Financial Ex-ante Valuation of IT Projects

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Please note: Tables and figures are consecutively numbered per chapter, and within Chapters II, III, and IV per section (each representing one research paper). References are provided at the end of each chapter or research paper, respectively.

Index of Research Papers

This doctoral thesis contains the following five research papers, out of which two are already published:

Research Paper 1 (RP 1):

Hänsch F (2015) How Intangible are Intangibles? A Review on the Financial Ex-ante Valuation of Intangible Benefits in IT Projects. Working paper. Submitted to *Information Systems Frontiers*

VHB-JOURQUAL 3: category B

Research Paper 2 (RP 2):

Hänsch F (2015) Finanzwirtschaftliche ex-ante Bewertung intangibler Benefits von IT-Projekten. *HMD Praxis der Wirtschaftsinformatik* 52(6):945-957, doi: 10.1365/s40702-015-0187-4

VHB-JOURQUAL 3: category D

Research Paper 3 (RP 3):

Häckel B, Hänsch F (2014) Managing an IT Portfolio on a Synchronised Level, or: The Costs of Partly Synchronised Investment Valuation. In *Journal of Decision Systems* 23(4):388-412, doi: 10.1080/12460125.2014.946781

VHB-JOURQUAL 3: category B

Research Paper 4 (RP 4):

Dorsch C, Häckel B, Hänsch F, Hertel M (2015) Creating Competitive Advantage in E-business Value Chains by Using Excess Capacity via IT-enabled Marketplaces. Working Paper. Submitted to *IEEE Transactions on Engineering Management*

VHB-JOURQUAL 3: category B

Research Paper 5 (RP 5):

Häckel B, Hänsch F, Hertel M, Übelhör J (2015) Assessing IT Availability Risks in Smart Factory Networks. Working Paper. Submitted to *Decision Support Systems*

VHB-JOURQUAL 3: category B

I Introduction

The increasing advances in information and communication technology and the on-going and ever-faster digitization in all economic sectors give companies new opportunities to outperform their competitors and to even spawn new business models from within existing operations. Accordingly, the significance of information technology (IT) for the economic success of companies has continuously risen over the last decades. Modern IT plays an important and central role within most business models and not only aims on supporting operational tasks but also is of strategic relevance bearing the ability to contribute to creating competitive advantages for companies (Aral and Weill 2007; Porter and Millar 1985). Nevertheless, the business value of IT has been intensively discussed in literature throughout the last decades. Especially, numerous studies take an ex-post perspective and are concerned with understanding to what extent IT projects have created value on a firm level (Schryen 2013). While a few early studies doubt the economic benefits of IT (Dos Santos et al. 1993; Hitt and Brynjolfsson 1996; Rai et al. 1997), the broad literature agrees on the value-adding character of IT and emphasizes that IT can generate significant business value for companies of all business sectors (Beccalli 2007; Brynjolfsson and Hitt 2003; Kohli and Grover 2008; Lee et al. 2011; Melville et al. 2004).

However, IT does not provide easy and guaranteed success and its potential benefits do not materialize by just assigning a certain portion of a company's budget to the IT department. Instead, companies have to aim on a goal-oriented and focused application and management of their IT. Thus, in order to achieve sustainable economic value from IT investments, companies need to ensure a structured and comprehensive management of the value implications associated with an IT project, i.e. of all corresponding costs and benefits. This is of central importance throughout the full life cycle of an IT project, and the *process of managing the value implications of an IT project* can be structured into three steps: *First*, companies have to identify and evaluate the value implications of an IT project in an *ex-ante* perspective to achieve a sound information basis for IT investment decisions. *Second*, if the examined IT project shows to be beneficiary and gets implemented, the performance of the IT project has to be valued continuously, i.e. in an *ex-nunc* perspective. Through this, the need for counteractive measures can be identified in case the benefit realization shows to fall behind planned targets or in case costs overrun planned budgets. *Third*, after project completion an *ex-post* examination of finally realized benefits and accrued costs and a comparison with the ex-ante valuation should be conducted. Based on that, companies can obtain valuable information on potential improvements regarding future IT projects. To summarize, the described process of comprehensively managing an IT project's value implications can be represented as follows:

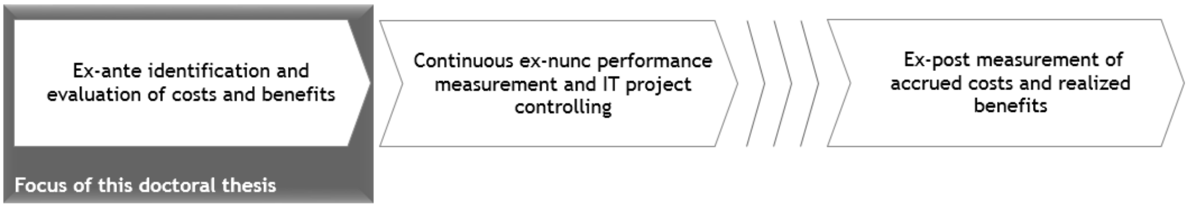

Figure 1. Process of managing the value implications of an IT project

Based on this general process, companies have to specify *how* to valuate IT projects. In this context, a common framework is given by the principle of value-based management (Coenenberg and Salfeld 2007; Copeland et al 1990; Stewart and Stern 1991) as a concretization of the shareholder value principle (Rappaport 1986). The concept of value-based management aims at maximizing the value of a company in a long-term oriented, holistic manner by aligning all business activities towards their value contribution. In order to exploit the full economic potential associated with IT projects and to support a long-term oriented value-based management, a comprehensive valuation should take into account both risk and return. Furthermore, the valuation should be based on cash flows and net present values (in contrast to periodical accounting measures), as the latter take into account the time value of money (Buhl et al. 2011; Renkema and Berghout 1997). Consequently, financial valuation approaches play an important role within a value-based management and are suitable to manage the value implications of IT projects throughout the full IT project's life cycle. In the first step of the valuation process, the financial ex-ante valuation provides a sound quantitative and monetary basis regarding an IT project's costs and benefits, and thus allows a well-founded justification of IT investment decisions in line with the goal of value-based management. In addition to ex-ante decision support, financial valuation techniques also facilitate a continuous benchmarking within ongoing and completed IT projects as the performance of IT projects can be checked with planned financial targets (Angell and Smithson 1991). Thus, financial valuation techniques may serve as an ex-nunc and ex-post control mechanism over costs and benefits of IT projects (Ayal and Seidmann 2009; Irani and Love 2002). Accordingly, the use of financial valuation approaches throughout the proposed valuation process has many advantages and supports sustainable economic growth. Moreover, as financial methods and measures are well known and understood, they support a transparent communication within a company (Ballantine and Stray 1998; Milis and Mercken 2004).

Against this background and in the context of the outlined valuation process, the present doctoral thesis focuses on the *ex-ante perspective*, and in particular on the *application of financial approaches* regarding the valuation of IT projects. Since a well-founded and thorough financial ex-ante analysis of IT projects lays the foundation for valuable investment decisions, this first step of the valuation process is of tremendous importance for the potential economic success of companies. This holds especially true as companies of all business sectors are increasingly exposed to economic and competitive pressure. (Rai and Sambamurthy 2006; Bacon 1992). However, the comprehensive ex-ante valuation of IT projects has demonstrated to be challenging for several reasons. Firstly, modern IT has evolved to provide extensive functionality and penetrates companies in nearly all business activities, leading to highly complex IT projects. Moreover, companies usually conduct a large number of IT projects simultaneously and thus should manage their IT portfolio in an integrated perspective to account for interdependencies. Furthermore, IT enables companies to offer business models that are based on complex digitized cross-company networks. This further complicates the determination and management of an IT project's value implications. Against this background, three particular challenges regarding the financial ex-ante valuation of IT projects are addressed in this doctoral thesis (Chapters II-IV):

(i) Financial valuation of intangible benefits of IT projects
(ii) Consideration of interdependencies between IT projects
(iii) Valuation of IT projects in digitized value networks

Regarding the first challenge: As discussed above, the role of IT has significantly changed over the last decades and companies of almost all business sectors have shown a distinct growing need for making IT a core component of their business model and success. Accordingly, IT affects nearly all business activities across different divisions and levels from top to bottom as well as external stakeholders such as customers or suppliers. These developments lead to an increasing complexity of IT projects that potentially affect all layers of the enterprise architecture, from the business model to the process, service, and infrastructure layer (Buhl und Kaiser 2008). This complexity hampers the financial ex-ante valuation of IT projects. While large parts of the costs of IT projects are directly measurable, difficulties regarding a comprehensive financial ex-ante valuation especially arise on side of the associated benefits as their implications are usually wide-ranging and multifaceted (Tallon et al. 2000; Wemmerlöv 1990). For example, IT projects may improve the efficiency of (cost-intensive) business processes, enhance staff productivity or management capabilities, or contribute to a higher service level fostering customer satisfaction. Consequently, as these examples indicate, the benefits of an IT project do not only comprise tangible benefits such as direct cost reductions, but also *intangible benefits* that are indirect, elusive or subtle (Dos Santos 1991; Hochstrasser 1990). Whereas tangible benefits can generally be quantified rather easily using financial valuation approaches, especially the financial impact of intangible benefits cannot be determined directly (Irani and Love 2001; Remenyi et al 1993; Hinton and Kaye 1996; Keen and Digrius 2003). Nevertheless, with respect to the importance of intangible benefits, literature agrees that intangible benefits have to be included in the ex-ante valuation to enable a sound justification of IT projects and to ensure value-adding investment decisions (Simmons 1996; Irani 2002; Rivard and Kaiser 1989; Willcocks 1992). As intangible benefits show no direct or obvious financial implications, decision-makers have to find ways to indirectly assign a financial value by determining the cause-and-effect relations between intangible benefits and the financial bottom line to support a comprehensive financial ex-ante valuation of IT projects. This challenge is addressed in the research papers included in Chapter II of this doctoral thesis.

Regarding the second challenge: A comprehensive ex-ante valuation is additionally complicated, as IT projects are usually regarded as highly risky and contribute substantially stronger to a company's overall risk position than other investment types (Dewan et al 2007). This impact is further leveraged as the large number of IT projects conducted simultaneously affects various business units as well as different areas of corporate activity. Accordingly, there are numerous interdependencies between IT projects that might heavily affect the risk of IT projects, respectively of the total IT portfolio. In this context, literature distinguishes between intertemporal and intratemporal interdependencies (Kundisch and Meier 2011). *Intratemporal interdependencies* exist between different IT projects at a certain point in time and occur if, for example, scarce resources are shared among different IT projects simultaneously (Cho and Shaw 2013; Gear and Cowie 1980). In contrast, *intertemporal interdependencies* exist between different points in time and occur if, for example, a current IT project leverages or reduces the value of a future project, and vice versa (Bardhan et al. 2004; Benaroch and Kauffman 1999). As those interdependencies are considered to have a significant impact on the risk-/return structure of a company's IT portfolio, their accurate assessment within a comprehensive ex-ante valuation is critical to avoid suboptimal IT investment decisions (Bardhan et al. 2004; Benaroch et al. 2007; Lee and Kim 2001; Santhanam and Kyparisis 1996). Consequently, the ex-ante valuation of IT investment alternatives has to take into account both the existing IT portfolio and the multifaceted interdependencies between different IT projects. In doing so, companies should carefully balance the risks and returns of the IT projects and therefore treat the entirety of a company's IT projects as a portfolio of assets similar to a financial portfolio (Cho and Shaw 2013; Jeffery and Leliveld 2004). To support a well-founded financial ex-ante valuation of IT projects, companies and decision makers require an integrated approach that allows evaluating and analyzing IT projects under consideration of intratemporal and intertemporal stochastic interdependencies. This challenge is addressed in the research paper included in Chapter III of this doctoral thesis.

Regarding the third challenge: The increasing advances in information and communication technology allow an ever-higher penetration of all business areas through IT and enable a continuous and extensive transformation of business models and value chains. The interplay between IT systems, Internet services and networked embedded systems enables an unprecedented level of data collection and processing that bears the potential for enormous advancements both in service and manufacturing industries (Amin et al. 2013; Barrett et al. 2015; Geisberger and Broy 2015; Kagermann et al. 2013). In the *service industry*, sophisticated IT systems offer extensive possibilities of vertical disintegration and foster a strong fragmentation of corporate value chains. The advances of IT-based communication and coordination systems have facilitated the integration of service providers in the value networks of companies and IT-based digital services can be accessed on a global level. Consequently, business partners are able to interact in a highly dynamic manner (Grefen et al. 2006; Moitra and Ganesh 2005). Those developments offer high economic potentials, but also bear additional risks regarding service levels or security, confidentiality and privacy. In the *manufacturing industry*, technological concepts such as the Internet of Things and Cyber-Physical Systems continue to interconnect the physical and the virtual world (Chui et al. 2010; Broy et al. 2012). In this context, so-called smart factories are one of the most promising application areas, as they lead to massive advancements in manufacturing (Lasi et al. 2014). The combination of physical production with digital information by connecting networked embedded systems forms highly automated manufacturing environments that enable a flexible production of individualized goods while increasing efficiency at the same time (Lucke et al. 2008; Radziwon et al. 2014). Besides these opportunities for creating competitive advantages, the criticality of information and communication systems increases the smart factory's vulnerability to IT security risks regarding availability (Amiri et al. 2014). Due to the digitization of economic activities in the service and manufacturing industry, companies have to manage the dynamic transformation of their existing business models in order to remain competitive in global markets (Geisberger and Broy 2015). Accordingly, companies require considerable investments in digitized value networks (Kagermann et al. 2013). By thoroughly investigating the impacts of IT projects in digitized value networks, companies can gain insights into necessary transformations of their business model or value chains. Accordingly, the valuation of IT projects in digitized value networks poses a substantial challenge from a business point of view. This challenge is addressed in the research papers included in Chapter IV of this doctoral thesis.

In summary, the financial ex-ante valuation of IT projects poses challenges regarding (i) the financial valuation of intangible benefits, regarding (ii) the consideration of interdependencies between IT projects, and regarding (iii) the valuation of IT projects in digitized, networked business environments. The following Section I.1 substantiates the objectives and structure of this doctoral thesis. Subsequently, in Section I.2 the corresponding research papers are embedded in the research context and the fundamental research questions are highlighted.

I.1 Objectives and Structure of this Doctoral Thesis

The main objective of this doctoral thesis is to contribute to the field of *Finance and Information Management* with a particular focus on the financial ex-ante valuation of IT projects. Table 1 provides an overview of the objectives and the structure of this doctoral thesis.

I Introduction	
Objective I.1:	Outlining the objectives and the structure of the doctoral thesis.
Objective I.2:	Embedding the included research papers into the research context of the doctoral thesis and motivating the fundamental research questions.
II The Value of Intangible Benefits in IT Projects (Research Papers 1 and 2)	
Objective II.1:	Providing a comprehensive overview of existing research that valuates intangible benefits of IT projects with financial approaches.
Objective II.2:	Identifying the key factors and methodological starting points for the financial ex-ante valuation of intangible benefits.
Objective II.3:	Providing practical oriented guidance for companies and decision-makers regarding the management and valuation of intangible benefits.
III Risk Quantification of IT Projects in Consideration of Stochastic Interdependencies (Research Paper 3)	
Objective III.1:	Providing a valuation approach offering an integrated view on risk and return in a portfolio context.

Objective III.2:	Analyzing the influence of stochastic interdependencies on the ex-ante valuation of IT projects.
Objective III.3:	Providing guidelines for improving the maturity of a company's IT portfolio management.
IV Valuation of IT Projects in Digitized Value Networks (Research Papers 4 and 5)	
Objective IV.1:	Analyzing the ex-ante capacity planning of IT service providers for standardized services in e-business value chains.
Objective IV.2:	Identifying and analyzing potential competitive advantages of the usage of excess capacity markets within e-business value chains.
Objective IV.3:	Developing a risk assessment approach supporting companies to identify and evaluate IT availability risks in smart factory networks.
Objective IV.4:	Analyzing different IT security measures and their risk reduction effect in smart factory networks.
V Summary and Future Research	
Objective V.1:	Summarizing the key findings of the doctoral thesis.
Objective V.2:	Highlighting starting points for future research.

Table 1. Objectives and structure of the doctoral thesis

I.2 Research Context and Research Questions

A sound and comprehensive ex-ante valuation of IT projects is a central success factor in order to foster the value creation goal of a company in accordance with the principles of value-based management. In this context, financial valuation approaches facilitate well-founded IT investment decisions by enhancing the quantitative information basis for companies and decision makers. Regarding the financial ex-ante valuation of IT projects, this doctoral thesis extends the body of knowledge of the discipline Finance and Information Management.

To address the associated challenges outlined in the previous section, (i) the valuation of intangible benefits of IT projects with help of financial approaches is thoroughly examined and methodological approaches and key success factors are discussed (Chapter II). Furthermore, (ii) an ex-ante valuation approach considering stochastic interdependencies between IT projects in a portfolio perspective is provided to examine the quantitative impact of interdependencies on IT investment decisions (Chapter III). Finally, (iii) this doctoral thesis presents approaches to analyze IT projects in innovative IT-driven business models in the service and manufacturing industry that are enabled by advances through the on-going digitization of value chains (Chapter IV). In the following section, the research papers included in this doctoral thesis are embedded in the research context and the respective research questions are motivated accordingly.

