figure III.2-k *- Permanence of dropouts*

Thus, the results indicate that the permanence of delivery dropouts increases with an increase in the shock intensity. The increase in shock intensity, therefore, leads to two opposite effects: a decline in the number and an increase in the permanence of delivery dropouts. To balance these two opposite effects, we contemplate the overall number of disruptions in relation to the different shock intensities depicted in Figure III.2-l. Additionally, we simulate different safety stocks to analyze the relation between stock reserve and shock impact, as an increase in the stock reserves seems to be the most practical measure to cope with a failure of delivery. We increase the initial safety stock of the manufacturer at stage C of the network, in steps of 25%, from 100% to 300%. For each safety stock we repeat the simulation from above while measuring the retailer's stock.

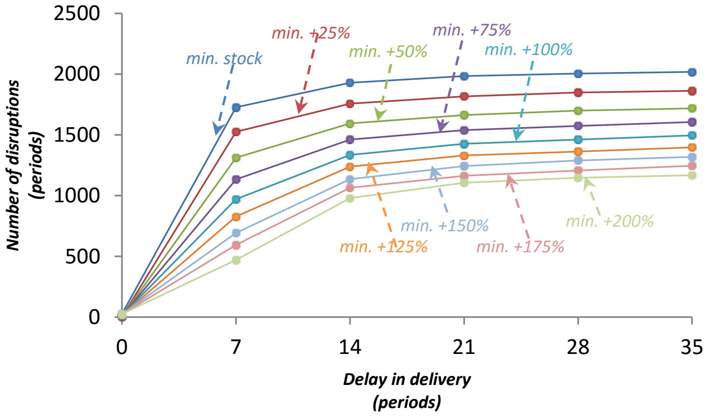

Figure III.2-l *- Overall number of disruptions for different levels of safety stocks*

We hypothetically expect that an increased safety stock reduces the number and the permanence of dropouts, and leads to a decline in the number of disruptions. Furthermore, we expect that the beneficial effect of continuously increasing the safety stock declines with the extent of the safety stock.

The results of the simulation indicate that the overall number of disruptions increases with an increase in the delay in delivery. Moreover, it is implied that an increased safety stock leads to a decline in the number of disruptions. In this regard, Figure III.2-m shows that the overall number of disruptions indeed declines with an increase in the safety stock.

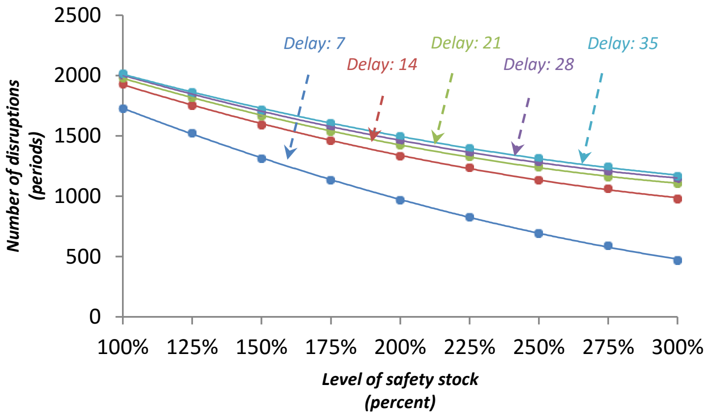

Figure III.2-m *- Overall number of disruptions depending on different levels of safety stock, illustrated for several shock intensities*

This is valid for all shock intensities, although the relative benefit from increasing the safety stock seems higher at lower shock intensities. Comparing this result with a corresponding cost function would enable the manufacturer to calculate an optimum safety stock.

We test the hypothesis (H1) that an increased safety stock leads to a decline in the number of disruptions by statistical means. A regression analysis leads to inefficient results, as the simulation bears auto-correlated residuals. Therefore, we do an approximated two-sample Gauss-Test. For an increasing safety stock, we compare the consecutive pairs of values, exemplarily, for a delay of seven periods. The results listed in Table VI.2-c in the appendix significantly confirm hypothesis H1 for the available data. The convexity of the lines in Figure III.2-m, moreover, indicates that the benefit from the increase in safety stock declines with the safety stock's extent. We constitute this as hypothesis (H2). We do the same test as for H1, considering the difference in the number of disruptions between 100% and 125% safety stock as μ_1, the difference between 125% and 150% as μ_2 and so on. Though, in this case the results (appendix – Table VI.2-c) are just partially significant, so we cannot significantly confirm the hypothesis H2.

Nevertheless, in order to reduce the number of disruptions at the retailers end, it might be more effective to convince multiple companies on the upstream to increase their safety stock than exceedingly pushing up just one company's safety stock. We constitute the hypothesis that increasing the safety stock of manufacturers A, B and C by 100% leads to a lower expected value of disruptions (μ_1) than increasing the safety stock of manufacturer A by 300% (μ_2). In this regard, we exemplarily do an approximated two-sample Gauss-Test for a delay of seven periods and a sample of 31 observations. The results shown in Table VI.2-d in the appendix confirm our hypothesis ($\mu_1 < \mu_2$). For our exemplary supply network we, consequently, can constitute that increasing the safety stock of manufacturer A, B and C by 100% leads to less disruptions at the retailers end than increasing the safety stock of manufacturer A by 300%.