I.2.1 Chapter II: The Value of Intangible Benefits in IT Projects

Research Paper 1*: "How Intangible are Intangibles? A Review on the Financial Ex-ante Valuation of Intangible Benefits in IT Projects"*

The value implications of IT projects are generally multifaceted and wide-ranging, and do not only comprise tangible aspects such as direct cost reductions. Instead, significant benefits of IT projects (such as improvements of customer satisfaction or management capabilities) are often indirect, elusive or subtle (Dos Santos 1991; Hochstrasser 1990). These *intangible benefits* are difficult to quantify. Nevertheless, literature agrees that intangible benefits should be integrated in the ex-ante valuation to enable a well-founded justification of IT projects and IT investment decisions in line with a value-based management (Simmons 1996; Irani 2002; Rivard and Kaiser 1989; Willcocks 1992). However, there are differing views on how to include intangible benefits in a comprehensive quantitative ex-ante valuation, especially with regard to the applicability of financial approaches. On the one hand, many studies argue that traditional financial valuation techniques are not capable to accurately assess IT projects as the financial impact of intangible value components cannot be quantified directly (Farbey et al. 1992; Tallon et al. 2000; Jelinek and Goldhar 1986; Meredith and Suresh 1986). Consequently, literature proposes alternative multidimensional valuation frameworks that assess intangible benefits using qualitative arguments or alternative non-financial measures such as score values (Meredith and Suresh 1986; Parker and Benson 1988; Stewart and Mohamed 2002). On the other hand, another stream of literature claims that all benefits – and hence also intangible benefits – finally affect the financial bottom line, and therefore should be quantifiable (Litecky 1981; Smith 1983; Whitten et al. 1989). Against this background, research paper 1 conducts a literature review and presents an analysis and discussion of research studies that determine financial values based on a thorough examination of the cause-and-effect relations between intangible benefits and the financial bottom line. The research paper aims to enhance the understanding of intangible benefits and the possibilities regarding their financial ex-ante valuation and lays the ground for further advances in research and practice. The research paper addresses the following research questions:

- Which methodological approaches and concepts have been applied in literature to include intangible benefits in a financial ex-ante valuation of IT projects?
- Which (areas of) intangible benefits have been examined in a financial ex-ante valuation of IT projects in literature?
- Concerning the financial ex-ante valuation of intangible benefits, which research gaps can be identified?

Research Paper 2: *"Finanzwirtschaftliche ex-ante Bewertung intangibler Benefits von IT-Projekten"*

Some decades ago, the first clerical IT systems primarily supported relatively simple operational tasks and aimed on achieving cost savings by exploiting efficiency potentials. The economic potentials of these IT systems could be quantified relatively easily by applying traditional methods of cost-benefit analysis. Nowadays, due to the variety and multitude of *intangible benefits* of modern IT systems, companies struggle to achieve a sound valuation of IT projects that supports well-founded investment decisions in line with a value-based management. Especially, the financial impacts of the intangible benefits cannot be quantified directly. Consequently, the financial analysis of IT projects usually relates only to the comparatively easy measurement of direct cost savings and the final decisions on investments are often made as an *act of faith* (Irani 1999; Irani 2002; Willcocks 1992; Hochstrasser and Griffiths 1991). With respect to the indisputable importance of intangible benefits, this lack of a comprehensive analysis and valuation, by all means, falls short, and bears the risk of systematic misevaluations and a sub-optimal allocation of available resources. At the same time, due to the ever-increasing global competition, there is a growing need to justify IT projects in financial terms. Consequently, a further financial analysis of intangible benefits is of increasing importance for companies of all business sectors. To support companies in this regard, research paper 2 analyzes the possibilities to evaluate intangible benefits by financial methods and shows how the financial implications of intangible benefits can be quantified through a detailed analysis of the underlying causal relationships. Moreover, the research paper suggests a structured evaluation process and discusses corresponding core challenges, practical methodological approaches and key success factors. With this, the research paper addresses the following research questions:

- How should a practice-oriented process for the financial ex-ante valuation of intangible benefits of IT projects be designed?

- Which methodological approaches support a financial ex-ante valuation of intangible benefits and what are the central success factors?

I.2.2 Chapter III: Risk Quantification of IT Projects in Consideration of Stochastic Interdependencies

Research Paper 3: *"Managing an IT Portfolio on a Synchronised Level, or: The Costs of Partly Synchronised Investment Valuation"*[1]

IT governance and IT strategy need to assist the business in realizing its goals by supporting the company-wide strategy through a well-defined IT portfolio management (ITPM) approach (Weill and Ross, 2004; Gottschalk, 1999). ITPM has emerged into a combination of practices and methods used to manage existing IT and IT projects and to measure and improve risk and return of a company's IT. In this context, the maturity of a company's ITPM can be categorized by four maturity levels: ad hoc, defined, managed and synchronized (Jeffery and Leliveld 2004; Oh et al. 2007; Reyck et al. 2005). Thereby, the empirical study of Jeffery and Leliveld (2004) indicates that usually only IT portfolios of such companies significantly contribute to long-term value creation, that manage their IT portfolio on a *synchronized level*. The capability maturity models define a set of central elements regarding practices and methods that have to be applied by a company in order to achieve an ITPM on a synchronized level (Jeffery and Leliveld 2004). Accordingly, companies have to e.g. synchronize their IT projects with corporate strategy, implement a standardized process for IT project selection, measure an IT project's value through its life cycle, sort out underperforming initiatives, or ensure frequent feedback between business and IT units (Jeffery and Leliveld 2004). Moreover, further key elements of a synchronized ITPM correspond to the basic concept of a value-based management. In particular, a synchronized ITPM, as well as a value-based management, has to take an integrated view on risks and returns of a company's IT and therefore should treat the entirety of a company's IT projects as a portfolio of assets similar to a financial portfolio (Jeffery and Leliveld 2004; Cho and Shaw 2009). For this, a sound valuation of IT projects is required, that is based on financial metrics and especially takes into account an IT portfolio's risks. In this context, a synchronized ITPM also has to take account of the risks that result from the various intratemporal and intertemporal interdependencies. Intratemporal interdependencies exist between different IT projects at a certain point of time

1 Please note that research paper 3 has been published in British English (BE) and consequently is included in BE in Section III.1. Furthermore, when mentioning the *full paper title* outside Section III.1, the spelling corresponds to BE. Beyond that, the doctoral thesis is written in American English (AE), and hence, any further explanations or discussions of research paper 3 outside Section III.1 correspond to AE.

(Gear and Cowie 1980; Cho and Shaw 2009), intertemporal interdependencies exist between different points of time (Bardhan et al. 2004; Benaroch and Kauffman 1999). Since those interdependencies can have a tremendous impact on the risk-/return structure of a company's IT portfolio, their careful consideration is crucial to avoid unfavorable IT investment decisions (Santhanam and Kyparisis 1996; Lee and Kim 2001; Bardhan et al. 2004; Benaroch et al. 2007). Research paper 3 proposes an optimization approach that is in line with a synchronized ITPM and thus with a value-based management. Based on that, the research paper shows that an ITPM that ignores stochastic interdependencies, referred to as *partly synchronized* ITPM, leads to sub-optimal investment decisions. Moreover, the research paper thoroughly analyzes how different risk-/return structures of IT investment opportunities affect the valuation by a comprehensive simulation study. Finally, a stepwise approach regarding the improvement of a company's ITPM is presented. Accordingly, the research paper addresses the following research questions:

- How big is the "valuation error" in case IT investments are valued based on an only partly synchronized ITPM which is neglecting (stochastic) interdependencies?
- How much should a company invest in improving the maturity of its ITPM regarding the consideration of interdependencies?

I.2.3 Chapter IV: Valuation of IT Projects in Digitized Value Networks

***Research Paper 4**: "Creating Competitive Advantage in E-business Value Chains by Using Excess Capacity via IT-enabled Marketplaces"*

The progressing digitization of business processes fosters a continuing transformation of e-business value chains as well as new and innovative forms of cooperation (Barua et al. 2001; Andal-Ancion et al. 2003; Ramirez et al. 2010). In this context, the concept of business process outsourcing (BPO) allows companies sourcing whole business processes from external providers that allocate all necessary technical and personnel resources (Sengupta et al. 2006). For standardized and digitized business processes, this approach has even evolved to the "business process as a service" (BPaaS) concept. By analogy with concepts such as software or infrastructure as a service, BPaaS describes a dynamic BPO relationship between a business process service provider (BPSP) and its business clients. The technical integration via Internet-based technologies, allows BPSP to deliver a wide range of digitized and standardized services within a flexible contract period and a consumption-based pricing model. Within this business model, most BPSP face very volatile demand but are not able to react to demand fluctuations by scaling their IT capacity or their personnel resources on short notice. Nevertheless, to avoid SLA-related penalties, the BPSP must be able to cover peak demand while also ensuring the efficient use of resources in times of average or low demand (Bassamboo et al. 2010a; Bassamboo et al. 2010b). Finding the right balance within this tradeoff is a major challenge to operate cost-efficient and thus is a precondition for achieving economic success in such cost-driven environments. Consequently, the BPSP has to ensure a sophisticated ex-ante planning of its in-house capacities. Innovative technologies such as service-oriented architectures, cloud-computing, and associated concepts may help, as they are catalyst for IT-driven marketplaces that allow business partners to interact in a highly dynamic manner (Grefen et al. 2006; Moitra and Ganesh 2005). These IT-driven marketplaces provide an information platform for a coordinated interplay of market participants and allow matching available excess capacity with excess demand. Consequently, these technological developments enable a demand-driven and temporary integration of business partners and allow exchanging excess capacity to mitigate the capacity-planning problem of BPSP. However, using excess capacity bears the risk that a BPSP is served only when capacity is available on the market. Against this background, research paper 4 examines the corresponding potential of IT-enabled excess capacity markets (ECM) to create competitive advantage in cost-driven e-business value chains by analyzing a BPSP's capacity-related optimization problem. The research paper provides an analytical model based on queuing theory and evaluates it through a discrete-event simulation applying a possible application scenario. Furthermore, as the usage of ECM requires high upfront-investments in information and integration capabilities, the quantitative results of the model provide evidence about reasonable investment costs. The research paper addresses the following research question:

- Which competitive advantages can be realized through an IT-enabled ECM within a BPSP's value chain regarding the processing of cost-driven service requests?

Research Paper 5: *"Assessing IT Availability Risks in Smart Factory Networks"*

The Internet-of-Things and Cyber-Physical Systems combine physical production networks with digital IT systems. This results in complex smart factory networks and leads to tremendous advancements and paradigm shifts in manufacturing (Lasi et al. 2014). Cyber-Physical Systems consist of embedded systems connected over the Internet or other network infrastructures and form dynamic and self-controlling networks (Broy et al. 2012; Schuh et al. 2014). Within these networks, smart objects control and monitor the production process collaboratively using sensors and actuators and machine-to-machine communication

(Hessman 2013; Schuh et al. 2014; Yoon et al. 2012). Smart factory networks offer a variety of benefits like increased flexibility and productivity, optimized processes, improved capacity utilization, reduced lead times or enhanced energy and resource efficiency (Chui et al. 2010; Radziwon et al. 2014; Schuh et al. 2014; Shrouf et al. 2014; Yoon et al. 2012). Furthermore, smart factory networks enable to produce highly individualized products in low batch sizes in a considerably short time-to-market at costs comparable to mass production (Lasi et al. 2014). This is of central importance for companies in all manufacturing industries, as customer expectations shift toward mass customization, ever-shorter innovation cycles, and customer participation models (Lasi et al. 2014; Yoon et al. 2012). As smart factory networks extensively rely on communication and real-time information synchronization, they largely depend on the underlying IT systems, which are mandatory for the reliable operation of the production infrastructure (Yoon et al. 2012; Zuehlke 2010). Due to this dependency, short-term non-availabilities of IT systems can interrupt the operation of the dependent production infrastructure (Lee 2008; Lucke et al. 2008; Zuehlke 2010). Targeted attacks, e.g. denial-of-service attacks, or technical failures can cause the unavailability of IT services, and thus affect the functionality of the production network and reduce its productivity (Amin et al. 2013; Lucke et al. 2008; Zuehlke 2010). These failures are especially problematic considering that smart factories are no longer isolated and closed systems like conventional, self-contained production facilities, but highly connected with both internal and cross-company networks, including suppliers, customers, and vendors (Smith et al. 2007; Yoon et al. 2012). Therefore, IT availability risks pose a significant threat potential to smart factories and cross-company smart factory networks. In order to respond to these threat scenarios, companies have to employ IT security measures to secure their infrastructure against IT availability risks. Appropriate IT security measures include, but are not limited to, redundancies through backup components, industrial hardware with integrated IT security mechanisms, intrusion detection systems, or appropriate service-level agreements (Byres and Lowe 2004; Cardenas et al. 2008; Yadav and Dong 2014; Zambon et al. 2007). Against this background, research paper 5 provides a risk assessment model that supports companies in identifying and evaluating the most critical areas of the information network while considering the underlying production network. The model provides a structured approach and considers network structures and interdependencies. The insights gained by the model present a profound economical basis for ex-ante investment decisions on IT security measures. Consequently, the research paper addresses the following research questions:

- How can a smart factory network consisting of dependent and connected production components and IT systems be modeled and formalized?
- How can IT availability risks of IT systems in a smart factory network be quantified in order to identify the most critical nodes?

I.2.4 Chapter V: Results and Future Research

Following this introduction, which aims at outlining the objectives and the structure of this doctoral thesis as well as at motivating the research context and formulating the fundamental research questions, the respective research papers are presented in Chapters II, III and IV. Subsequently, the key findings are summarized and starting points for future research are highlighted in Chapter V.

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II The Value of Intangible Benefits in IT Projects

The research papers in Chapter II focus on the financial ex-ante valuation of intangible benefits of IT projects. A comprehensive financial ex-ante valuation of IT projects is one of the major challenges within IT management and IT governance as IT projects usually comprise multitudes of intangible benefits that are difficult to quantify. Given the complexity to evaluate intangible benefits of IT projects, investment decisions are often made as an act of faith and lack a comprehensive analysis and valuation. However, without detailed knowledge about the financial implications of an IT project, companies cannot base their IT investment decisions on a profound basis and resources may be allocated in a non-value-adding way. With respect to the indisputable importance of intangible benefits, this "valuation approach", by all means, falls short.

Against this background, research paper 1 (*"How Intangible are Intangibles? A Review on the Financial Ex-ante Valuation of Intangible Benefits in IT Projects"*) provides an overview of existing research on the financial ex-ante valuation of intangible benefits by conducting a corresponding literature review. The research paper analyzes the methodological approaches that have been used in existing studies to identify and quantify the relevant intangible benefits. Moreover, the literature review presents an overview on the types of intangible benefits that have been evaluated financially in literature so far. In doing so, the research paper aims to analyze how intangible benefits of IT projects have been valuated using financial valuation approaches in an ex-ante perspective, and which intangible benefits have been considered. The paper enhances our understanding on intangible benefits and their valuation and lays the ground for further advances in research and practice.

Moreover, research paper 2 (*"Finanzwirtschaftliche ex-ante Bewertung intangibler Benefits von IT-Projekten"*) proposes a structured evaluation process for the financial ex-ante valuation of intangible benefits and shows how the financial implications of intangible benefits can be quantified through a detailed analysis of the underlying causal relationships. In this context, corresponding core challenges, practical methodological approaches and key success factors are discussed. The research paper supports companies and decision makers in improving their quantitative, financial information basis needed for profound IT investment decisions. Furthermore, the research provides recommendations for the implementation of a corresponding valuation process in companies.

II.1 Research Paper 1: "How Intangible are Intangibles? A Review on the Financial Ex-ante Valuation of Intangible Benefits in IT Projects"

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Abstract: *Literature agrees that the value implications of IT projects are generally multifaceted and wide-ranging, and not only comprise tangible aspects, such as direct cost reductions, but also significant intangible benefits, such as improvements of customer satisfaction or management capabilities. Consequently, these intangible benefits have to be included in the ex-ante valuation of IT projects to ensure value-adding investment decisions. However, there are differing views regarding the applicability of financial approaches for the ex-ante valuation of intangible benefits. In order to address this field of tension, we conduct a literature review and present an analysis and discussion of research studies that determined financial values based on a thorough examination of the cause-and-effect relations between intangible benefits and the financial bottom line. Our study thereby enhances the understanding of intangible benefits and the possibilities regarding their financial ex-ante valuation, and offers starting points for further research.*

Keywords: *Intangible Benefits, Tangible Benefits, IT Valuation, Ex-ante Valuation, Financial Valuation, Systematic Review*

II.1.1 Introduction

Modern information technology (IT) and information systems (IS) play a central role within most businesses. They not only aim on supporting operational tasks, but are also of significant strategic relevance with the ability to create competitive advantages for companies (e.g., Porter and Millar 1985; Cash and Konsynski 1985; Bacon 1992; Aral and Weill 2007). There has been some discourse on whether IT investments create value, but literature has agreed on the value-adding character of IT investments (e.g., Beccalli 2007; Brynjolfsson and Hitt 2003; Han et al. 2011; Kohli and Grover 2008; Lee et al. 2011; Melville et al. 2004). To exploit the potential value associated with IT and IS, companies must invest in IT projects that are in line with its business objectives and will contribute to the company's financial bottom line. A thorough analysis and ex-ante valuation of investment alternatives is of utmost importance in order to make valuable investment decisions regarding IT projects. This holds especially true as companies of all business sectors are increasingly exposed to economic and competitive pressure, and have to ensure a mindful allocation of their limited resources and investment budgets (Bacon 1992; Carlyle 1990). However, the comprehensive ex-ante valuation of IT projects has demonstrated to be quite complex. This is especially owed to the fact that the value implications of IT projects are multifaceted and wide-ranging, and they affect many areas within an organization as well as its external stakeholders, such as customers or suppliers. IT projects may initiate changes in business processes, enhance the capabilities and productivity of staff and managers, or contribute to higher customer satisfaction. The benefits of an IT project not only comprise tangible aspects, such as direct cost reductions, but are often indirect, elusive, or subtle (Dos Santos 1991; Hochstrasser 1990). Such benefits are mostly referred to as *intangible benefits*. Although there are some different perceptions of the notion "intangible" ranging from "non-quantifiable" to "difficult to quantify", literature commonly agrees that especially the financial impact of intangible benefits cannot be determined directly (Irani and Love 2001; Remenyi et al 1993; Hinton and Kaye 1996; Keen and Digrius 2003).

Given the complexity of evaluating the intangible benefits of IT projects, decisions on IT investments are often made as an *act of faith* (Irani 1999; Irani 2002; Willcocks 1992; Hochstrasser and Griffiths 1991) and lack a comprehensive analysis and valuation. With respect to the indisputable importance of intangible benefits, this "valuation approach" falls short. Instead, literature agrees that intangible benefits must be included in the ex-ante valuation to enable a sound justification of IT projects and to ensure value-adding investment decisions (Simmons 1996; Irani 2002; Rivard and Kaiser 1989; Willcocks 1992). However, there are differing opinions as to how to include intangible benefits in a comprehensive ex-ante valuation. Many studies argue that traditional financial and economic valuation techniques cannot accurately assess IT projects, as the financial impact of intangible benefits cannot be quantified directly (Farbey et al. 1992; Tallon et al. 2000; Jelinek and Goldhar 1986; Meredith and Suresh 1986). Therefore, intangible value components are often assessed by using qualitative arguments or alternative non-financial measures, such as score values (Meredith and Suresh 1986; Parker and Benson 1988; Stewart and Mohamed 2002). In contrast, another branch of the literature supports the view that all benefits affect a company's financial bottom line, and in principle, should be quantifiable (Litecky 1981; Smith 1983; Whitten et al. 1989). This applies just the same for intangible benefits, although intangible benefits show no direct or obvious financial implications. For example, the intangible benefit *improved customer satisfaction* could be related to a quantifiable increase in a company's sales, and thus would allow a financial value to be *indirectly* assigned to the intangible benefit. Consequently, to be able to grasp their financial impact, decision-makers must find ways to determine the cause-and-effect relations between intangible benefits and the financial bottom line.

However, the possibilities in relating an intangible benefit to the financial bottom line in order to achieve an indirect financial valuation can differ widely between different intangible benefits. Referring to exemplary intangible benefits, such as *improved decision making* or *improved service quality*, the determination of a causal chain is more abstract and difficult for *improved decision making* than for *improved service quality* where the relation to a potential increase of a company's turnover seems more obvious. Furthermore, some benefits labeled "intangible" may even be easy to measure, for example, *timeliness of delivery*, and it could be argued that such benefits are tangible, at least partly. Thus, there is no clear boundary between tangible and intangible, and the benefits of IT projects fall along a spectrum of quantifiability (Sassone and Schaffer 1978).

Whether intangible benefits can be quantified and included in a financial valuation or not, consequently is not a question of black or white but, instead, is a grey area. Due to the significance of intangible benefits, and due to the relevance of financial valuation techniques for research as well as for companies and decision-makers, it is necessary to shed light on this field of tension. Therefore, we review the existing literature to enhance our understanding and to lay the groundwork for further advances in both research and practice. In doing so, we focus on analyzing existing research papers that apply methods to achieve a financial valuation of intangible benefits in an ex-ante perspective. Consequently, we aim to examine what already has been achieved in this context, analyze how intangible benefits have been incorporated in the financial ex-ante valuation of IT projects, and analyze which intangible benefits have been considered. We state the following research questions:

Research Question RQ1: Which methodological approaches and concepts have been applied in literature to include intangible benefits in a financial ex-ante valuation of IT projects?

Research Question RQ2: Which (areas of) intangible benefits have been examined in a financial ex-ante valuation of IT projects in literature?

Research Question RQ3: Concerning the financial ex-ante valuation of intangible benefits, which research gaps can be identified?

By answering these research questions, we systematically evince what already has been done in the context of the financial ex-ante valuation of intangible benefits. Accordingly, we aim to increase the awareness of intangible benefits and their impact on companies' financial bottom line. Moreover, we present potential starting points for future research, which could enhance the theoretical foundation for a successful financial ex-ante valuation of intangible benefits; also, we present starting points for companies aiming to improve their information basis for IT investment decisions, and thus, enhancing their existing valuation approaches and processes regarding the consideration of intangible benefits. To answer the research questions, we follow well-accepted research processes for literature reviews (Cooper and Hedges 1994; Webster and Watson 2002). After describing the research problem and the focus of our study in the introduction, we discuss the basic literature dealing with intangible benefits of IT projects and their valuation. Thereafter, we elaborate on our evaluation of the literature in order to identify research that has focused on performing a financial ex-ante evaluation of intangible benefits in IT projects. We then discuss differences and commonalities of the presented studies as well as starting points for further research. Finally, we present concluding remarks.

II.1.2 Theoretical Foundations

In this section, first, we will discuss different classifications of IT benefits, and definitions of the notion "intangible". Thereafter, we will present an overview of IT valuation frameworks that include intangible benefits to give an idea of the diversity of such approaches, and subsequently, will discuss the potential of financial approaches for the valuation of IT projects.

II.1.2.1 Intangible Benefits in IT Projects

A study of King and Schrems (1978) is among the first to offer a structured discussion on IT benefits and their potential classification. King and Schrems (1978) group benefits from IT projects into the following benefit categories: *contributions of calculating and printing tasks*, *contributions to record-keeping tasks*, *contributions to record-searching tasks*, *contributions to system restructuring capability*, *contributions of analysis and simulation capability*, and *contributions to process and resource control*. These benefit categories primarily reflect transactional benefits, which is not surprising since the first clerical IT systems primarily aimed on supporting simpler operational tasks. The conviction that IT projects may involve more strategic benefits was established later, and is elaborated upon by many studies, such as those of Parsons (1983), Cash and Konsynski (1985), Porter and Millar (1985), Bakos and Treacy (1986), or Piccoli and Ives (2005). According to Porter and Millar (1985), IT "is transforming the nature of products, processes, companies, industries, and even competition itself' (p.149). This emphasizes the strategic role of IT projects and their ability to create competitive advantages by giving companies new ways to outperform their competitors, and even spawn new businesses from within existing operations (Porter and Millar 1985).

Considering these wider objectives, and IT projects' potential benefits, Weill (1992) builds on the work of Turner and Lucas (1985) and offers an analysis of benefits, classifying IT projects based on different types of objectives; namely, *strategic*, *informational*, and *transactional*. Strategic IT aims to gain competitive advantage, and is expected to support growth or new businesses. Informational IT provides the informational infrastructure of a company, including, for example, production planning, communications, accounting, or other management tasks. Transactional IT helps to cut costs by substituting capital for labor, and therefore enhances operational management. Mirani and Lederer (1998) follow Weill (1992) and use the same categories to classify IT benefits. Based on a thorough literature research and subsequent empirical studies, Mirani and Lederer (1998) identify and validate a comprehensive list of benefits. Those are assigned to the mentioned benefit categories - strategic, informational and transactional – with each group containing three further types of benefits: *competitive advantage*, *alignment* and *customer relations* under strategic benefits; *information access*, *information quality* and *information flexibility* under informational benefits; and *communication efficiency*, *systems development efficiency* and *business efficiency* under transactional benefits.

Other than such general classification schemes for IT benefits, similar approaches focus on specific types of IT projects. For example, Irani and Love (2001) and Irani (2002) examine the benefits of manufacturing information systems. Building on Harris' (1996) benefit taxonomy, Irani and Love (2001) and Irani (2002) assign a comprehensive list of benefits to the *strategic*, *tactical*, and *operational* classes. Additionally, they examine all benefits regarding the possibilities of measurement distinguishing in *financial*, *non-financial* and *intangible*. According to the works of Irani and Love (2001) and Irani (2002), intangible benefits are benefits that cannot be quantified by financial or non-financial measures. Therefore, in their perception the notion "intangible" is congruent with "non-quantifiable." This view is widespread and was also applied by Gunasekaran et al. (2001) and Wemmerlöv (1990). The study of Irani and Love (2001) further discusses that the benefits in the different benefit categories move from being primarily intangible and hard to quantify in the class of strategic benefits, to being primarily tangible and directly quantifiable in the class of operational benefits. This underscores that it is not possible to draw a precise line between tangible and intangible benefits.

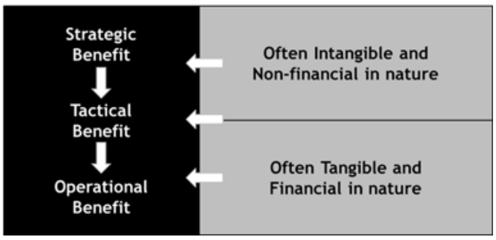

Figure 1. Strategic, Tactical, Operational Benefits, according to Irani and Love (2001)

A different definition of "intangible" is offered by Remenyi et al. (1993), and differentiates between the two dimensions *intangible* and *quantifiable*. According to Remenyi et al. (1993), a tangible benefit "…is one which directly affects the firm's profitability." A quantifiable benefit may be measured easily, but doesn't always directly affect a firm's profitability, and therefore may as well be intangible, i.e., a *reduced number of customer complaints* is an intangible benefit, but can be quantified quite easily. Although this intangible benefit is quantifiable by a non-financial figure, its value implications remain rather elusive. Some papers, similar to Mirani and Lederer (1998), Irani and Love (2001), and Irani (2002), specify structured lists of IT project benefits and are based on this definition proposed by Remenyi et al. (1993). For example, Shang and Seddon (2000) and Shang and Seddon (2002) identify and classify benefits for enterprise systems and focus on enterprise resource planning (ERP) systems. In their framework, the benefits of ERP systems are attributed to five benefit dimensions: *operational*, *managerial*, *strategic*, *IT infrastructure*, and *organizational*. Based upon this framework, Murphy and Simon (2002) examine each benefit in the context of ERP systems, whether it is tangible or intangible, and whether or not it is quantifiable. Murphy and Simon (2002) conclude that it is increasingly more difficult to measure strategic, organizational, and managerial benefits than operational and infrastructure benefits, which generally is in line with the findings of Irani and Love (2001) and Irani (2002) (cf. Figure 1).

Another vague definition supported by Hares and Royle (1994), Milis and Mercken (2004), and Hinton and Kaye (1996) describes all benefits as "intangible" that are *difficult to measure*. Based on this definition, Hares and Royle (1994) present a classification of only intangible benefits that are arranged regarding their increasing difficulty of measurement. They consider that the impact of intangible benefits is often exposed to a significant time lag (Dos Santos 1991; Brynjolfsson 1993; Brynjolfsson and Hitt 2003) and therefore they distinguish between *ongoing* intangible benefits and *future* intangible benefits.

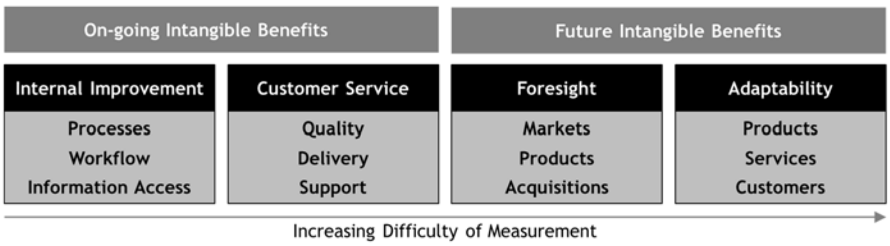

Figure 2. Classification of Intangible Benefits, according to Hares and Royle (1994)

As these considerations have shown, the definition of intangible benefits is not fully consistent, and some differing definitions exist which depict intangible as synonymous to *non-quantifiable*, *indirect effect on firm performance*, or *difficult to measure*. Apart from the differences in these definitions, all have in common, that the value implications of intangible benefits, especially regarding their financial value, are somehow elusive, vague, or subtle. Consequently, the financial impact of intangible benefits from IT projects cannot be quantified directly in an ex-ante perspective. Considering these commonalities, and with respect to the aim of our paper and the associated research questions, we in the following focus on this characteristic, and consider an intangible benefit as a benefit that implies *no directly quantifiable financial value*. Due to these rather vague definitions, and given the multitude of potential benefits and investment-specific conditions, these explanations still cannot provide a clear segregation between tangible and intangible benefits, and companies will always operate within a grey area when discussing tangible and intangible benefits. Regardless of this lack of clarity, the previous discussion made clear that the elusive or intangible benefits are significant value components of IT projects. Furthermore, Willcocks and Lester (1994) found that IT systems' intangible benefits were widely perceived by senior managers as being as important as tangible benefits. Various authors state that the intangible benefits often exceed the purely tangible benefits, and particularly for strategic, innovative, and/or very complex projects (Hinton and Kaye 1996; Bacon 1992; Hochstrasser 1990).

II.1.2.2 Ex-ante Valuation Frameworks for IT Projects

The previous discussions substantiate that intangible benefits are of utmost importance, and must be included in the ex-ante valuation in order to achieve a sound justification of IT investment decisions (Simmons 1996; Irani 2002; Rivard and Kaiser 1989; Willcocks 1992). A comprehensive ex-ante valuation of IT projects involves tangible as well as intangible benefits, generally leading to a variety of financial and non-financial measures, as well as qualitative assessments of these multifaceted value aspects. Responding to this challenge, literature has suggested a variety of valuation frameworks and multi-dimensional models that enable a more comprehensive analysis and valuation of IT projects, and especially include intangible benefits in a structured way. In the following, we do not aim to provide a complete overview on the existing literature in this area. Instead, we focus on presenting approaches that received much attention, and are widely applied in management practice, to give an idea of structured multi-dimensional frameworks that include non-financial valuations of intangible benefits.

The balanced scorecard concept (BSC) is a widespread generic valuation framework, and its suitability for the valuation of IT is discussed by Milis and Mercken (2004), Willcocks and Lester (1994), and Walter and Spitta (2004). In general, the underlying BSC framework of Kaplan and Norton (1992) aims to support management in taking an integrated look at a company or at investments by suggesting four value perspectives: *financial*, *customer*, *internal business*, and *innovation and learning*. Various papers tailored the framework of Kaplan and Norton to the specific requirements of IT investment valuation (Masli et al. 2011; Van Grembergen et al. 2003; Martinsons et al. 1999; Edberg 1997; Van der Zee and De Jong 1999), and, for example, adopted the applied perspectives, such as Martinson et al. (1999) that substituted *customer* with *user orientation*. Anyhow, regardless of the detailed elaboration of the perspectives, the multi-perspective view of the BSC approaches on the value of an IT project leads to a consideration of financial as well as non-financial value implications. In each perspective, the relevant benefits are identified, and subsequently, each benefit is valued with appropriate measures, such as a scoring of customer satisfaction or on-time delivery rates in the customer perspective, the improvement of capacity utilization rates in the internal business perspective, or a monetary term for direct costs savings in the financial perspective (Milis and Mercken 2004; Willcocks and Lester 1994).

Parker and Benson (1988) presented another popular multi-dimensional framework: the Information Economics (IE) approach. It aggregates score values for various aspects of benefits and risks. Parker and Benson (1988) distinguish between the *business domain*, comprised of *return on investment*, *strategic match*, *competitive advantage*, *management information support*, *competitive response*, and *project and organization risk*, and the *technology domain*, comprised of *strategic IS architecture*, *definition uncertainty*, *technical uncertainty*, and *IS infrastructure risk*. Each benefit and risk aspect is scored on a five-point Likert scale, and the financial value components are also converted to a non-financial score. Subsequently, all scores are aggregated under consideration of specific weights and probabilities depending on the company's current situation. This basic framework has been widely discussed and adapted by various other studies, such as Bakos and Kemerer (1992), Willcocks (1992), and Milis and Mercken (2004).

Many valuation frameworks further take into account the multifaceted value of IT projects by applying *multi-criteria utility theory*. For example, Stewart and Mohamed (2002) present a valuation approach based on the IE framework of Parker and Benson (1988), and use a hierarchical structure of value criteria and the decision maker's utility functions to determine an overall utility value for an IT project. Further studies using utility theory to determine the value of IT projects are presented, for example, in Ahituv (1980), Keeney and Raiffa (1976), Evans (1984), Dyer et al. (1992), and Köksalan and Sagala (1995). Similar to the multi-criteria approaches, the method of value analysis (Keen 1981; Money et al. 1988; Rivard and Kaiser 1989) classifies tangible and intangible benefits into homogeneous groups using statistical techniques, and subsequently attaches utility weights to each group of benefits.

The presented valuation approaches and frameworks are a sample from existing literature. For comprehensive and detailed examinations of existing evaluation frameworks, we also refer to Farbey et al. (1992), Farbey et al. (1993), Powell (1992), Renkema and Berghout (1997), Irani et al. (1997), Stewart and Mohamed (2002), or Sylla and Wen (2002).