We already confirmed the hypothesis (H1) that increasing the safety stock of one manufacturer (C) reduces the overall number of disruptions at the retailers end. Yet it is unclear how an increased safety stock influences the two opposite effects from above in detail. Therefore, we illustrated the number and the permanence of dropouts depending on the different levels of safety stock. The results shown in Figure III.2-n indicate that an increased safety stock reduces the number of dropouts.

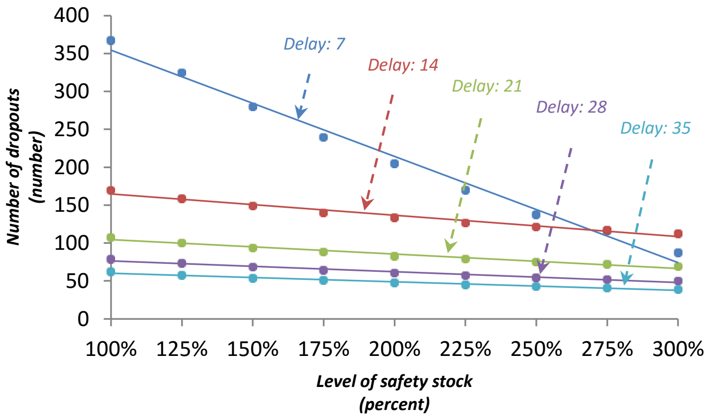

Figure III.2-n *- Number of dropouts depending on different levels of safety stock, illustrated for several shock intensities*

Here it is peculiar that line one (Delay: 7) intersects line two (Delay: 14), which is explained as follows: The initial safety stock is considered to be two periods of an average order, and an increased safety stock leads to a declining permanence of dropouts. If the initial safety stock of two periods is increased by 300%, it leads to a stock that, on average, is able to buffer a dropout with a permanence of six periods. At a high level of safety stock (e.g. 300%) and low shock intensity (e.g. Delay: 7), former dropouts, hence, become disruptions. Consequently, the gradient of the line is much higher for a delay of seven periods than a delay of 14 periods, resulting in an intersection. While Figure III.2-n shows that an increased safety stock reduces the number of dropouts, the results of Figure III.2-o imply that an increased safety stock also reduces the permanence of dropouts. Both observations are independent of the specific shock intensity. Though, in both cases the gradient of the regression line implies that for less intensive shocks an increased safety stock leads to a slow decline in permanence, but a fast decline in the number of dropouts. In order to consolidate these conjectures, we constitute the following hypotheses: The number of dropouts declines with an increase in the safety stock (H3); the permanence of dropouts declines with an increased safety stock (H4). We test these hypotheses H3 and H4 analogously to hypothesis H1 and can significantly confirm them for the available data. The corresponding test results are listed in Table VI.2-c in the appendix.

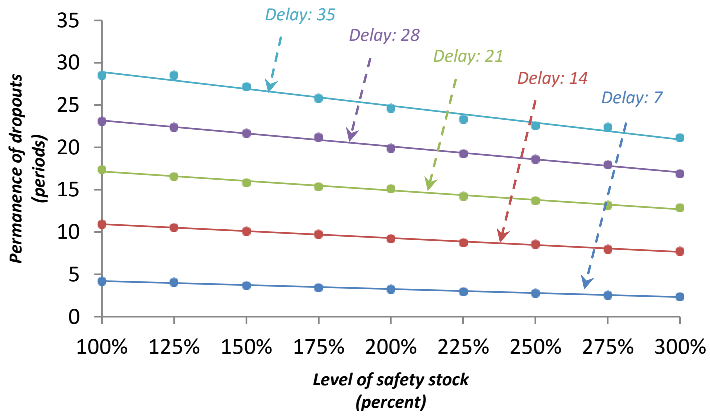

Figure III.2-o *- Permanence of dropouts depending on different levels of safety stock, illustrated for several shock intensities*

Assuming, that the cost of a dropout is directly proportional to its permanence, it could be of interest to know which loss will just be exceeded with a specific level of probability in a specified time interval. In this regard, we calculated a dropout-quantile that depicts which permanence of dropouts will just exceed in 1% of all cases of our simulation. Figure III.2-p shows these ratios for all simulated safety stock and shock intensities.

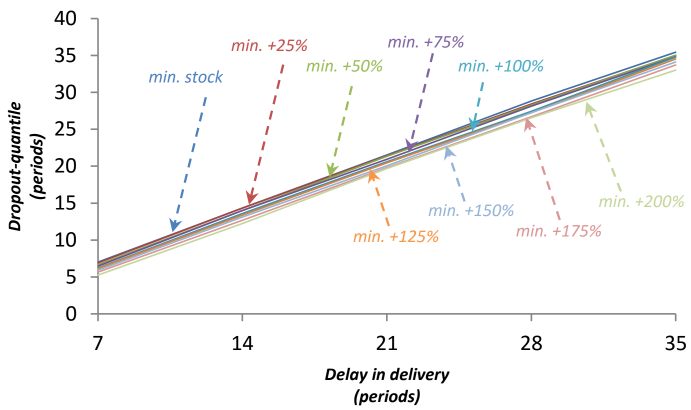

Figure III.2-p *- Dropout-quantiles depending on different delays in delivery, illustrated for several safety stocks*

Besides smaller variations due to the underlying stochastic variable, we find that an increased safety stock leads independent of the intensity of shock to a declining dropout-quantile. However, it seems remarkable that the decrease in the dropout-quantile is disproportionately low compared to the increase in the safety stock. This arouses the question whether increasing the safety stock is the appropriate action to reduce the loss and the respective permanence of disruptions. However, such questions are topic for further research.