These multi-dimensional frameworks offer guidance and structure as to how to value IT projects, including any elusive or intangible aspects. Regarding the valuation of intangible components, most frameworks go beyond a purely qualitative assessment, and apply subjective score-based methods or utility values to achieve a quantitative, but non-financial, valuation of intangible benefits. The methodological complexity in these approaches varies considerably from simple Likert scales, as in the IE approach of Parker and Benson (1988), to more elaborate approaches based on multi-criteria utility theory, as with Stewart and Mohamed (2002) or Evans (1984). Moreover, the frameworks differ regarding the overall presentation of results: often the various qualitative and/or quantitative values or scores are presented side by side, and represent the overall picture of the value of the respective IT investment as a basis for the decision-maker, such as in the BSC approaches. Alternatively, other approaches, especially in the field of utility theory, aggregate the different value components, and even tangible benefits are converted and aggregated with intangible benefits in one quantitative, non-financial result. Although this aggregation provides the advantage of enabling a comparison and ranking between different IT projects, there is a loss of detailed information on financial impacts and values.

Within the presented frameworks, the financial appraisal is only one part of the valuation, and is conducted only for the direct and tangible benefits. As we aim to analyze the possibilities to include intangible benefits in a financial ex-ante valuation, we will discuss the challenges, advantages, and disadvantages of financial valuation techniques regarding IT projects in more detail in the next section.

II.1.2.3 Financial Valuation of IT Projects

Many researchers emphasize the need to justify investments by carefully weighing costs and benefits, and comparing and ranking investment alternatives to ensure a mindful allocation of financial resources (Bacon 1992; Ballantine and Stray 1998; Dehning and Richardson 2002; Irani 2010). In addition to ex-ante decision support, financial valuation techniques also enable a benchmarking within ongoing projects, and the performance of IT projects can be checked with planned targets (Angell and Smithson 1991; Ginzberg and Zmud 1988). Thus, financial valuation techniques may serve as control mechanisms for the costs and benefits of IT projects (Ayal and Seidmann 2009; Irani and Love 2002). The use of a financial valuation has the advantage of being related to the concept of a value-based management and the objective of maximizing shareholder value. This is especially the case if the financial valuation is based on the net present value (NPV), in contrast to periodical accounting measures, as it takes into account the time value of money and supports decision making in the long term (Renkema and Berghout 1997; Buhl et al. 2011). Another argument is that in contrast to non-traditional valuation techniques, financial valuation techniques are well known and understood as they are based on generally accepted principles (Ballantine and Stray 1998; Clemons and Weber 1990; Milis and Mercken 2004) and support clear communication, both within a company and to the decision-maker (Lumby 1981). Therefore, the relevance of financial valuation techniques in companies' decision making is significant (Boaden and Dale 1990). Financial valuation approaches allow a comparatively easy integration of risk, such as adjusting the discount rate for the calculation of a NPV according to the IT investment's specific risk (Verhoef 2005). Apart from these arguments, the importance of financial valuation techniques is reflected by their widespread use in research on the ex-ante valuation of IT projects (Ballantine and Stray 1998; Bardhan et al. 2004; Benaroch et al. 2007; Schober and Gebauer 2011).

However, many studies argue that financial valuation techniques cannot accurately assess IT projects, especially as decision-makers find it difficult to financially quantify the intangible benefits (Aggarwal 1991; Farbey et al. 1993; Lefley and Sarkis 1997; Piotrowicz and Irani 2010). These studies highlight that financial valuation is an important part, but not the only part, of IT project valuation, and they argue that the valuation of IT projects requires a multi-dimensional approach to consider non-financial and intangible benefits (Alshawi et al. 2003; Irani 2010; Simmons 1996; Ayal and Seidmann 2009; Irani and Love 2002). Consequently, literature proposes alternative approaches, such as those presented in the previous section, that suggest a qualitative assessment, or the use of non-financial measures for intangible value components.

In contrast, other studies argue that intangible benefits can be considered for inclusion in a financial analysis as they are expected to affect the financial bottom line (Aris 1974; Litecky 1981; Smith 1983; Whitten et al. 1989). Aris (1974) admits that some effects may be difficult to measure, but consequently, should not be excluded from evaluation. Given the arguments supporting a financial valuation, we agree that decision-makers should try to incorporate as many benefits as possible into the financial bottom line. As the financial implications of intangible benefits cannot be quantified directly, decision-makers must find ways to *indirectly* determine their financial values (Primrose 1990; Keen and Digrius 2003; Tayyari and Kroll 1990). The aim should be to determine the causal chain that relates an intangible benefit to its ability to affect the financial bottom line, and to then measure or estimate this financial impact. This general procedure and some methodological recommendations have also recently been discussed in the practically oriented contribution of Hänsch (2015). However, the determination of such causal chains may be difficult, and perhaps not possible for every intangible benefit. Many intangible benefits lie in a grey area of quantifiability, which underlines that intangible benefits should not be excluded from a financial ex-ante valuation *by default*. To enhance our knowledge of how intangible benefits can be considered in the financial ex-ante valuation, and to analyze which intangible benefits have successfully included, we in the following present a literature review analyzing and discussing studies that successfully conducted a financial ex-ante valuation of intangible benefits.

II.1.3 Review on the Financial Ex-ante Valuation of Intangible Benefits

In this section, we will conduct a literature review identifying and discussing studies that determined financial values for intangible benefits to answer research questions RQ1 and RQ2. We conducted a structured web search of the online databases Proquest, ScienceDirect, EbscoHost, IEEE Xplore, and AIS Electronic Library combining the search terms (“information technology” OR “information system” OR “IT investment” OR “IS investment” OR “IT project”) and (“value” OR “benefit”) and (“intangible” OR “qualitative” OR “indirect” OR “non-financial” OR “nonfinancial”), as well as title, abstract, and keywords as search fields. These search terms are relatively broad, but allowed to identify studies that focus on the value or benefits of IT projects. As the literature regarding the value of IT projects is broad, we limited our search by specifically relating to the notion “intangible” respectively alternative and closely related terms. Due to the specific focus of our study, we did not further limit our search to certain journals or a specific time period. Our search led to 596 results after eliminating duplicates. As our search still contained numerous unrelated articles, we screened the resulting hits for relevance, and checked titles and abstracts regarding their context and thematic orientation. We then conducted forward and backward reference searches. The subsequent results contained 198 studies that have been examined in detail. The majority of the studies (183) discussed various aspects of intangible benefits (e.g., their importance or general challenges regarding their valuation), but did not focus on their financial ex-ante valuation. Consequently, only 15 studies made efforts to include intangible benefits in a financial ex-ante valuation of IT projects, which has been the decisive criterion for the inclusion of a study. We present an analysis and discussion of these studies in the subsequent section. It is important to note that this study does not claim to be fully comprehensive, although every effort has been made to include all existing studies of relevance.

II.1.3.1 Structured Overview

Previous discussions have indicated that the process of financially quantifying intangible benefits of an IT project can be segmented in two process steps. First, decision-makers must identify the intangible benefits and define the causal chain that relates an intangible benefit to its ability to affect a company’s financial bottom line. In this connection, intangible benefits, for example, may contribute to maintaining or increasing sales, justifying a higher price, or saving money by reducing costs. Second, based on the determined causal chain, the financial impact of an intangible benefit must be quantified. This process is similarly discussed in studies such as Hares and Royle (1994), although they segment the process in four steps, and is reflected in the examined studies' common procedure. Therefore, we use this two-step process to structure the presentation of the results (Table 1) as well as the subsequent analyses and discussions. We also include an analysis of the benefit areas, such as customers, internal processes, etc., that are examined in the identified studies. Table 1 presents a compact overview:

Author (Year)	Applied Concepts in Step 1: Identification	Applied Concepts in Step 2: Quantification	Focused application area or examined benefits
Matlin (1979)	Analysis of business objectives	Estimations of management	General approach
Litecky (1981)	Discussion of analysts	Estimation of analysts and management; Risk-adjusted discounting; Sensitivity analysis	General approach
Smith (1983)	Analysis of structured checklists according to business functions (*Benefits Profile Chart*)	Expected values, incremental analysis or value analysis	General approach
Schell (1986)	Deriving expected decisions with and without the IT system (Decision Analysis)	Expected values based on estimates (management, specialists); Sensitivity analysis	Focus on improved decision making
Primrose (1990)	Analysis of benefit checklists for MRP II systems	Computer-aided calculations based on estimates and company data	Focus on MRP II systems
Belcher and Watson (1993)	Interviews with users and managers; Analysis of usage statistics	Estimations of management, analysts and internal users	Focus on EIS systems
Hares and Royle (1994)	Analysis of Critical Success Factors (CSF), checklists	Market surveys, estimation of management, or comparative case studies	General approach
Anandarajan and Wen (1999)	Structured discussion according to different business perspectives	Expected value (NPV) based on estimates; Sensitivity analysis	General approach; Case study on benefits in the area of *customers* and *internal improvements*
Murphy and Simon (2001), Murphy and Simon (2002)	Classification framework; data collection, (semi-) structured interviews, survey information	Calculation of NPV based on company data and estimates (management, customers)	Focus on ERP systems; Case study on *improved customer satisfaction*
Dutta (2004)	Modeling cause-and-effect relations with System Dynamics approach	Simulation of multiple value settings; Sensitivity analysis	General approach; Case study on improved customer satisfaction and enhanced reputation
Peacock and Tanniru (2005)	Analysis of indirect performance effects by use of Activity-based justification	Calculation of NPV based on company data and estimates	Focus on process improvements; Case study on *reduction in sales effort*
Brun et al. (2006)	Analysis of key performance indicators; Questionnaires and interviews; Activity-based justification	Expected values based on company data and estimates (management, analysts); Risk analysis	Focus on SCM systems; Case study on *timeliness of deliveries*
Wu et al. (2006)	Structured analysis based on a list of 9 value drivers	Score-based value index model; fuzzy assessment approach for conversion to NPV.	Focus on ERP systems
Beer et al. (2013)	Structured analysis according to "benefit areas"	Expected value (NPV) based on estimates (management, consultants); Integrated approach considering risk	General approach; Case study on benefits in the area of *customers*

Table 1. Structured Results of the Literature Review

In the following, we will analyze and discuss commonalities and differences of these approaches regarding the two process steps to answer research question RQ1, and examine the areas of intangible benefits that have been included in the presented studies to answer research question RQ2.

II.1.3.2 Analysis and Discussion of Step 1: Identification

The identification of intangible benefits and the associated causal chains to the financial bottom line require a clear structure to allow for a comprehensive analysis. Many of the examined studies refer to different kinds of structured checklists that support a guided discussion and analysis of intangible benefits. Those checklists, for example, are based on the company's critical success factors (CSFs) that include many benefits that are considered intangible (Hares and Royle 1994). Also, a company's key performance indicators (KPIs) (Brun et al. 2006) or general business objectives (Matlin 1979) offer an excellent starting point for the further discussion of an IT project's benefits. Similarly, Wu et al. (2006) identify intangible benefits through a structured analysis based on a list of nine value drivers (e.g., creation ability, product quality, or enterprise environment). Another possibility to structure benefits is the use of a theoretical classification framework, such as that of Mirani and Lederer (1998) and Shang and Seddon (2000). Murphy and Simon (2002) use this as a starting point for further examination and build their study on Shang and Seddon's (2000) framework. A different approach can be found in further studies, such as that of Smith (1983), Anandarajan and Wen (1999), or Beer et al. (2013), which apply a stakeholder-related structuring of intangible benefits. Smith (1983) suggests the *benefit profile chart*, a type of checklist that structures benefits along the business functions of the considered organization, and through this, takes account of the project's effects on different internal stakeholders, for example, engineering, employees, human resources, or general management. Similarly, Anandarajan and Wen (1999) apply the perspectives of the production, sales, marketing, engineering, and accounting business functions to identify and structure IT benefits. Beer et al. (2013) assign each benefit to the area in which it occurs to consider the different stakeholders, for example, the customers' or employees' area.

Generally, there are many different approaches to support a structured discussion of the intangible benefits of an IT project. The selection of a certain approach or framework is very much related to company specifics or preferences as well as the specific IT project. A stakeholder-related structure seems especially suitable for projects that affect various business functions, or even customers or suppliers. Furthermore, the use of characteristics, such as CSF, KPI, or business objectives, may offer the additional advantage of being aligned with overall IT respectively business strategy. Anyway, a clear structure is of utmost importance to support a guided and comprehensive analysis, and we derive the following finding:

Finding F1: The majority of studies are based on a clear structure to initially identify the relevant intangible benefits, for example, by the use of structured checklists or benefit classification schemes.

The relevance of considering different stakeholder groups is not only reflected in the structure of some identification approaches, but many studies also emphasize the advantages of involving different internal or external stakeholders in a detailed analysis of cause-and-effect relations. For example, the studies of Murphy and Simon (2001) and Murphy and Simon (2002) rely on internal assessments to examine the intangible benefit *customer satisfaction*, but additionally incorporate detailed customer opinion, which has been gathered through comprehensive customer surveys. Similarly, Belcher and Watson (1993) include internal users as well as business analysts, technical specialists, and involved managers, and Beer et al. (2013) include external consultants in the analysis of the IT project's benefits. Given the multifaceted and often far-reaching impacts of many IT projects, the consideration of different affected stakeholders in the analysis seems reasonable in order to achieve a comprehensive picture of an IT project's implications. This view is not only observed in examined studies which aim for a financial valuation of intangible benefits, but also supported by various other studies dealing with the valuation of IT projects, such as Willcocks (1992), Hinton and Kaye (1996), or Serafeimidis and Smithson (1996). We derive the following finding:

Finding F2: Many studies emphasize the importance of including different stakeholders in the analyses to consider the multifaceted value implications of IT projects.

We already discussed as per the above that decision-makers must find ways to relate an intangible benefit to the financial bottom line in order to determine its financial value in step two. Accordingly, intangible benefits must be analyzed regarding their ability to, for example, increase or maintain sales, justify higher prices, or reduce costs. In the simplest case, the causal chain is not specified in much detail, such as in the work of Belcher and Watson (1993), in which managers are asked to directly state their financial estimate, for example, for the intangible benefit *improved decision making*. However, most studies emphasize that aspect and specify causal chains in more detail. For example, Anandarajan and Wen (1999) relate the intangible benefit *increased flexibility* to the anticipated decreases in downtime, and subsequently, to potential cost reductions, or *higher quality* to an increase in customer turnover and, consequently, revenue. Hares and Royle (1994) re-express the intangible benefit *improved product quality* in the more measurable terms *customer retention*, which helps to maintain or increase sales; *defect reduction,* which supports cost reductions and enables higher prices; and deduc*tion in quality assurance expenses*, which reduces costs. Primrose (1990) also concludes that the intangible benefit *improved quality* may lead to increased sales and reduced costs through reduced rework, warranty costs, or quality control.

In general, the studies present various examples on causal chains relating an intangible benefit to the financial bottom line. Nevertheless, the level of detail significantly differs between the studies. The more detailed and specific the cause-and-effect relations can be expressed in quantifiable terms, the more precise and accurate calculations are possible in the next step. The determination of a well-founded causal chain is perceived as the central challenge for enabling a subsequent financial valuation of intangible benefits. We derive the following finding:

> *Finding F3: The level of detail in determining a causal chain relating an intangible benefit to the financial bottom line is of utmost importance, but significantly differs between the studies.*

The overview on the examined studies in Table 1 and the previous discussions already indicated that the first process step is primarily based on comprehensive management and expert discussions, which are supported by, for example, structured interviews, management questionnaires, or survey information, as well as a thorough data analysis (Matlin 1979; Murphy and Simon 2002; Belcher and Watson 1993). Only a few studies justify their analyses and discussions using more elaborate methods. At this, the concept of *activity-based costing* or justification has been adopted by Peacock and Tanniru (2005) and Brun et al. (2006) in order to deduct and depict the cause-and-effect relations to the financial bottom line. These studies thoroughly analyze the detailed activities (and related company data, e.g. cost and cycle time data) of business processes respectively the parts of the value chain that are affected by a specific IT project. By comparing the processes respectively the activities with and without an IT project, it is possible to relate intangible benefits such as *reduced sales efforts*, to potential cost reductions. Generally, activity-based approaches are widely used for the detailed analysis of processes and value chains (Chen 1996; Hoogeweegen et al. 1998; Sherer et al. 2002). Nevertheless, only the studies of Peacock and Tanniru (2005) and Brun et al. (2006) applied them to quantify indirect effects on the financial bottom line within the justification of IT projects. Another methodological approach to model cause-and-effect relations applied in the study of Dutta (2004) is *system dynamics*. Initially developed by Jay W. Forrester in the 1950s to analyze industrial processes (Forrester 1961; Radzicki and Taylor 2008), the approach of system dynamics has been applied in various areas of management or politics (Coyle 1998; Richardson 1996). As the system dynamics approach allows for analysis of complex problems, it seems well suited to depict and examine the cause-and-effect relations associated with intangible benefits by linking, for example, *customer satisfaction* or *enhanced reputation* to observable outcomes, such as increased turnover. Dutta (2004) emphasizes that "the causal relationships that are identified when linking the benefit to its observable outcomes must be defensible on the basis of some evidence, whether theoretical or empirical" (p.397). Despite the support from more elaborate techniques, such as activity-based approaches or system dynamics, solid assessment by management or experts (respectively further involved stakeholders) as well as comprehensive analyses of existing company data is still important. Regarding the methodological aspects of the first process step, we derive the following finding:

> *Finding F4: The studies determine intangible benefits and related causal chains through structured discussions and the analysis of available company data. Few studies support the analysis of causal chains by the use of elaborate methods (e.g., activity-based approaches or system dynamics).*

Summing up this section, we see that most studies rely on comprehensive analyses and discussions by management or experts in this first step, mostly supported by structured checklists, comprehensive data analysis, or the involvement of different business perspectives and stakeholders. In doing so, the studies aim to determine detailed cause-and-effect relations by linking intangible benefits with their ability to, for example, increase or maintain sales, or reduce costs. Consequently, the specification of these causal relations is the basis to indirectly determine financial values for intangible benefits in the next step. Or, as Primrose (1990) puts it: "The problem has now changed from the inability to include benefits, to the accuracy with which they can be estimated. This is a completely different, and manageable problem" (p.57).