Although, this small simulation was just an exemplary application of the presented approach, it nevertheless presented some interesting economical indications. As the relative benefit of increasing the safety stock declines with the intensity of shock, an increased safety stock might not be the most effective action to reduce the number of disruptions in case of an intensive shock. Besides, the benefit of increasing the safety stock declines with the extent of safety stock. Hence, it seems less effective to excessively increase the safety stock of one company compared to increasing the safety stock of several companies on the upstream on average. To reduce the number of disruptions at the retailer's end, thus, it might be better for a manufacturer to support his suppliers on the upstream by increasing their storage capacities than increasing just his own storage capacity. Also from an economical point of view, the allocated increase in multiple inventories seems more reasonable, as the excessive increase of one company's inventory usually becomes progressively expensive with the inventory's extent.

III.2.6 Summary, Conclusion, and Limitations

Although the impacts of exogenous shocks on global supply networks are hard to predict, the incidences in the last few years show the necessity for research in this area. We develop a modular Petri Net approach based on a modification and enhancement of the DA_NET approach of Wu et al. (2007) to quantify and simulate the impacts of exogenous shocks on supply networks and to gain information on the network's behavior and stability. Furthermore, we present a modularization of Petri Nets to facilitate the analysis and depiction of complex supply networks. We define a standardized module structure and identify five different modules to model complex supply networks on a high-level of abstraction. In order to verify the presented approach, we finally design, simulate, and analyze exemplary supply networks. The presented approach provides the possibility to visualize and analyze different supply networks and their dynamics as well as impacts of different exogenous shocks. It even gives insights, in which specific attributes of the participating entities are affected to which extent. The modularization facilitates the flexible composition of supply networks in order to identify the most appropriate structure theoretically. In order to validate the introduced method, we furthermore simulate different intensities of a specific exogenous shock impacting an exemplary supply network. The plausible results of this simulation process indicate that the presented method is appropriate for the analysis of such networks. The flexibility and scalability of the introduced method enables its implementation in various industry sectors.

However, this approach is not without limitation. With reference to the three stage cycle for research activities in operations research of Meredith et al. (1989), we were not yet able to proceed from the explanation to the testing stage based on a real world example, despite various efforts to gather data. One possible reason could be the kind of data required for the model. Today, companies are oftentimes not able to provide information about their supply network on this granularity level since it is not available to them. This again might be due to data privacy issues between the companies of a supply network. However, there are also some industries where this kind of information is compulsory to some extent for legal reasons e.g. in the pharmaceutical industry, food industry, etc. or where companies are already trying to gather this information for risk mitigation reasons e.g. in the automotive industry. Therefore, future research should not only feel encouraged to investigate and test the presented method based on real world data, but also to explore novel data sharing methods, which enable the exchange of specific data without infringing the data sovereignty of the cooperation companies. As supply networks are becoming increasingly complex and opaque, the application of high-performing Information Systems (IS) is necessary to handle, route and process the huge amount of critical information compulsory for the analyses of such networks. Such IS, moreover, could contain predefined and standardized modules, which can be composed to different supply networks, mutually managed by the purchase and risk management department. Consequently, scenario analysis could be accomplished in order to identify weaknesses of the different network compositions.

Therefore, if research is continued in this area, it should investigate appropriate integrated systems to enable and facilitate the analysis of complex supply networks. Hence, research could induce a stabilizing effect on the otherwise unstable and endangered parts of our economy.

IV Summary and Future Research

In the following sections, the key findings of this doctoral thesis are summarized (Section IV.1) and potential starting points for future research are presented (Section IV.2).

IV.1 Summary

With all its consequences, the ubiquitous deployment of IT solution in the age of digitalization keeps on revolutionizing business and society. The resulting increasingly complex, dynamic, and interdependent structures, still bear major challenges for companies regarding both, their internal management and their external interaction. To assert their market position in the age of digitalization, companies need to address these challenges by assessing and managing the accordingly emerging risks. Therefore, the main objective of this doctoral thesis was to contribute to the extant risk management body of knowledge, focusing on specific risks that arise as to the outlined challenges in the light of digitalization. Investigating operational risks as to a company's internal management, Section II particularly focused on the assessment and management of risks related to the increasing complexity and dynamics of IT projects as drivers for digital progress. Examining systemic risk arising from increasing interdependence, Section III focused likewise on companies' challenges as to internal management and external interaction by using the exemplarily subject areas of IT projects and value creation networks. It particularly investigated the criticality of IT projects to their overall IT portfolio, as well as the propagation and extent of systemic risk in supply networks. In the following, the key findings and major contributions of each section are outlined consecutively.

Section II.1 investigated the complexity of IT projects, which is supposed to be one major risk in the context of IT project failures. Since neither practice nor research outlined a coherent picture about what is concealed within IT project complexity, this section provided conceptual clarity regarding the construct of IT project complexity, by examining and outlining the causalities of aspects that are supposed to somehow relate to the complexity of IT projects in extant literature *[Objective II.1]*. Establishing a foundation to grasp and manage IT project complexity, this section moreover proposed a two-dimensional framework based on generic antecedents and context-specific project areas, with the former dimension describing what causes complexity and the latter describing where complexity is located *[Objective II.2]*. Consequently, it enables a clear and unambiguous understanding of what is meant by IT project complexity and enables researcher and practitioners to assess and manage IT project complexity and associated risks more properly, based on the introduced framework.

Sections II.2 and II.3 examined the assessment and management of specific risks related to IT projects, which among others originate from the increasing complexity, dynamics, and interdependence of the projects' environment. Focusing on the ex ante investment decision of an IT project, which usually is based on a business case calculation, Section II.2 on one hand examined the assessment of IT projects' benefits, since they are not properly considered in extant evaluation methods. In doing so, it suggested monetarization rules to quantify even vague and difficult to grasp benefits of IT projects in a quantitative manner *[Objective II.3]*. On the other hand, it investigated the integration of multiple relevant aspects for IT project evaluation, since most existing methods primarily focus on cost. Therefore, it developed an integrated quantification approach for IT projects, considering not only cost, but also benefits, risk, and dependencies *[Objective II.4]*. In doing so, it aggregated benefits of IT projects based on the assumption of a normal distribution and utilized portfolio theory of Markowitz (1952) as well as a preference function to comprehensively consider cost, benefits, risk, and dependencies in an integrated risk-adjusted project value. Thereby, it also considers the level of a decision maker's risk aversion, which is derived by an approach of behavioral finance. To ensure practicability, this approach has been jointly developed by research and practice. Consequently, it enables companies to evaluate their IT projects more holistically and reduces the risk of misjudgments regarding investment decisions, which might also lead to an overall decrease in the number of IT project failures.

Addressing the increasing dynamics of the projects' environment, Section II.3 focused on the continuous quantitative management of IT projects. It enhanced the integrated ex ante evaluation approach provided in Section II.2, to address the risks arising from changing circumstances during a projects lifecycle. Therefore, it introduced a differentiation between uncertain estimated cash flows, like prevalent in an ex ante business case calculation, and definite accomplished cash flows that become certain with the projects' progression. Thereupon, it developed two measures for continuous project monitoring and project steering, with the former measure enabling decisions based on the comparison between estimated and actual project progression and the latter enabling decisions based on an expected residual IT project value. Along with triggers that have been defined for both measures, this approach enables a continuous assessment and management of IT projects during their lifecycle *[Objective II.5]*. To meet the needs for a likewise rigor and practicable method, also this approach has been jointly developed by research and practice. Consequently, it empowers companies to measure the current progression of an IT project, provides control mechanisms for project deviations as well as project continuation, and mitigates the risks arising from changing circumstances in the project's environment, by enabling to initiate timely countermeasures.

Representing the link between the specific subject area of IT projects, being used to illustrate a company's challenges as to internal management, and the more generic subject area of value creation networks, being used to depict a company's challenges as to external interaction, Section III particularly focused on dependencies and associated systemic risk. Considering IT project portfolios as IT project networks, with nodes representing projects and arcs representing dependencies amongst them, Section III.1 investigated the coherence between dependencies and systemic risk, taking a company's internal management perspective. In doing so, it outlined different kinds of existing dependencies as well as current corresponding assessment methods. In this context it has been found, that existing methods for dependency assessment are not able to consider different dependencies properly. Especially indirect dependencies are mostly neglected. This section hence adapted centrality measures, which are based on graph theory and are considered as an appropriate means for network analysis, to the subject area of IT projects. It examined different centrality measures whether they are appropriate to account for the different dependencies within IT portfolios. Moreover, it provided an alpha-centrality-based approach to appropriately assess direct and indirect dependencies of IT portfolios *[Objective III.1]*. Indicating the criticality of an IT project to its corresponding IT portfolio, this approach enables companies to manage the risk arising from the underlying dependency structure, by allocating limited resources more effectively.

Drawing on supply networks as one instantiation of value creation networks, Section III.2 investigated systemic risk by taking a company's external interaction perspective. To be more concrete, it examined the propagation of systemic risk over several periods of time and several stages in supply networks, which have been shown to be increasingly prone to systemic risk by recent occurrences like earthquakes and floodings. In particular, it provided a modular Petri Net approach to illustrate and simulate the propagation of exogenous shock impacts on supply networks *[Objective III.2]*. Considering the network structure, its characteristics at a specific point in time, and the intensity of an exogenous shock, this approach furthermore enables to quantify an impact's extent to any assigned entity of the network *[Objective III.3]*. Based on the definition of five standardized Petri Net modules for specific types of entities, it also simplifies the analyses and depiction of complex supply networks on a high level of abstraction. Moreover, to verify the provided approach, it outlines, simulates and analyzes an exemplary supply network. Consequently, the developed modular Petri net approach enables to visualize and analyze different network structures, their dynamic, and their exposure to systemic risk. It allows to assign different attributes to the networks entities and gives insights in the extent to which these attributes are prone to risk. Moreover, the modularization enabling the flexible compositions of different network topologies, theoretically facilitates to determine the most appropriate or resilient network structure.