II.1.3.3 Analysis and Discussion of Step 2: Quantification

Based on the identified causal chains, the studies use available company data and estimates to derive a financial value for intangible benefits. While the estimates of managers or experts are subjective, many studies involve different internal or external stakeholders, such as managers from different business functions, technical experts, or even consulted customers, as this is expected to enhance the validity of the estimations (Wu et al. 2006). Furthermore, the use of company data, such as information on customers or process times, has the major advantage of enabling a partly objective valuation. However, to be able to include objective company data, an intangible benefit must be defined in such detail that the causal chains contain measurable elements. For example, Murphy and Simon (2000) and Murphy and Simon (2002) relate the intangible benefit *improved customer satisfaction* to expected customer service improvements, for example, time reduction for order entry, inquiry response, or shipping and billing. These are improvements that can be achieved on the customer service side through the examined IT project, and are measurable in that they can be calculated very precisely based on available company data and the technical specifications of a new IT system. Furthermore, through customer surveys the decision-makers obtained data on the importance of each specific improvement. However, the estimation of the effects of these improvements on customer satisfaction is in turn more subjective, just as the subsequent forecast of increased sales revenues. The subsequent calculation of a financial value for improved customer satisfaction is at least partly based on objective data, which can be expected to improve the validity of the financial calculations. Similarly, detailed company data is used in the study of Peacock and Tanniru (2005) to determine the expected time saved in performing all activities in a sales process after the introduction of a new sales system in order to relate reduced sales effort to potential cost reductions. We derive the following finding:

> *Finding F5: The estimations by management, experts, or further stakeholders can be supported with objective company data, if a detailed causal chain containing measurable elements was determined in step 1.*

The derived estimates and data are subsequently included in traditional financial approaches, such as in the calculation of net present values (NPV). In doing so, many studies do not naively rely on fixed point estimates, but calculate and state expected values and possible deviations using discrete probability distributions (Anandarajan and Wen 1999; Beer et al. 2013; Brun et al. 2006; Schell 1986; Smith 1983). Similarly, the system dynamic approach by Dutta (2004) simulates multiple value settings for the determined cause-and-effect relations to derive reliable results. Litecky (1981) emphasizes that conservative estimates should be used in order to enhance the credibility of the valuation, and further considers the uncertainty by risk-adjusted discounting of the estimates for future intangible benefits. The relevance of adequately considering the estimates' uncertainty is also discussed in Beer et al. (2013). They define the specific requirement of including a reasonable risk assessment, and present a NPV-based approach considering risk and interdependencies as well as the decision-maker's risk attitude. Generally, the majority of studies examined mindfully include subjective estimates and objective company data in traditional financial approaches that consider the given uncertainty. We derive the following finding:

Finding F6: The majority of studies apply traditional financial methods of cost-benefit analysis, mostly including a consideration of the risks associated with estimating the benefits.

Other than the consideration of the given uncertainty through the use of, for example, expected values, most studies subsequently conduct sensitivity analyses, or at least discuss their importance, in order to give an idea of the margin of error in quantitative estimates (Dutta 2004; Schell 1986; Litecky 1981; Anandarajan and Wen 1999). Sensitivity analyses are not only a practical way to depict the margin of error, but also allow analyzing the impact of specific input parameters on an IT project's total value. Consequently, the results of sensitivity analyses may further offer some insights that allow refining the determined cause-and-effect relations. Generally, the incorporation of intangible benefits in financial approaches offers the central advantage of providing a clear quantitative basis for subsequent comprehensive sensitivity analyses. We derive the following finding:

Finding F7: Many studies emphasize the importance of comprehensive sensitivity analyses to examine possible deviations and to identify central impact parameters.

Other than the use of rather traditional quantification techniques, a different approach is applied by Wu et al. (2006) that includes a score-based valuation in a value index model, based on the model of Kalafut and Low (2001), and subsequently converts the non-financial value of the intangible benefits to financial values. Consequently, they use non-financial methods, which initially have been developed to serve as alternatives for traditional financial approaches, as a basis for their financial valuation. To convert the non-financial values to financial values, Wu et al. (2006) apply a fuzzy assessment approach that is based on the fuzzy set algebra developed by Zadeh (1965). Fuzzy approaches formalize vague and qualitative criteria and consider its uncertainty. Therefore, they seem appropriate to treat imprecise estimates in uncertain environments, such as at the valuation of IT projects (Zandi and Tavana 2011; Abdel-Kader and Dugdale 2001; Kahraman et al. 2007; Sharif and Irani 2006; Bhattacharyya and Khasnabis 2007). Nevertheless, only the study of Wu et al. (2006) applies fuzzy assessment for the financial ex-ante valuation of intangible benefits. We derive the following finding:

Finding F8: Non-financial valuation approaches can be used as a starting point for a subsequent conversion of intangible benefits to financial values.

Summing up this section, we can state that companies do not necessarily need sophisticated methods to quantify intangible benefits financially. Once detailed cause-and-effect relations have been determined, a mindful application of rather traditional quantification approaches may be sufficient to calculate a financial value based on objective data and subjective estimates. Furthermore, well-accepted methods of risk and sensitivity analysis may allow for deeper insights, and enable companies to draw a comprehensive picture of the extent, and possible deviations, of the financial value of intangible benefits.

II.1.3.4 Analysis and Discussion of Examined Intangible Benefits

Most of the examined studies focus on discussing the methodological approaches, and represent either general approaches, or focus on specific types of IT projects, such as ERP systems (Murphy and Simon 2000; Murphy and Simon 2002; Wu et al. 2006), SCM systems (Brun et al. 2006), or MRP II systems (Primrose 1990). A small number of studies focus on the examination of specific areas of intangible benefits. By analyzing the presented studies in this regard, we see a focus on intangible benefits in the areas of *internal improvement* and *customers* (cf. Figure 2).

The studies of Peacock and Tanniru (2005) and Brun et al. (2006), which use activity-based approaches, are focused on benefits that can be achieved through *internal process improvements*. This is particularly owed to methodological approaches that specifically aim to analyze the detailed activities of business processes, and therefore are appropriate to quantify potential cost savings through efficiency gains. It should be noted that many indirect or intangible benefits in the area of process improvement, such as *reduction in sales effort* or *timeliness of deliveries*, are not as elusive as other intangible benefits, for example, *improved decision making*, and it can be argued that these benefits fall outside the definition of an intangible (Hares and Royle 1994). However, the business cases presented in these papers showed that re-expressing such benefits potentially requires complex causal chains to indirectly determine related cost reductions.

The second benefit area often addressed is that of *customers*. The studies of Murphy and Simon (2000), Murphy and Simon (2002), Dutta (2004), and Beer et al. (2013) present case studies focusing on intangible benefits in this area, and convert the intangible benefit *improvement of customer satisfaction* to financial values. As presented in previous sections, the methodological quantification approaches differ among the studies, but the basic causal chains determined are similar: all studies first analyze the expected improvements of customer satisfaction that can be achieved through an improved customer service level. Subsequently, the expected impact on maintaining or increasing sales is quantified. Further intangible benefits in the customer area that have been examined are, for example, *increased reputation* (Dutta 2004), *reduced customer call losses* (Beer et al. 2013), expected value of *faster response time* (Anandarajan and Wen 1999), or *higher quality* (Anandarajan and Wen 1999; Primrose 1990). Although other studies, such as that of Hochstrasser (1992), doubted that the elusive benefit of customer satisfaction could be included in a quantitative financial analysis, or such as Simmons (1996), who stated that measuring improved customer service is fraught with difficulty, the presented approaches successfully demonstrate that a financial ex-ante valuation in this benefit area may be possible. We derive the following finding:

Finding F9: The studies mainly focus on the financial valuation of intangible benefits in the areas of internal improvements and customers.

Other than these two benefit areas, many other intangible benefits have been mentioned in the studies, but for the most part, the causal chains as relevant to the financial bottom line have not been determined or analyzed in detail. The intangible benefit *improved decision making* has been especially discussed, and is addressed in studies such as those of Belcher and Watson (1993), Litecky (1981), or Schell (1986). Belcher and Watson (1993) ask managers to directly state their financial estimate for this intangible benefit, and Litecky (1981, p.17) suggests a rough estimation such as "every 'fifth' decision will result in a 'fifty' percent higher payoff". Schell (1986) derives a financial value for improved decision making by comparing the decisions' expected values with and without a new IT-based sales forecasting system. These financial values must be treated with caution, as they are not based on a detailed causal chain. Consequently, a mindful application of conservative estimates and the use of thorough risk and sensitivity analyses are especially important in such cases. We derive the following finding:

Finding F10: Some intangible benefits can be related to the financial bottom line only vaguely, as a detailed causal chain cannot be determined.

Summing up this section, we can state that many different intangible benefits have been quantified successfully in financial terms by the presented studies. The areas of *internal improvements* and *customers* have especially been examined in detail. The presented studies primarily acknowledge that it may never be possible to grasp the intangible benefits to a full extent, and there will always remain intangible benefits that can be only approximately converted to financial values. Some intangible benefits may remain elusive. However, many intangible benefits that lie in the grey area between tangible and intangible can be quantified, and even converted to financial values.

We presented an analysis and discussion on studies that successfully included intangible benefits in the financial ex-ante valuation of IT projects. This financial valuation holds many advantages, and does especially represent an improved quantitative decision basis for IT investment decisions. Furthermore, a thorough and detailed analysis of the intangible benefits is expected to lead to an improved understanding of, and broader information on, the examined IT project, which is not only helpful in an ex-ante perspective, but also for the subsequent ongoing management. We have seen that a comprehensive analysis and financial quantification of intangible benefits needs much effort. Sometimes reliable quantitative data may be available, but the necessary effort and the costs of a comprehensive data analysis and subsequent discussions and estimations would exceed the benefits (King and Schrems 1978; Whiting et al. 1996). This has to be considered, and the detailed financial examination of all intangible benefits may not always be appropriate in the context of ex-ante valuation, as companies must balance the costs and benefits of a thorough financial analysis. However, the benefits of a comprehensive financial valuation are only known ex-post, and therefore, represent a classical information paradox. We thus suggest a gradual approach to the valuation: first, decision-makers should conduct a rough estimation of intangible benefits, for example, based on some kind of structured checklist or classification framework. Second, based on this first indication, decision-makers should be able to decide whether a more detailed examination is necessary or reasonable. In general and by trend rather complex, wide-ranging, or large IT projects are expected to imply extensive intangible benefits, which then justify a detailed and comprehensive analysis regarding potential intangible benefits.

II.1.4 Further Research

Existing literature shows that the financial ex-ante valuation of intangible benefits is complex, but can be achieved at least in part through a comprehensive analysis of the underlying cause-and-effect relations and a mindful application of financial valuation techniques. Nevertheless, there still is a significant need to further progress in theory and in practice. Our literature review identified research gaps that should be addressed in future research (Webster and Watson 2002), and will be discussed in the following to answer research question RQ3. The results of our literature search show that many studies deal with the challenges associated with the consideration of intangible benefits in the ex-ante valuation of IT projects. Although the importance of a comprehensive valuation of intangible benefits is widely recognized, there are very few research papers focusing on the financial ex-ante valuation of intangible benefits, and almost no recent research is available. It can then be asserted that the literature in this field needs further progress and increased attention in future research.

As intangible benefits are manifold, and many intangible benefits have yet to be thoroughly analyzed, future endeavors should focus on examining specific intangible benefits, for example, through validating relevant business cases. Analyses of the underlying causal chains are of particular interest, as this is a central aspect in order to be able to achieve an indirect financial valuation. As our research was restricted to examining existing literature in the ex-ante perspective, a further analysis of ex-post literature regarding specific intangible benefits of IT projects is a promising starting point for future research. This could enhance the understanding of the cause-and-effect relations between specific intangible benefits and a company's financial bottom line, and could assist both academics and practitioners in redefining their approaches. Furthermore, these analyses should offer further guidance for decision-makers regarding the financial ex-ante valuation of intangible benefits, for example, through proposing practically oriented procedure models for specific intangible benefits respectively specific types of IT projects. In developing such approaches, a close collaboration of research and practitioners seems advisable in order to uphold scientific rigor, and to simultaneously gather feedback from companies and decision-makers regarding the methods' effectiveness and applicability. To achieve this goal, applied research projects, or research approaches such as *Action Design Research* (Sein et al. 2011), may be supportive. We derive the following research opportunity:

> *Research Opportunity RO1: Further examine the causal chains relating specific intangible benefits to the financial bottom line (e.g., through focused case studies), and develop related practically oriented procedure models to guide decision-makers through the process of financial ex-ante valuation.*

Furthermore, we found that existing valuation frameworks include a variety of non-financial or qualitative assessments for intangible benefits, and therefore may be an excellent starting point to make another step toward a financial valuation. For example, within the BSC approach, intangible aspects such as customer satisfaction are usually valued using a scoring approach, or transactions per employee are determined to determine the efficiency of internal business processes (Milis and Mercken 2004; Willcocks and Lester 1994). Our research shows that detailed causal chains can be derived for many such intangible benefits, especially in the areas of customers and internal processes. Research and decision-makers should aim to convert the non-financial or qualitative assessments to a financial valuation, increasing the number of financially assessed value components, for example, within the customer or internal process perspective of a BSC approach. We derive the following research opportunity:

Research Opportunity RO2: Analyze the possibilities to transfer non-financial value components within multi-dimensional approaches and frameworks to a financial valuation.

Moreover, we found that the analysis and consideration of related company data support the identification and determination of detailed and well-founded causal chains, and may also enhance the validity of the financial valuation. Given the high volumes and variety of today's company or customer data, as well as the capabilities of modern data analytic systems (Chen et al. 2012; LaValle et al. 2013), we expect further advances regarding support to the financial valuation of intangible benefits. Due to the rapid digitization of companies and their business environments (Dutta et al. 2012; Bilbao-Osorio et al. 2013), we feel confident that the possibilities are nowhere near the end. For example, the increasing digitization of modern production facilities through embedded systems, such as sensor and actuator technology, allows for a detailed measurement of process-related data. Based thereupon, the indirect financial impact of even complex process improvements that are induced by an IT project can potentially be measured and calculated more easily and especially faster. Furthermore, the analysis of vast customer data enables the company to analyze customer satisfaction and its relation to, for example, the development of sales figures. In doing so, companies are no longer restricted to internal and structured customer databases, but may be able to use unstructured external data, such as from online social networks, due to a successful use of Big Data initiatives. Furthermore, aside from enhancing existing causal chains, modern methods of Big Data and data analytics may enable the discovery of new patterns that allow relating rarely examined intangible benefits to the financial bottom line. Another relevant aspect related to the further advances of data analytics is that of costs. In the previous section, we concluded that intangible benefits analyses are complex and may require extensive time and resources. Modern data analytics may allow for a cost reduction associated with a thorough databased examination and valuation of intangible benefits. The application of comprehensive data analyses for the financial valuation of intangible benefits provides significant worth, and we propose the following opportunities for further research.

Research Opportunity RO3: Examine how increasing company data can be used to enhance the understanding of the causal chains relating intangible benefits to the financial bottom line.

Research Opportunity RO4: Examine how increasing company data can be used to improve the validity of the financial ex-ante valuation of intangible benefits.

The presented research opportunities show that there are various starting points to further contribute to an improved understanding regarding the financial ex-ante valuation of intangible benefits, even though some research does already exist. A multitude of related and highly relevant issues is still missing.

II.1.5 Conclusion

Our research emphasizes that intangible benefits are highly relevant value components of IT projects, but are difficult to include in a financial ex-ante valuation as they cannot be quantified directly. Nevertheless, our review shows that some studies achieve an *indirect* financial ex-ante valuation of intangible benefits through a structured and comprehensive analysis of the underlying causal chain to the financial bottom line. Based thereupon, the studies apply traditional financial valuation approaches that demonstrate to be appropriate given a mindful application. We come to the conclusion that it falls short to exclude intangible benefits from a financial ex-ante valuation by default. In contrast, many intangible benefits lie in a grey area of quantifiability and potentially could be included in financial approaches. With regard to the high relevance and widespread use of financial justification techniques in companies' budgeting processes, and with regard to ever-increasing economic and competitive pressure, this is a highly relevant topic. However, it may never be possible to account for all relevant intangible benefits in a financial ex-ante valuation. Moreover, the possibilities to evaluate intangible benefits financially in an ex-ante perspective may differ between companies, and may depend on company or industry details or specific stakeholders. In this context, the available data may be decisive for a sound quantification. Consequently, financial valuation techniques will never give a final answer to the question of whether or not to invest, but their usage can help to improve decisions on investments in IT projects and provide a profound decision basis in line with the concept of value-based management. Aside from the importance of the ex-ante valuation, it must be emphasized that a structured and focused management throughout a IT project's life cycle, and thus also a comprehensive ex-nunc and ex-post controlling of IT benefits, is essential in order to exploit the full economic potential of IT projects. Companies can identify the need for counteractive measures in case the benefit realization falls behind planned targets, or in case costs overrun planned budgets. Moreover, companies obtain valuable information on potential improvements regarding future IT projects as they regard future valuation processes. Consequently, the ex-ante, ex-nunc, and ex-post examination and valuation of IT projects must be harmonized and appropriately interlocked.

This paper may demonstrate some limitations, in spite of the previously highlighted benefits. First, although we performed a broad literature search, it is likely that not all relevant articles have been identified, as intangible benefits are multifaceted constructs and the general literature on IT valuation issues is very broad. Moreover, the keywords used may not have been a complete list of possible search terms. Second, literature was only analyzed with regard to the financial ex-ante valuation of intangible benefits; thus, our perspective is narrower and more focused. Despite these limitations, our research delivers further insights into the financial ex-ante valuation of intangible benefits in IT projects. We hope that it helps to encourage further research on this topic, for example, through addressing the research opportunities presented above, and to advance the body of knowledge regarding the financial ex-ante valuation of intangible benefits in IT projects.

II.1.6 References

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II.2 Research Paper 2: "Finanzwirtschaftliche ex-ante Bewertung intangibler Benefits von IT-Projekten"

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Abstract: *Eine vollumfängliche und ökonomisch fundierte ex-ante Bewertung von IT-Projekten ist im heutigen kompetitiven Umfeld für Unternehmen aller Branchen essentiell, um eine zielgerichtete Allokation der zur Verfügung stehenden Ressourcen und eine wertorientierte Steuerung des IT-Portfolios zu gewährleisten. Aufgrund der hohen Komplexität moderner IT-Systeme sind die Implikationen von IT-Projekten meist vielfältig und weitreichend und umfassen insbesondere auch eine Vielzahl sogenannter intangibler Benefits, welche schwer quantifizierbar sind, wie z.B. eine verbesserte Informationsgrundlage oder eine verbesserte Servicequalität. In diesem Zusammenhang fokussiert der Beitrag auf die Möglichkeiten, intangible Benefits mittels finanzwirtschaftlicher Methoden zu bewerten und zeigt auf, wie durch eine detaillierte Analyse der zugrundeliegenden Wirkungszusammenhänge die finanzwirtschaftlichen Implikationen intangibler Benefits quantifiziert werden können. Hierzu wird ein strukturierter Bewertungsprozess vorgestellt und Kernherausforderungen, praxisorientierte methodische Ansatzpunkte und zentrale Erfolgsfaktoren werden diskutiert. Anschließend werden anhand konkreter IT-Projekte eines globalen Technologiekonzerns Erfahrungen aus der Praxis aufgezeigt und die Vorgehensweisen bei der finanzwirtschaftlichen Bewertung verschiedener intangibler Benefits erläutert.*

Keywords: *Intangible Benefits, Bewertung von IT-Projekten, Finanzwirtschaftliche Bewertung, Ex-ante Bewertung, Wertorientierte Steuerung*

III Risk Quantification of IT Projects in Consideration of Stochastic Interdependencies

The research paper in Chapter III examines the influence of interdependencies between IT projects on the ex-ante quantification of the risks of IT projects. As IT projects are generally regarded as highly risky, a comprehensive ex-ante valuation of associated risks is highly relevant. In this context, companies face the challenge of considering interdependencies between numerous IT projects conducted simultaneously and e.g. drawing on the same scarce resources. Those interdependency risks have a significant impact on the risk-/return structure of a company's IT portfolio and their accurate consideration in a well-founded ex-ante valuation is essential to avoid suboptimal IT investment decisions.

Against this background, research paper 3 (*"Managing an IT Portfolio on a Synchronised Level or: The Costs of Partly Synchronised Investment Valuation"*) analyzes the economic advantages of a mature synchronized ITPM that is in line with a value-based management. Within a synchronized ITPM approach, a sound ex-ante valuation of IT projects is required that is based on financial metrics and especially takes into account an IT portfolio's risks including the risks that result from various intratemporal and intertemporal interdependencies. Research paper 3 provides an optimization approach that is in line with a synchronized ITPM and, furthermore, shows that an IT investment valuation that ignores stochastic interdependencies leads to sub-optimal investment decisions. Moreover, the research paper presents a comprehensive simulation study analyzing how different risk-/return structures of IT investment opportunities affect the valuation. Finally, a stepwise approach for the implementation of a comprehensive decision support system within a synchronized ITPM is discussed.

III.1 Research Paper 3: “Managing an IT Portfolio on a Synchronised Level, or: the Costs of Partly Synchronised Investment Valuation”

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Abstract: *Information technology (IT) investments are usually risky by nature and account for a considerable part of annual investment budgets. Though value-based information technology portfolio management (ITPM) aims at sustained economic growth and long-term value creation regarding IT investments, companies often fail to implement a synchronised ITPM approach that considers all relevant risk-/return components within IT investment valuation. In this paper, we compare a synchronised and an only partly synchronised valuation of IT investments within a company's ITPM by means of an optimisation model. We show that an only partly synchronised IT investment management leads to sub-optimal investment decisions as especially stochastic interdependency structures are neglected. Furthermore, we analyse how different risk-/return structures of IT investment opportunities affect the valuation error resulting from an only partly synchronised IT investment valuation, and conduct a comprehensive simulation study to further validate our findings.*

Keywords: *IT Investment Valuation, Risk-/Return Management, IT Portfolio Management, Stochastic Interdependencies, Capability Maturity Models*

IV Valuation of IT Projects in Digitized Value Networks

The research papers in Chapter IV focus on the valuation of modern IT systems in digitized business environments. The advances in information and communication technology enable a continuous transformation of business models and value chains and bear great potentials. In order to exploit these potentials, companies have to manage the digitization of their economic activities and need to invest in IT projects enabling the usage of digitized value networks in order to remain competitive in global markets. By thoroughly investigating the impacts of such investments, companies increase their understanding and gain insights into necessary transformations of their business model or value chains. Accordingly, the ex-ante valuation of IT projects in digitized value networks presents a major challenge and is essential for a successful and value-oriented transformation of companies' business models.

Focusing on the service industry, research paper 4 (*"Creating Competitive Advantage in E-business Value Chains by Using Excess Capacity via IT-enabled Marketplaces"*) examines the economic potential of IT-enabled ECM in e-business value chains. In this context, the research focuses on analyzing potential competitive advantages regarding the provision of standardized services. As the ex-ante capacity planning is a major challenge for service providers in such cost-driven business environments, the research paper provides an analytical model based on queuing theory and evaluates the impact of the usage of IT-enabled ECM on the capacity planning of a service provider through a discrete-event simulation. Based on that, different strategies for realizing competitive advantages are analyzed.

Focusing on the manufacturing industry, research paper 5 (*"Assessing IT Availability Risks in Smart Factory Networks"*) examines the risk assessment of IT availability risks in smart factory networks by developing a quantitative risk assessment model. As smart factory networks extensively rely on underlying IT systems, the security and availability of the IT components is of utmost importance for exploiting the economic potentials of such modern production networks. The presented model provides a structured approach that supports companies in identifying and evaluating the most critical areas of the information network while considering the underlying production network. Consequently, the model presents a profound economical basis for ex-ante investment decisions on IT security measures within smart factory networks.

IV.1 Research Paper 4: "Creating Competitive Advantage in E-business Value Chains by Using Excess Capacity via IT-enabled Marketplaces"

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Abstract: *Innovations through the "business process as a service" (BPaaS) concept have shaped new business opportunities for business process service providers (BPSP). Technological progress allows BPSPs to offer a wide range of digitized and standardized services to business clients. Within this business model, capacity planning is a major challenge as costs are the decisive factor in the competitive business environment of digital service provision. Accordingly, BPSPs must tackle inefficiencies in capacity planning resulting from both idle capacity and lost revenue caused by volatile demand. However, recent technological developments offering dynamic integration and information capabilities may help, as they enable the dynamic exchange of excess capacity between business partners. We examine the corresponding potential of IT-enabled excess capacity markets to create competitive advantage by analyzing a BPSP's capacity-related optimization problem. We build an analytical model based on queuing theory and evaluate it through a discrete-event simulation. By solving the optimization problem, we identify a remarkable cost advantage in using excess capacity as a first competitive advantage. Building on this cost advantage, we furthermore identified differentiation advantages realizable without raising prices.*

Keywords: *Design Science, Competitive strategy, Service supply chain, Electronic value chains, Service oriented architecture (SOA), Cloud computing, Interorganizational systems, Volatility*

IV.1.1 Introduction

The increasing digitization of business processes, along with modern information technology (IT), allowing a fast and easy integration of business partners leads to a continuing and radical transformation of e-business value chains as well as new and innovative forms of cooperation [1], [2], [3]. Companies can now source whole business processes from external providers that allocate all technical, personnel, and other resources necessary to ensure an effective and efficient process operation [4]. Especially for standardized, IT-driven, and digitized business processes, the well-known business process outsourcing (BPO) approach has already evolved, leading to the "business process as a service" (BPaaS) concept. By analogy with concepts such as software or infrastructure as a service, BPaaS describes a dynamic BPO relationship between a business process service provider (BPSP) and its business clients: Both parties technically integrate their processes via Internet-based technologies, allowing the BPSP to deliver its service within a flexible contract period and a consumption-based pricing model. Moreover, the BPSP can share its resources among different business clients flexibly in order to ensure service provision as stipulated in the applicable service level agreement (SLA) [5].

As companies usually keep core business processes in-house (e.g., to avoid drain of critical business knowledge), BPSPs mostly offer standardized support for business tasks that do not demand specialized competencies. The range of business processes currently available as services include online payment processing, human resources and procurement services, and other back-office tasks [5], [6]. These services are usually commodities with few distinguishing characteristics and can be offered by a wide range of BPSPs. Especially for such commodity services, business clients aim to minimize the costs of service purchasing; thus, service price is the decisive competition factor among BPSPs. Accordingly, to succeed in this cost-driven environment, BPSPs must identify and raise potentials for more cost-efficient service provision to realize competitive advantages. To outperform its competitors, a BPSP must either provide the established service level at less than the competitive price or provide improved service at the established price.

An important strategic lever for achieving cost and price leadership is a sophisticated ex ante planning of the BPSP's in-house capacities. This is especially important due to the characteristics of service provision: most BPSPs face very volatile demand but are not able to react to demand fluctuations by scaling their IT capacity or their personnel resources on short notice. At the same time, business clients usually specify service quality such as fast response times by contracting SLA with penalty payments in case of insufficient service provision [7],

[8]. Consequently, to avoid SLA-related penalties, the BPSP must be able to cover peak demand while also ensuring the efficient use of resources to avoid idle costs in times of average or low demand [9], [10]. Finding the right balance within this tradeoff is a major key to superior resource usage and a foundation for generating competitive advantage in such cost-driven environments.

In addressing this tradeoff, most methods of handling analogous capacity planning problems in manufacturing (e.g., producing on stock to cover peak demand) cannot be applied to BPSP due to the aforementioned specific service characteristics. However, when focusing on IT-driven and digitized services, the development of innovative technologies such as service-oriented architectures, cloud-computing, and associated concepts may help mitigate this capacity planning problem. As these technological developments strongly foster firms' integration capabilities, making even the *on-demand integration* of third-party providers possible, they are also the catalyst for *IT-driven marketplaces*, allowing business partners to interact in a highly dynamic manner [11], [12]. At this, an IT-driven marketplace provides an information platform for a coordinated interplay of its market participants that allows matching available excess capacity with excess demand. Consequently, these new possibilities enable a demand-driven and temporary integration of business partners and offer a promising opportunity for exchanging excess capacity to address the tradeoff between idle costs and waiting costs. The in-house capacity of the BPSP can be reduced because excessive demand can be routed to third-party providers with underutilized IT and/or personal capacities forming the excess capacity market (ECM).

However, using excess capacity bears additional risk. As only the excess capacity that would otherwise remain idle is offered, its availability can be limited. Consequently, a service provider is served only when capacity is available on the market, which might cause delays and thus waiting costs. Hence, a BPSP has to consider the risk of waiting times at the ECM when deciding about its in-house capacity and must balance it against the potential economic benefits of an ECM.

This economic potential may be hampered, as, even for very standardized services, not all service requests can or will be routed to the ECM. That means, service requests are usually not fully homogeneous, as single service requests are likely to differ in terms of specific characteristics such as data quality, legal requirements, or confidentiality [13], [14]. For example, a BPSP may want to keep service requests in-house that are expected to require customer callbacks due to expertise and reliability, or, in an insurance context, a BPSP may prefer to keep service requests in-house that exceed a certain loss amount. Thus, when deciding ex ante about the appropriate level of in-house capacity, the BPSP must consider the inhomogeneity of service requests and, in particular, the expected number of such requests that can or will not be routed externally.

Against the background of a highly competitive market for cost-driven inhomogeneous services, we examine how a BPSP can create competitive advantages through an IT-enabled ECM within its value chain. The central research question of our paper is as follows:

> *Which competitive advantages can be realized through an IT-enabled ECM within a BPSP's value chain regarding the processing of cost-driven inhomogeneous service requests?*

To evaluate the ECM's potential to create competitive advantage, we use a design-science driven research approach and follow its basic paradigm of gaining knowledge by developing and evaluating specific artifacts [15], [16]. We start with the development of an artifact, an optimization model depicting the capacity planning problem of a BPSP considering the option of using an ECM. Based on our model we demonstrate the potential of an ECM for creating competitive advantages. We evaluate our model through a discrete event simulation, a widely accepted experimental design evaluation method [17].

The remainder of this paper is organized as follows: First, we analyze the literature to highlight the research gap this study addresses (Section IV.1.2). Second, we develop the optimization model using queuing theory (Section IV.1.3). We then perform a discrete-event simulation in a case study of online identification and authorization services for retailers such as online banking or trading platforms (Section IV.1.4). Finally, we summarize the key findings of the paper and discuss possibilities for future research (Section IV.1.5).

IV.1.2 Related Work

Several streams of literature are considered to carve out the research gap and provide the theoretical foundation for our optimization model. First, we briefly overview the literature concerning IT's general role in gaining competitive advantages (Section IV.1.2.1). Then, we discuss the literature related to the problem of ex ante capacity planning for services (Section IV.1.2.2). Finally, we overview the literature on the use of IT-enabled excess capacity markets for services and their potential for ex ante capacity planning (Section IV.1.2.3).

IV.1.2.1 IT and Competitive Advantages

The strategic significance of IT and its relevance for creating competitive advantages has been broadly addressed in the literature. According to Porter and Millar [18], IT is "transforming the nature of products, processes, companies, industries, and even competition itself." Therefore, IT can affect and reshape business value chains as well as change the structure of whole industries. Furthermore, IT can create competitive advantages by giving companies new ways to outperform their competitors and spawn new businesses from within existing operations [18]. Powell and Dent-Micallef [19] show that companies have gained competitive advantages by using IT to leverage human and business resources. Various other studies, such as Peteraf [20], Grant [21], and Barney [22], follow this resource-based view and emphasize that a company`s ability to generate competitive advantages is directly determined by its superior usage of resources and capabilities. Furthermore, numerous empirical studies confirm the strong relationship between a company's IT capabilities and firm performance (e.g., Bharadwaj [23], Santhanam and Hartono [24], Aral and Weill [25], Rai et al. [26], Stoel and Muhanna [27] or Ravichandran et al. [28]).

For BPSPs operating in a cost-driven market and following the basic principles of Porter and Millar [18], there are two possible business strategies. It can offer the established service at less than the competitive price, or it can offer an improved service (e.g., through an improved SLA) at the established (competitive) price. Differentiation strategies such as offering a significantly improved service for a *higher* price are barely relevant for the provision of very standardized services, as price is the decisive factor. The relevant differentiation strategies for BPSP in such a cost-driven market must therefore build directly on cost advantages. A BPSP will obtain these cost advantages mainly through superior usage of resources (i.e., by providing cost-efficient services). Thus, the usage of an IT-enabled ECM might offer the potential to reduce fixed costs for maintaining internal capacities, generating a competitive cost advantage. According to Mata et al. [29], this competitive advantage can be either sustained or temporary depending on the level of challenges competing firms face when trying to imitate and reproduce the strategy. The competitive advantage created through the usage of IT-enabled ECM is therefore not expected to be fully sustainable, since it decreases over time as an increasing number of competitors acquire the competencies and resources (e.g., IT capabilities and skilled personnel) necessary to duplicate the strategy. Nevertheless, companies can create at least a temporary competitive advantage by implementing ECM usage before most of their direct competitors do. As a functioning ECM requires a minimum number of participants, it is important to understand that, due to the high degree of service standardization, both competitors as well as non-competing companies can participate in the ECM. This supports the possibility of using excess capacity to realize at least a temporary competitive advantage, as the participation of direct competitors in the ECM is not a prerequisite for its emergence.