This doctoral thesis finally contributed to the extant risk management body of knowledge by providing insights and means to assess and manage risks associated with IT projects and value creation networks, arising from the increasing complexity, dynamics and interdependence driven by digitalization. Although it investigated some likewise important and difficult to handle risks, this doctoral thesis only covered a fractional part of all risks emerging in this context. It therefore can only be considered as a modest first step to a comprehensive assessment and management of these emerging risks. Since this is a huge research area that will preoccupy research for several years, it encompasses many different research topics in several risk and subject areas (cf. Section I.2). Also within the risk and subject areas that have been considered in this doctoral thesis, there are plenty of research topics that remain untouched besides the particularly investigated ones. For instance, the assessment of systemic risk in IT penetrated network structures based on load networks or similarly related methods from other scientific areas would be an interesting topic to examine in this context. Finally, also the specific risk investigations of this doctoral thesis yielded topics for further research that are outlined in the following section.

IV.2 Future Research

Based on the limitations of means and approaches proposed in this doctoral thesis, continuative questions emerge that might serve as a basis for further research.

Section II, which strives to enhance IT project assessment to cope with increasing complexity and dynamics, provides the following starting points for further research:

Since IT project complexity is supposed to be one major risk leading to IT project failures, Section II.1 proposed a two-dimensional framework to assess IT project complexity based on its antecedents and the project area of its occurrence. Although, this framework provides a first modest step towards a clear and unambiguous assessment of IT project complexity and its antecedents, it does not empirically prove evidence about whether the antecedents, that have been derived by literature and verified by practice, actually are significantly causal for IT project complexity. Therefore, the significance of the stated antecedents for IT project complexity should be examined in depth. Furthermore, since the proposed framework has only been applied to one real world case study so far, further applications to different real world cases should be performed, to further verify the frameworks usability.

Dealing with an integrated ex ante quantification approach for IT projects, considering cost, benefits, risk, and dependencies, Section II.2 used the standard deviation as a measure of risk. It consequently assumed risk as symmetric deviation from an expected value. This might not picture reality in every case. Furthermore, the feedback gathered from practice indicated that other risk measures like the *Value at Risk* might be easier to comprehend. Therefore, different means for the consideration of risk in an integrated approach seem to be an interesting topic for further research. Moreover, this approach assumed cost of IT projects to be deterministic. Hence, further research might enhance the provided integrated approach for IT project evaluation by investigating means to additionally consider stochastic cost.

Extending the integrating quantification approach of Section II.2, Section II.3 provided a dynamic approach to mitigate the risk arising during a projects lifecycle. In doing so, it assumed the project’s cash flows to be normally distributed. Although, assuming a normal distribution for cash flows of IT projects is a common procedure, it might be valuable to investigate whether and how different distributions of cash flows can be considered within the presented approach. Furthermore, since this approach only considers direct dependencies based on an Bravais-Pearson correlation coefficient, it could be an interesting topic to not only investigate how to account for also indirect dependencies (cf. Section III.1), but to develop means that are able to account for direct as well as indirect dependencies within an integrated quantification approach for IT projects and portfolios.

Section III endeavored to assess and manage systemic risk emerging from underlying dependency structures. In this context, the following starting points for further research can be denoted:

Focusing on an in depth analysis of direct and indirect dependencies that enable systemic risk and have generally been identified as a major risk in the context of IT projects and portfolios, Section III.1 proposed and outlined the idea to assess the criticality of IT projects based on alpha-centrality. Like almost any other approach to dependency assessment, also this approach is based on expert estimations regarding the strength of dependencies between two or more IT projects. Hence, further research should be accomplished to enhance these current estimation procedures. Alpha-centrality generally enables to account for external influences by a separate vector. So far, the presented approach however widely neglected this vector for reasons of simplicity. Therefore, further research should feel encouraged to investigate the possibilities of alpha-centrality for additionally considering external influences like project size or regulatory importance, while assessing the criticality of IT projects based on the inherent dependencies. Since this section only provides the first idea of using centrality measures to investigate dependencies of IT project portfolios, it does not explicitly differentiate between different kinds of dependencies. Therefore, further research should strive to consider and integrate different kinds of dependencies within a centrality-based approach. Since the presented approach has only be verified by on example case so far, the application in real-world settings by further research would ensure its validity and might yield further starting points for improvement.

Section III.2 provides means to assess the dynamic aspects of systemic risk, i.e. the propagation of impacts in network structures and the resulting damage to the networks entities. It used a modular stochastic Petri Net approach to model and simulate an exemplar supply network. In doing so, it presupposed the network structure, representing the underlying dependencies of the network, to be known. As networks are becoming increasingly complex and opaque, this probably not pictures reality. Future research hence should feel encouraged, to investigate new ways and methods to increase transparency of network structures. Due to the lack of information regarding the structure of real world supply networks, the proposed approach could not yet be applied in practice. Therefore, once new ways towards increased transparency of network structure have been found, further research should strive to proof the practical validity of the proposed approach by applying it to different real world settings.

Summarizing, this doctoral thesis examined different research questions regarding complex risk structures in the light of digitalization. Therefore, it contributed to the existing body of knowledge by introducing different methods and techniques for risk assessment and management in the investigated subject areas. However, due to the fast pacing environment and ongoing developments in the context of IT projects and value creation networks, the proposed methods and techniques might prospectively require enhancement and adjustment to serve as rigor means for future risk management. Nevertheless, it is desirable that the provided means might be a first modest step to mitigate the risk that particularly complex structures are increasingly prone to in the current age of digitalization.

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VI Appendix

VI.1 Section II.1

Table VI.1-a *- Identified manifestations of complexity and their sources*

ID	Specific Aspects	Author
1	objective novelty	(Tatikonda and Rosenthal, 2000)
2	breadth of product program	(Größler et al., 2006)
3	interdependency between outsourcing partners	(Fridgen and Müller, 2011)
4	interrelationships between the activities in a schedule	(Nassar and Hegab, 2006)
5	quantity of organizational subtasks	(Tatikonda and Rosenthal, 2000)
6	difficulty of the project objectives	
7	diversity of technologies	(Meyer and Utterback, 1995)
8	diversity of customers	(Größler et al., 2006)
9	diversity of inputs	(Baccarini, 1996)
10	diversity of outputs	(Baccarini, 1996)
11	diversity of parts in the work flow	(Gidado, 1996)
12	diversity of products	(Größler et al., 2006)
13	diversity of tasks/actions regarding technology	(Baccarini, 1996)
14	diversity of tasks/actions regarding territory	(Baccarini, 1996)
15	diversity of tasks/actions regarding time	(Baccarini, 1996)
16	diversity of team members regarding location	(Baccarini, 1996)
17	diversity of team members regarding specialist field	(Baccarini, 1996)
18	diversity of team members regarding time	(Baccarini, 1996)
19	extent of interactions required to manage components	(Novak and Eppinger, 2001)
20	interaction between the project organisational elements	(Baccarini, 1996; Vidal et al., 2013)
21	interdependencies within a network of tasks	(Baccarini, 1996)
22	interdependency between inputs	(Baccarini, 1996)
23	interdependency between operations	(Baccarini, 1996)
24	interdependency between parts in the work flow	(Gidado, 1996)
25	interdependency between subprojects	(Lindemann et al., 2009)
26	interdependency between tasks	(Baccarini, 1996)
27	interdependency between teams	(Baccarini, 1996)
28	interdependency between technologies	(Baccarini, 1996)
29	interdependency between work packages	(Vidal et al., 2007)

30	interdependency of technological elements (transitions, interfaces, data structures,…)	(Cardoso, 2005)
31	specification interdependence	(Vidal et al., 2013)
32	length of feedback loops	(Lindemann et al., 2009)
33	length of product life cycle	(Größler et al., 2006)
34	product novelty	(Novak and Eppinger, 2001)
35	magnitude of organizational subtasks	(Tatikonda and Rosenthal, 2000)
36	number of technological elements (transitions, interfaces, data structures,…)	(Cardoso, 2005)
37	modifications to existing products	(Clift and Vandenbosch, 1999)
38	number of tasks/actions	(Baccarini, 1996)
39	nature of subtask interactions	(Tatikonda and Rosenthal, 2000)
40	new-to-the-world products	(Clift and Vandenbosch, 1999)
41	number of communication paths	(Aladwani, 2002)
42	number of customers	(Größler et al., 2006)
43	number of different technologies	(Meyer and Utterback, 1995)
44	number of employees	(Gidado, 1996)
45	number of levels in hierarchical structure	(Baccarini, 1996)
46	number of inputs	(Baccarini, 1996)
47	number of organizational units	(Baccarini, 1996)
48	number of outputs	(Baccarini, 1996)
49	number of parts in the work flow	(Gidado, 1996)
50	number of process types	(Größler et al., 2006)
51	number of product components	(Novak and Eppinger, 2001)
52	number of specialities involved on a project (subcontractor, trades)	(Baccarini, 1996)
53	number of stakeholders	(Vidal et al., 2013)
54	geographic location of stakeholders (and their mutual disaffection)	(Vidal et al., 2013)
55	variety of the interests of stakeholders	(Vidal et al., 2013)
56	team cooperation and communication	(Vidal et al., 2013)
57	building type of technology	(Baccarini, 1996)
58	nature of organizational subtasks	(Tatikonda and Rosenthal, 2000)
59	difficulty of location for technology	(Baccarini, 1996)
60	bargaining power of customers	(Größler et al., 2006)
61	overlap of design and construction	(Baccarini, 1996)
62	level of scientific and technological knowledge required	(Gidado, 1996)