IV.1.2.2 Capacity Planning for Service Provision

The general problem of ex ante capacity planning for non-storable goods and services under uncertain demand has long been examined in the scientific literature. In particular, the topic of call center outsourcing, which reflects a common example for capacity planning for services, has been widely discussed. These studies usually distinguish between the two basic sourcing models that companies can use: volume-based contracts and capacity-based contracts [36], [37]. Volume-based contracts ("pay-for-job") involve payments only for the used capacity, whereas capacity-based contracts ("pay-for-capacity") involve payments for all capacity, whether employed or not. Considering these basic sourcing models, Aksin et al. [37] determine the optimal capacity levels and partially characterize the optimal pricing conditions for each type of contract. Gans and Zhou [36] analyze the centralized capacity and queuing control problem within this context. Studies dealing with outsourcing decisions in a service setting include Cachon and Harker [38], Allon and Federgruen [39], and Ren and Zhou [40]. Cachon and Harker [38] study the competition between two service providers with price- and time-sensitive demand by modeling this setting as a queuing game. Allon and Federgruen [39] analyze volume-based contracts and their effects on supply chain coordination. Ren and Zhou [40] study contracting issues between a client and a vendor and analyze contracts the client can use to induce the vendor to choose staffing and effort levels that are optimal for the supply chain. The aforementioned studies analyze various aspects of volume- and capacity-based contracts in the context of capacity planning for services, but they do not consider the option of IT-enabled exchanges of excess capacities.

IV.1.2.3 IT-enabled Markets for Excess Capacity

This paper focuses on how new technologies foster the exchange of excess capacities between companies and thus addresses the problem of ex ante capacity planning for BPSPs. The basic idea of exchanging capacities to facilitate ex ante planning has been discussed in production and supply chain management studies on the so-called "surplus markets" [30]-[35]. These papers are related to our approach, as firms with a shortage of capacity or inventory can buy available overcapacities or excess inventories from other firms. In a fundamental difference, however, these papers deal with physical products and examine the trading of physical excess inventories.

By contrast, we seek to facilitate capacity planning for digital, non-storable IT services by using IT-enabled ECM. The usage of IT-enabled ECM and the potential for the ex ante capacity planning for digital services has been examined only recently by Dorsch and Häckel [41]-[43]. Dorsch and Häckel examine the cost advantage to service providers of the on-demand integration of business partners [41] and analyze the environmental sustainability benefits of excess capacity markets in cloud service environments [42]. The advantages of combining the usage of on-demand surplus capacity with classical models of capacity supply (dedicated capacity and elastic capacity) are also elaborated [43]. Though this research provides valuable insights into the impact of an IT-enabled ECM on capacity planning for services, it focuses on the realization of cost advantages in processing homogeneous services. Our approach differs in two key ways. First, we explicitly consider the given inhomogeneity of service requests [13], [14] by acknowledging that not all requests can or will be processed on external markets. Second, we investigate how a BPSP can gain differentiation advantages through an IT-enabled ECM. We therefore extend the existing models significantly and examine how competitive advantages can be generated in this distinctly more complex and realistic scenario.

In the following chapter, we present a modeling approach to help optimizing the ex ante capacity planning of a BPSP when considering the option of using an IT-enabled ECM. Within this modeling approach, we consider the inhomogeneity of service requests. The results of this optimization model provide valuable findings on the possible competitive advantages enabled by IT-driven ECM.

IV.1.3 Modeling the Business Process Service Provider's Value Chain

To substantiate the idea of IT-enabled ECM and demonstrate our model, we first describe the general setting and discuss the necessary information and integration capabilities (Section IV.1.3.1). Then, we define the model and its assumptions, starting with the underlying capacity optimization problem (Section IV.1.3.2.), followed by a description of the in-house unit and the ECM (Section IV.1.3.3) and all relevant parameters and (objective) functions (Section IV.1.3.4). Finally, we introduce a routing algorithm necessary to solve the optimization problem (Section IV.1.3.5).

IV.1.3.1 General Setting and Necessary Information and Integration Capabilities

We consider a three-stage e-business value chain, as illustrated in Fig. 1. Here, a BPSP offers an IT-driven service to numerous business clients. The activities necessary to provide the service require IT as well as personnel resources because some activities require manual interventions. As the execution of the service is time-critical, the BPSP offers an SLA to its business clients (arrow number 1). The business client's requests are characterized by volatile demand (arrow number 2). As neither the IT capacity nor the personnel resources are fully scalable on short notice, the BPSP faces a capacity optimization problem for its in-house unit: to avoid both costly violations of the committed SLA due to capacity shortages in times of peak demand and idle costs in times of low demand, internal resources must be properly balanced. In addition, the BPSP can use the ECM to route certain service requests to third-party providers, offering their temporarily unused capacity (arrows number 3 and 4).

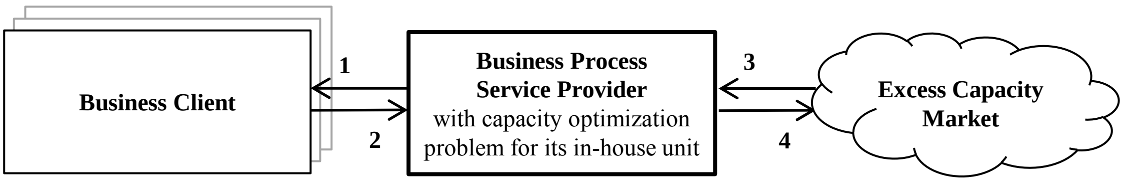

Figure 1. The business process service provider's value chain

Though service requests have standardized purposes, they are inhomogeneous in terms of the requirements of individual requests. Thus, the BPSP divides incoming requests into two categories: requests that can be routed to the ECM (the *regular requests*) and those that need to be processed by the in-house unit of the BPSP (the *special requests*). Special requests may require specific expertise only available at the BPSP's in-house unit, or they must be processed in-house due to legal or confidentiality requirements. Therefore, the BPSP has to consider these two categories when optimizing the BPSP's in-house capacity. As a consequence, the competitive advantages that can be achieved through an ECM as well as the appropriate level of in-house capacity are highly dependent on the inhomogeneity of incoming service requests. Furthermore, as excess capacity can be booked only on short notice, it is usually not SLA-backed, and its use tends to be more risky (due to possible delays) but also cheaper than in-house processing (as there are no idle costs). Thus, to decide whether an external execution of regular requests is preferable, the BPSP has to compare the costs for external execution and the risk of possible delays against the total processing costs of the in-house unit.

To operationalize the use of excess capacity, the BPSP must develop several *integration and information capabilities*. Building these capabilities is an essential precondition of realizing competitive advantages through excess capacity. In concrete terms, the BPSP must be able to (1) automatically determine which of the third-party providers is offering excess capacity on the market at any point during operation, (2) gather all the information relevant to its decision (e.g., current waiting time until external capacity is available, price for processing the request), and (3) connect its IT system to that of the third-party provider. Thus, its own IT system has to allow for a continuous evaluation of the ECM, and all necessary information must be provided by the ECM. The supply of information is supported by high-level frameworks for information exchange such as BizTalk, ebXML and RosettaNet as well as by various B2B platforms offered by product vendors (e.g., Oracle, Microsoft, IBM). In recent years, the web service paradigm emerging with service repositories and well-described services based on standardized description languages have evolved into one of the primary standards for the dynamic evaluation and integration of service providers [11]. Through these technological developments, a decentralized information exchange between various service providers regarding the usage of excess capacity is possible. Furthermore, a more centralized approach has been enabled by the development of (on-demand) service marketplaces such as SAP Service Marketplace, HubSpot, or Zimory, by which firms offering or/and seeking certain services can interact in a highly dynamic manner [11], [44].

IV.1.3.2 Underlying Capacity Optimization Problem

As mentioned, each incoming request triggers a service execution. The arrival rate λ (i.e., the number of time-critical requests sent from the business clients per time unit) is random. The statistical distribution of λ can be approximated based on historical data. The planning horizon considered is finite and divided into equidistant time units. After the BPSP has finished all activities necessary to complete the request, it is returned to the respective business client. The time frame between the accepting and returning of the request is called the *processing time*. Service level s (e.g., a maximum processing time with penalty payments for each time unit the request exceeds this limit) is guaranteed to the business clients for this processing time. Any request that fails to maintain this service level causes costs subsumed within c_s.

Taking these characteristics into account, the BPSP must decide ex ante on the capacity (i.e., the number of requests $y \in IN_0$ that can be handled simultaneously) to allocate to its in-house unit, which minimizes its *total processing costs c*. The simplified objective function for this discrete optimization problem is therefore given by

$$\min_{y} c(\lambda, y, s)$$

Concerning these main characteristics (e.g., random demand, limited capacity), it is appropriate to model the capacity optimization problem using *queuing theory*. In the following, we therefore rely on its basic assumptions as described, for example, in Gross et al. [45], while extending them by the necessary parameters and functions.

IV.1.3.3 Service System of In-house Unit and Excess Capacity Market

Unless all capacity units within the in-house unit are busy, the execution of a request starts immediately after its arrival in the BPSP's IT system. If all units of capacity are busy, each incoming request lines up in an infinite waiting queue. The queued requests are executed immediately when capacity is available (first in/first out). Free units of capacity are idle and cannot be used to accelerate the execution of other requests. The timeframe within which the request stays in the queue in front of the in-house unit is called *waiting time*. The timeframe between the beginning of the service's first activity and the end of the last is called *execution time*. Accordingly, waiting and execution time sum up to the *processing time* mentioned above. Hence, long waiting times might lead to processing times that do not maintain the agreed service level and cause corresponding costs.

In addition to the in-house unit, third-party providers offer excess capacity for temporary use, forming an ECM. On this market, capacity cannot be booked in advance, and constant availability is not enforced by SLA. The availability of capacity on the ECM therefore changes constantly, and a non-negligible and risky waiting time must be considered when relying on the ECM. This exogenous waiting time for capacity on the ECM has to be provided constantly by third-party providers. Timeframe a denotes the time a request must wait in the ECM queue. With $a > 0$, requests cannot be executed immediately, and the exogenous waiting time might be too long to keep up with the service level agreed with the business clients, causing corresponding costs.

When considering the ECM as a second queuing system, the combination of in-house capacity and ECM forms a *service system* that offers two separate *execution paths* for incoming service requests. Thus, as illustrated in Fig. 2, the BPSP can decide whether it routes a (regular) request to the in-house unit or to the ECM. As mentioned, special requests can be executed only in-house due to reasons of competence, confidentiality, or legality.

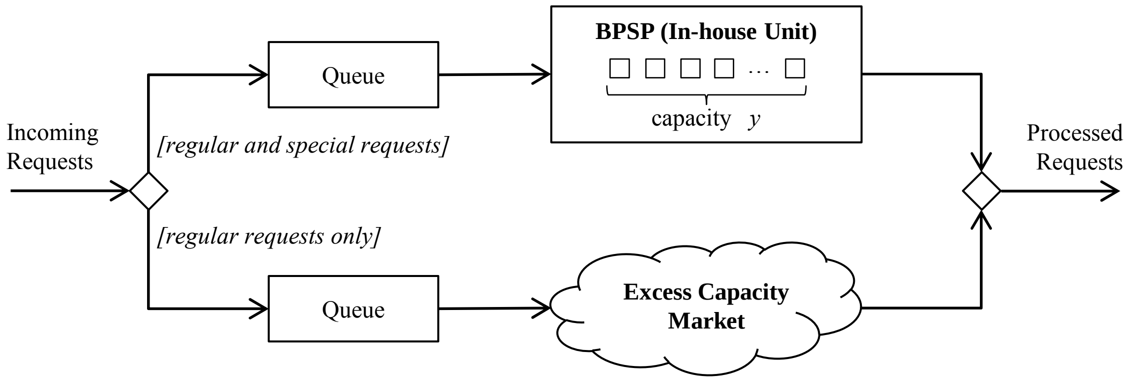

Figure 2. Service system with two queuing systems

IV.1.3.4 Total Processing Costs and Detailed Objective Function

To determine the actual total processing costs c, additional parameters specifying the two queuing systems are necessary and the *execution time* for regular and special requests must be determined: Considering a special request, the statistical distribution of the execution time t_s within the in-house unit can be derived based on historical data. Likewise, the statistical distribution of the execution time t_r for a regular request can be determined. The *in-house unit* causes *fixed costs* c_f per unit capacity but no additional *variable costs*. The fixed costs considered for one unit of capacity contain recurring capacity costs such as employee wages, running costs for the IT system and other equipment, overhead costs, and all non-recurring initial costs. The total number of regular requests finally processed in-house is denoted by $o_{i,r}$, and the total number of special requests executed in-house is denoted by $o_{i,s}$. The *external execution* involves no fixed costs, but variable costs c_e for each request sent to the ECM. As prices may change during operations, price c_e must be provided along with the information about the waiting time a, as described above. The total number of externally routed regular requests is denoted by o_e.

We can now determine the BPSP's total processing costs. The detailed objective function reads

$$\min_{y} c = c_f\, y + c_e\, o_e + c_s(\lambda, y, o_{i,r}, o_{i,s}, o_e, s, t_r, t_s, a)$$

As mentioned, the total processing costs considered in this model consist of the fixed costs c_f of in-house capacity, the variable costs c_e of using excess capacity, and the costs c_s resulting from requests that violated the SLA (i.e., *compensations* for delayed requests and *penalties* for requests that remain unexecuted). Consequently, the optimization problem is related to the amount of capacity y the BPSP allocates to the in-house unit. Integrating the ECM changes the total processing costs c, as the processing costs of regular requests differ depending on the execution path and overall waiting times. Solving the objective function for the integer values of y results in the optimal amount of capacity the BPSP should allocate in-house to minimize total operating costs.

IV.1.3.5 Routing Algorithm Necessary to Solve the Optimization Problem

To solve this optimization problem, it is not sufficient to evaluate the two queuing systems representing the in-house unit and the ECM separately. Rather, the service system must be evaluated as a whole because the two queuing systems interact during operations and influence waiting times. Although queuing theory provides a strong mathematical foundation, this cannot be done analytically since the two queuing systems have different characteristics, especially concerning their distribution of processing times.

The routing decision must take place during operations for every single request immediately after arrival. In the beginning, the IT system must separate regular requests from special ones. Then, the routing decision requires a routing algorithm that links the two interacting queuing systems and decides about the execution path for a regular request.

The routing algorithm works as follows. First, it determines the processing time for each queuing system. This is easily determined for the in-house unit, as the state of the system depends on its own capacity y, the arrival rate of requests λ, and the execution time t_r. Besides, the timeframe a until free capacity is available on the ECM has to be determined. Second, if these processing times result in a violation of agreed-upon service level s, SLA-induced compensations and penalties must be calculated. The tradeoff between additional variable external execution costs c_e and a possible reduction of compensations and penalties c_s builds the basis for this decision. Third, having determined processing times and considered the SLA effects, the processing costs of each execution path for each request, and thus the preferable path for the execution, can be determined.

To demonstrate our model, we present an application scenario based on a real-world example in Section IV.1.4. We perform a discrete-event simulation, an established method for analyzing queuing systems [45]. Our simulation implements the quantitative optimization model described above with all relevant cost functions and parameters of the described tradeoff. Furthermore, the necessary routing algorithm is implemented to evaluate the interaction of both queuing systems. Through this method, a simulation-based optimum ("optimal capacity" hereafter) can be determined for different scenarios in order to answer our research question.

IV.1.4 Evaluating the Potential of Excess Capacity Markets

To evaluate the potential of integrating excess capacity to create competitive advantages, we present the application scenario of a specific BPSP, a payment service provider (PSP) offering online identification and authorization services and electronic payment processing (e.g., Amazon Payments, PayPal). These services are typical tasks required by online retailers such as stores, trading platforms, and financial institutions. We first define the process subject to our exemplary application and describe the related capacity planning problem of the PSP (Section IV.1.4.1). Next, we determine the input data of our application scenario that are necessary to parameterize our model (Section IV.1.4.2). We then describe the simulation approach to determine the optimal in-house capacity for the process (Section IV.1.4.3). Finally, we analyze the resulting cost advantage (Section IV.1.4.4) as well as possible differentiation opportunities (Section IV.1.4.5).

IV.1.4.1 Characteristics of the Authorization Process

The digitized business process considered is the identification and authorization process for new customers of online retailers, as illustrated in Fig. 3. This task is usually sourced as a service from specialized PSPs linked with the corresponding institutions (e.g., credit card-issuing banks, credit rating agencies, government offices) necessary to identify (e.g., check and verify personal data, address data, and credit card information) and authorize (e.g., after a credit assessment) a customer. The customer data required for the request are forwarded by the retailer to the PSP for processing.

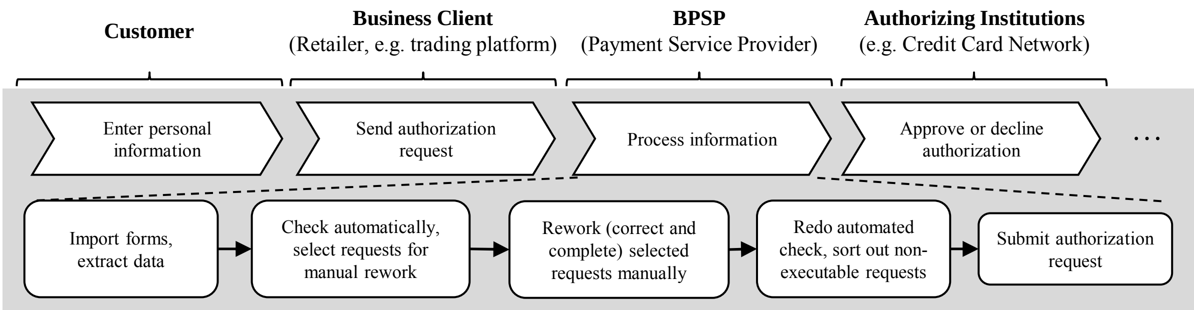

Figure 3. Simplified identification and authorization process

Though this service is mostly digitized and highly standardized through common interfaces and standard input forms, it requires both intensive IT-supported and manual interventions, such as for reviewing customer inputs (due to reasons of data quality and validity) and identifying erroneous entries. As the correctness of all entered data is essential, the PSP must perform adjustment processes such as (auto)correction, or, if necessary, it must contact the customer for further inquiries. Due to the possibility of customer or third-party interactions, the authorization process must occur during business hours.