VI.2 Section III.2

***Table VI.2-a** - Model parameters and corresponding descriptions*

Parameters	Description
$\boldsymbol{t_j}$	Transitions nodes $j = 1 \dots n$
$\boldsymbol{p_i}$	Place nodes $i = 1 \dots m$
$\boldsymbol{D_j = [d_{1j}, d_{2j}, \dots, d_{Lj}]}$	Attribute set of each transition t_j: d_{lj} with $l = 1 \dots L$
$\boldsymbol{C_k = [c_{k1}, c_{k2}, \dots, c_{km}]}$	Attribute set of each place p_i: c_{ki} with $k = 1 \dots K$
$\boldsymbol{C = \begin{bmatrix} c_{11} & \cdots & c_{1m} \\ \vdots & \ddots & \vdots \\ c_{K1} & \cdots & c_{Km} \end{bmatrix}}$	Attributes of place nodes
$\boldsymbol{Z_k = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{m1} & \cdots & z_{mn} \end{bmatrix}}$	Matrix $\boldsymbol{Z_k}$ denoting modifications of the underlying attribute c_k caused by transition t_j for each place p_i
$\boldsymbol{f_j(c_{ki}, d_{lj})}$	Function $f_j(c_{ki}, d_{lj})$ relating the attributes c_{ki} of the places with the attributes d_{lj} of the transitions
$\boldsymbol{E_j}$	Decision logic E_j, which decides whether a transition t_j is fired or not: E_j = IF (constraint) THEN (consequence).
$\boldsymbol{I = \begin{bmatrix} Pre(p_1, t_1) & \cdots & Pre(p_1, t_n) \\ \vdots & \ddots & \vdots \\ Pre(p_m, t_1) & \cdots & Pre(p_m, t_n) \end{bmatrix}}$	Input matrix depicting arcs pointing from transitions to places, denoted as $Pre(p_i, t_j) \in \{0; 1\}$
$\boldsymbol{O = \begin{bmatrix} Post(t_1, p_1) & \cdots & Post(t_n, p_1) \\ \vdots & \ddots & \vdots \\ Post(t_1, p_m) & \cdots & Post(t_n, p_m) \end{bmatrix}}$	Output matrix depicting arcs pointing from places to transitions, denoted as $Post(t_j, p_i) \in \{0; 1\}$
$\boldsymbol{M^h = [M^h(p_1), M^h(p_2), \dots, M^h(p_m)]}$	Marking vector at stage $h \in N^0$ with $M^h(p_i) \in \{0; 1\}$
$\boldsymbol{B^h = [b_1^h, b_2^h, \dots, b_n^h]}$	Firing vector with $b_j^h \in \{0; 1\}$ indicates whether a transition t_j is fired at stage h
$\boldsymbol{V^h = M^h \cdot I}$	Support vector
$\boldsymbol{Y}$	Vector containing the sum of each column of the input matrix $\boldsymbol{I}$
$\boldsymbol{F(C_k, Z_k, B)}$	Functional algorithm defining how the firing of activated transitions affects the initial attribute sets of the different places

Table VI.2-b *- Simulation parameters, corresponding descriptions, and justifications*

Parameter:	Description and justification of initial parameter values:
Storage capacity	Description: *The storage capacity represents the maximum volume of commodities that can be stored by a specific entity in the supply network.* Since storage and warehouse optimization are not objective of our research, we considered the storage capacity of all entities to be infinite without loss of generality. Various storage capacities can easily be assigned to specific entities, though.
Processing capacity	Description: *The processing capacity represents the maximum volume of commodities that can be processed (e.g. mined, conveyed, manufactured, etc.) by a specific entity in the supply network in one period.* For convenience, the processing capacities of the resource supplier, the retailer and the logistic service provider has been assumed infinite. The processing capacities of manufacturer A, B, and C have been made-up to be 2500, 6500 and 35000. These values have been chosen randomly and can easily be adjusted. Assuming the processing capacity not to restrict the order and delivery volume under normal conditions (without shock impact), it just influences the velocity of the bearing replenishment. To analyze the robustness of our model, we increased all processing capacities of the manufacturers by 10% resulting in a decrease of disruptions at the retailer's end of about 1%. Since these 1% also could derive from the stochastic variation of the retailers order, we consider the model as relatively robust regarding changes of processing capacity.
Input/ output ratio	Description: *The input/output ratio represents the ratio of input to output goods or commodities being processed by a specific entity in the supply network. It determines the number on input units that have to be available (in one place) in order to accomplish a specific activity (transition).* The input/output ratios of manufacturer A, B, and C have been made-up to be 2:1, 3:1 and 4:1. As indicated by the different input/output rations of the manufacturers in our exemplary network, it can be easily adjusted and specifically set for each entity of the network. It determines the number of input units that have to be available (in one input place) in order to accomplish a specific activity (transition) and produce a specific output (in one output place). Therefore, it is closely connected to the safety stock of the manufacturers. To check the robustness of the model, we increased the input/output ratios of all manufacturers by 100% and assumed a corresponding safety stock (cf. the safety stock calculation below). As expected, a likewise increase of both parameters does not influence the number of disruptions at the retailer's end significantly.
Stochastic demand	Description: *The stochastic demand is the volume of commodities used by the final consumer of the network in one period.* The stochastic demand of the retailer is based on a normal distribution with $\mu = 100$ and $\sigma = 50$. Since we measure the disruptions at the retailer's end, which should be based on exogenous shocks rather than on endogenous network

	properties, we had to ensure order volumes > 0. Therefore, the distribution has been cut at μ ± 90. Consequently, values < 10 are set to 10 and values > 190 are set to 190, which leads to a mean value of 110. Increasing the safety stock by 10% (μ=110 and σ = 55) lead to a mean value of about 115 and an increased in disruptions at the retailer's end of about 4.8%. However, this increase is just plausible, since in this example, the safety stock of the manufacturers is closely linked to the order volumes. Increasing the retailer's demand - that equals the order placed by manufacturer A - without similarly increasing the safety stock leads to a higher number of disruptions.
Safety stock	Description: *The safety stock represents the minimum volume of commodities that is held available in the bearing of a specific entity of the supply network.* In our exemplary supply network only the manufacturers were considered to have a bearing and therefore a safety stock. The delivery time between the manufacturers A and B alike B and C is assumed to be 2 periods. The average volume of ordered goods by the retailer is 110. Therefore, the safety stock of manufacturer A is calculated by multiplying the number of periods with the average volume of ordered commodities and the input/output ratio and is consequently set to 2*110*2=440. According to the input/output ratio of manufacturer A, the average ordered volume of commodities for manufacturer B equals 2*110=220. Therefore its safety stock is 2*220*3=1320. As the delivery time between manufacturer and the resource supplier is considered to be 3 periods, the safety stock of manufacturer C is 3*660*4=7929. We chose these safety stocks since we wanted to measure the number of disruptions at the retailers end based on the impact of exogenous shocks rather than from the stochastic order volume of the retailer. Assuming normal conditions (without shock impact) and a deterministic demand of 110, the chosen safety stocks are the minimal ones to run the exemplarily simulation setting without disruptions. Any other safety stock values can be set up, though.

Table VI.2-c - *Test results for hypothesis H1 – H4.*

		Expected value (μ)		Variance (σ^2)		Test statistic
		Sample 1	*Sample 2*	*Sample 1*	*Sample 2*	
H1	$\mu_{125} < \mu_{100}$	1507,419	1737,355	409,318	402,437	-44,934***
	$\mu_{150} < \mu_{125}$	1308,710	1507,419	404,413	409,318	-38,785***
	$\mu_{175} < \mu_{150}$	1125,065	1308,710	391,196	404,413	-36,250***
	$\mu_{200} < \mu_{175}$	983,194	1125,065	334,361	391,196	-29,325***
	$\mu_{225} < \mu_{200}$	838,903	983,194	262,624	334,361	-32,880***
	$\mu_{250} < \mu_{225}$	699,323	838,903	436,959	262,624	-29,382***
	$\mu_{275} < \mu_{250}$	588,387	699,323	477,045	436,959	-20,430***
	$\mu_{300} < \mu_{275}$	481,032	588,387	432,299	477,045	-19,822***

H2	$\mu_2 < \mu_1$	198,710	229,935	1003,013	904,796	-3,980***
	$\mu_3 < \mu_2$	183,645	198,710	680,437	1003,013	-2,044*
	$\mu_4 < \mu_3$	141,871	183,645	818,516	680,437	-6,008***
	$\mu_5 < \mu_4$	144,290	141,871	605,613	818,516	0,357
	$\mu_6 < \mu_5$	139,581	144,290	860,385	605,613	-0,685
	$\mu_7 < \mu_6$	110,935	139,581	833,529	860,385	-3,875***
	$\mu_8 < \mu_7$	107,355	110,935	915,103	833,529	-0,477
H3	$\mu_{100} < \mu_{125}$	320,903	368,323	21,690	34,092	-35,350***
	$\mu_{125} < \mu_{150}$	280,226	320,903	40,781	21,690	-28,655***
	$\mu_{150} < \mu_{175}$	240,290	280,226	44,480	40,781	-24,081***
	$\mu_{175} < \mu_{200}$	207,290	240,290	60,146	44,480	-17,963***
	$\mu_{200} < \mu_{225}$	173,548	207,290	41,789	60,146	-18,608***
	$\mu_{225} < \mu_{250}$	139,613	173,548	58,912	41,789	-18,829***
	$\mu_{250} < \mu_{275}$	113,419	139,613	73,252	58,912	-12,686***
	$\mu_{275} < \mu_{300}$	87,000	113,419	38,200	73,252	-13,933***
H4	$\mu_{100} < \mu_{125}$	4,408	4,527	0,006	0,003	-6,960***
	$\mu_{125} < \mu_{150}$	4,257	4,408	0,006	0,006	-7,770***
	$\mu_{150} < \mu_{175}$	4,113	4,257	0,005	0,006	-7,527***
	$\mu_{175} < \mu_{200}$	4,034	4,113	0,005	0,005	-4,436***
	$\mu_{200} < \mu_{225}$	3,901	4,034	0,005	0,005	-7,551***
	$\mu_{225} < \mu_{250}$	3,780	3,901	0,007	0,005	-6,072***
	$\mu_{250} < \mu_{275}$	3,673	3,780	0,006	0,007	-5,246***
	$\mu_{275} < \mu_{300}$	3,605	3,673	0,005	0,006	-3,639***

***significant at the 0.001 level (critical value: -3,2905)

**significant at the 0.01 level (critical value: -2.5758)

*significant at the 0.05 level (critical value: -1.9600)

Table VI.2-d - *Results of the approximate two-sample Gauss-Test*

Expected value (μ)		**Variance (σ^2)**		**t-statistic**	**Critical t-value**
Sample 1	*Sample 2*	*Sample 1*	*Sample 2*		
193.355	310.581	340.770	2623.052	-11.989*	3.319

*significant at the 0.001 level