The online identification and authorization service is a typical application scenario addressed by our model, as many requests characterized by volatile demand must be processed in time to avoid penalties or loss of customer interest. Therefore, detailed service levels concerning the timeframe for execution are agreed between the retailer and the PSP.

Allocating IT capacity and employees to the in-house unit charged with processing the registration procedures is an important optimization problem for the PSP. As the margins are small, the in-house unit's capacity should be kept as small as possible to keep the corresponding costs to a minimum. Along with the volatile arrival rates of incoming requests, there is a tradeoff between idle times and delayed execution.

An ECM can be used through the technologies and standards described above; requests submitted into the provider's gateway are not executed by its respective in-house unit but with the ECM capacity. However, only procedures that do not require adjustments of input data or customer callbacks can be routed to the external market due to reasons of expertise and reliability. Accordingly, the PSP has to decide for each incoming request if the external execution path is suitable (i.e., regular requests) and then if routing the request to an external provider would reduce overall processing costs.

IV.1.4.2 Input Data of the Authorization Process

We determine the input data characterizing the authorization process for our simulation. Authorization requests can be processed each day between 8 a.m. and 6 p.m. Requests that arrive outside these hours are still accepted, but authorization will be executed on the following day. Analyzing the historical data reveals different peaks for incoming request arrival depending on exogenous factors such as customer behavior and demand. Dividing the ten hours of processing time in six timeframes, the arrival rate within each timeframe can be approximated by a negative exponential distribution with different means (per minute), as summarized in Table I.

We assume that 30% of all authorization requests require specialized interventions or callbacks with customers due to incomplete or incorrect application forms. Accordingly, these *special requests* have to be executed in-house, notwithstanding the existence of an ECM. The interventions performed on a regular or special request require one unit of capacity for about 12:00 minutes on average regardless of its execution path. As only one employee can work on one request, idle capacity cannot be used to accelerate the execution of other requests. Cost accounting reveals that one unit of capacity within the in-house unit causes fixed costs of $350 per day.

In e-business, requests must be executed in time to meet external deadlines and avoid loss of customer interest. Furthermore, especially for the sake of reputation, satisfaction, and the retailer's economic interests, no request must be left unexecuted. Therefore, the SLA between the retailer and the PSP consists of two deadlines. First, each request has to be processed within 26:00 minutes after arrival. If a request exceeds this timeframe, a compensation that increases with the duration of the time exceeding this deadline is due. The agreed-upon compensation is determined by $\$0.03 * (minutes\ exceeded)^{1.5}$. Second, there is a final processing deadline for each day: All incoming requests have to be processed until 8:00 p.m. For each request not processed within this deadline, the compensation payment is increased by a penalty of $300. Through this penalty, the retailer offers a strong incentive to execute all incoming requests within a day. Compared with the revenues earned by processing a request, the penalty for the final processing deadline is prohibitive.

For simplicity, the variable costs for one request routed to the ECM are fixed at $8 in the simulation. The waiting time for excess capacity can be approximated based on historical data provided by the external service providers. For one day, three timeframes with different availabilities of the external service provider's capacities are identified. Each timeframe shows different waiting times for free capacity, which can be approximated by a normal distribution, as outlined in Table II. Requests routed to the ECM have to wait according to the timeframe valid at the time the request is routed to the ECM. With these characteristics, the discrete event simulation now can be established.

Timeframe	Mean [min]
08:00 a.m.–09:30 a.m.	50
09:30 a.m.–11:30 a.m.	3
11:30 a.m.–12:00 noon	30
12:00 noon–01:30 p.m.	5
01:30 p.m.– 04:00 p.m.	10
04:00 p.m.– 06:00 p.m.	40

Table 1. Incoming requests

Timeframe	Distribution [min]
08:00 a.m.–12:00 noon	μ = 16:40; σ = 4:00
12:00 noon–02:00 p.m.	μ = 12:00; σ = 2:10
02:00 p.m.–06:00 p.m.	μ = 10:00; σ = 4:00

Table 2. External waiting times

IV.1.4.3 Discrete Event Simulation

To determine the optimal capacity allocated to the in-house unit, we apply the following procedure within the simulation software used to implement the model. We perform multiple *simulation experiments* with increasing integer values for the capacity of the in-house unit. Each experiment consists of 800 *simulation runs*. The total processing costs are determined for each run. Starting the experiments with one unit of in-house capacity, we increase the value by one unit before the next experiment begins. This is done until the results of an experiment show that no waiting costs occur in front of the in-house unit for all runs. Consequently, an increase in capacity has no positive effect on the total processing costs. Finally, comparing the average total processing costs for each experiment and choosing the one with the lowest costs produces the optimal in-house capacity.

Regarding the simulation time, it is convenient that all days of our application scenario are independent of each other (e.g., with no unexecuted requests left due to the processing deadline at 8:00 p.m.), and the relevant events determining the optimal in-house capacity are recurrent each day. It is thus sufficient to simulate a single day to determine the optimal capacity.

For each simulation run, incoming requests are generated randomly following their statistical distributions. Whenever a new timeframe is reached, the arrival rate is adapted. Concerning the availability of excess capacity, a random value is generated from the corresponding statistical distribution at the beginning of each timeframe outlined in Table II. This random value represents the waiting time until the request can be executed externally; this is used by the routing algorithm to determine the processing costs of external execution. Repeating a simulation run 800 times, the risk of waiting times in case of using excess capacity is considered when determining the optimal in-house capacity.

Incoming requests characterized as *special requests* cannot be routed to the ECM; they are routed straight to the in-house unit (specifically, the waiting queue in front of it). For *regular requests*, the routing algorithm determines the current processing costs of both paths and then routes the request to the path with lower costs. The processing costs of the in-house execution thus result only from the SLA with the retailer; there are no variable costs connected with the in-house unit, and all fixed costs are sunk costs, which hence must not be taken into account. Regarding the SLA, costs can occur in two different ways: if a request cannot be processed ahead of the final processing deadline, the penalty has to be considered in the processing costs. Otherwise, if the agreed-upon processing time per request is exceeded, compensation costs per minute are charged. For the external execution, the processing costs consist of the variable cost per request and the costs resulting from the SLA determined analogously.

IV.1.4.4 Scenario 1: Determining the Cost Advantages of Excess Capacity

Performing the discrete event simulation *with* and *without* the opportunity to use excess capacity reveals the cost advantages of the ECM (scenario 1). The relation between total costs and assigned in-house capacity is shown in Fig. 4. The minima of both cost patterns (indicated by the dotted lines) represent the optimal level of capacity within the in-house unit. The optimal level of capacity *without* access to the ECM is reached at 362 units, corresponding to total costs of \$144,292 per day, while the optimal level of capacity *with* access to the ECM equals 147 units, corresponding to total costs of \$122,982 per day. Thus, total costs can be reduced by \$21,310 (14.77%) per day if the ECM was available, although the sourcing of special requests is rejected a priori. In Fig. 4, this cost advantage is indicated by the distance between the two dotted lines.

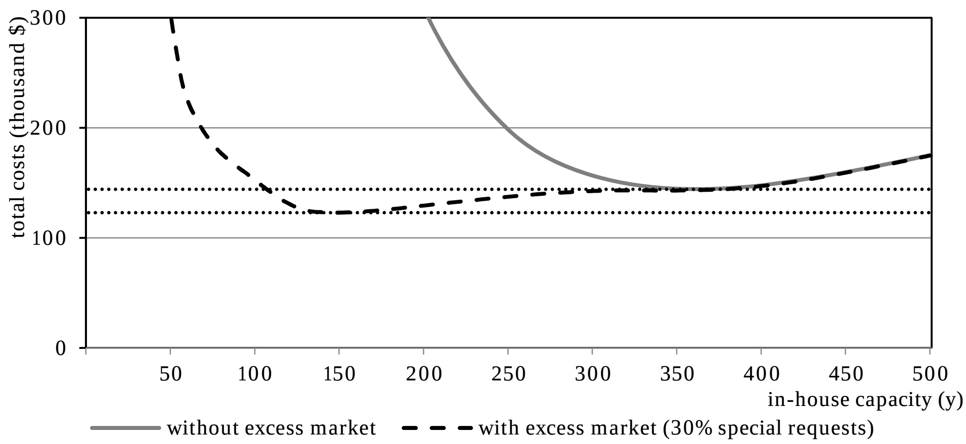

Figure 4. Total costs with and without excess capacity

An analysis of the functions that sum up to the total costs (i.e., fixed costs for in-house capacity, variable costs for requests routed to the ECM, compensations and penalties for exceeding the agreed SLA) reveals the following:

For the scenario *without* ECM integration, very small in-house capacity produces long waiting times, and the total costs are high due to the corresponding SLA-induced compensations and penalties. With increased in-house capacity, more requests can be processed ahead of the final processing deadline; thus, total costs decrease drastically due to the fewer violations of the agreed-upon SLA processing time of 26:00 minutes and fewer requests exceeding the final processing deadline. Regarding the optimal level of capacity *without* access to the ECM (362 units), as indicated in Fig. 4, no further cost savings are possible beyond this point, as the costs of additional capacity exceed the cost savings from it.

By contrast, in the scenario *with* ECM integration, the possibility of using excess capacities reduces the risk of exceptionally high SLA-induced compensations and penalties because the ECM allows the execution of regular requests that are left unexecuted in the other scenario. The high penalty for unexecuted requests ensures that the routing algorithm chooses the external execution path. Furthermore, as regular requests arriving in peak times (e.g., the early morning or evening) can be routed to the ECM, the waiting times in the queue in front of the in-house unit are reduced. Overall, special requests also benefit from excess capacities, as the waiting time in front of the in-house unit and the corresponding waiting compensations are reduced. Again, with the increased in-house capacity, waiting costs decrease to the point where the costs of additional capacity exceed the waiting-cost savings (147 units).

Thus far, we have used a percentage of 30% of authorization requests that require specialized interventions or customer callbacks due to incomplete or inaccurate registration forms in our simulation. However, this percentage may vary depending on the service considered. For example, the number of data required for the identification and authorization service, its complexity (e.g., dependencies between data packages) as well as the target group of the service (e.g., retailer focuses on customers with little online experience) can strongly influence the error rate induced by the user. To examine the influence of the number of incoming special requests, we vary the percentage of special requests while all other parameters are kept at their initial values.

Fig. 5 summarizes the total costs assuming different percentage rates for special requests. The costs when employing the optimal level of in-house capacity combined with the ECM are lower for each setting (e.g., 10%, 30%, 50%) than in the solution without external service providers.

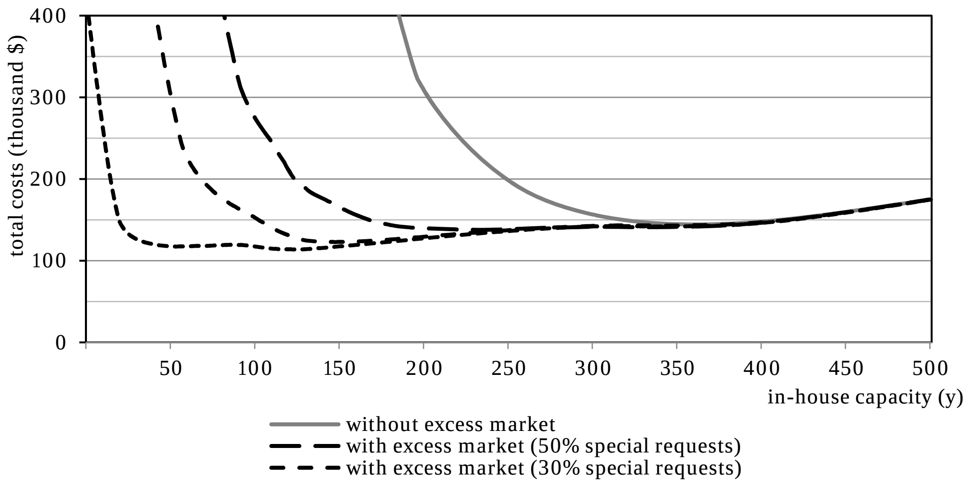

Figure 5. Cost patterns for different percentage rates for special requests

This *general cost advantage* can be explained the following way. In the scenario without ECM integration, all requests (whether regular or special) must be processed by the in-house unit, which leads to the cost disadvantages mentioned above. Likewise, in the scenario with ECM integration, a PSP would have to process all requests in-house if they were all categorized as special. Thus, the scenario without ECM integration corresponds exactly to a setting of 100% special requests, as, in both scenarios, the PSP has to execute all requests in-house. Accordingly, the optimal setting with ECM integration is preferable for all levels of special requests to the optimal setting without ECM integration. This is caused, inter alia, by the fact that ECM integration involves only the variable costs for each request sent to external providers. Accordingly, integrating excess capacity enables a general cost advantage which, however, decreases by the percentage rate of special requests. Table III summarizes this general cost advantage by presenting both optimal in-house capacity and the associated costs for the different percentage rates of special requests as well as the corresponding cost advantages compared to the scenario without ECM utilization.

	w/o ECM	**w/ ECM (10% SR)**	**w/ ECM (30% SR)**	**w/ ECM (50% SR)**
Optimal In-house Capacity [units]	362	125	147	233
Total Costs [USD]	144,292	113,665	122,982	137,808
Cost Advantage [%]	-	21.23	14.77	4.49

Table 3. Cost advantages for different percentage rates of special requests (SR) with ECM access compared to the scenario without ECM access

So far, we have identified a general cost advantage for the PSP as an opportunity to gain a competitive advantage by using ECM. In a cost-driven market environment, this cost advantage can be used for price differentiation on the side of the PSP in order to establish price leadership. However, based on the innovative opportunities of the on-demand integration of excess capacity, further strategies for gaining competitive advantages become evident. In the following section, we therefore analyze how cost leadership can be used to create differentiation advantages besides that of price in competitive cost-driven markets.

IV.1.4.5 Scenarios 2 and 3: Determining the Differentiation Advantage of Excess Capacity

By pursuing a differentiation strategy, the PSP can create a unique selling proposition aside from cost leadership. Due to the cost-effective processing of requests via ECM, the PSP can use its cost advantage to create a variety of differentiation advantages; the PSP can distinguish its services regarding qualitative benefits and offer more cost-intensive services, while the cost advantage of ECM ($21,310 in our simulation) allows equal-cost market competition. In the following, we demonstrate differentiation strategy options and examine their benefits.

The starting point of our consideration is the model parameters set forth above. We employ the basic setting of our simulation (30% special requests). Furthermore, we consider parameters representing qualitative aspects for differentiation opportunities. For example, the PSP can offer an improved service level, meaning that it commits to a shorter processing time for incoming requests (scenario 2). Alternatively, the execution time the in-house unit spends on special requests can be expanded, allowing the in-house unit more time to increase the processing quality for special requests (scenario 3). For both differentiation strategies, we now determine to what extent a PSP *with* access to excess capacity can improve its service quality and thereby develop a substantial differentiation advantage.

In scenario 2, we examine the reduction of the agreed-upon SLA processing time in order to identify a lower limit for it. The benchmark for this optimization is represented by a competitor *without* access to excess capacity. First, we gradually reduce the SLA processing time (starting at 26:00 min) and determine the minimum of the total costs for each level of SLA processing time. Each experiment consists of 800 simulation runs. This is repeated until the minimum of the total costs of the PSP *with* access to the ECM equals the minimum of the total costs of the competitor *without* access to the ECM. Fig. 6 shows the cost patterns leading to identical costs. According to this staged optimization approach, the PSP *with* ECM access can offer an SLA processing time of 10:54 minutes (as a lower limit) instead of 26:00 minutes while realizing the same total costs as a competitor *without* ECM access. This means that the PSP can offer an SLA that is 58% stricter at an identical price. Accordingly, any SLA between 26:00 and 10:54 minutes generates both differentiation advantages (a more attractive SLA) and cost advantages (the remaining cost benefit) when utilizing ECM.

In scenario 3, we use the same staged optimization approach to determine the upper limit of the extra time the in-house unit can spend on special requests. Starting with our basic simulation setting, we gradually increase the processing time for special requests (starting at 12:00 minutes) until the minimum of the total costs of the PSP *with* access to the ECM equal the costs of the competitor without it. As shown in Fig. 7, the PSP can increase the processing time for requests by 4:13 to 16:13 minutes (upper limit). Consequently, the in-house unit has about 35% more time for correcting and post-processing and for contacting customers to complete identification and authorization procedures.

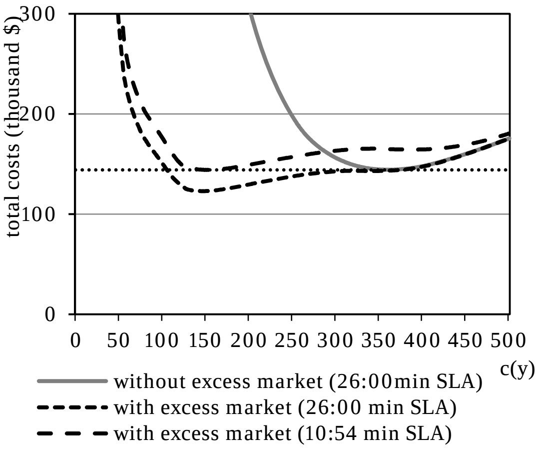

Figure 6. Improved SLA

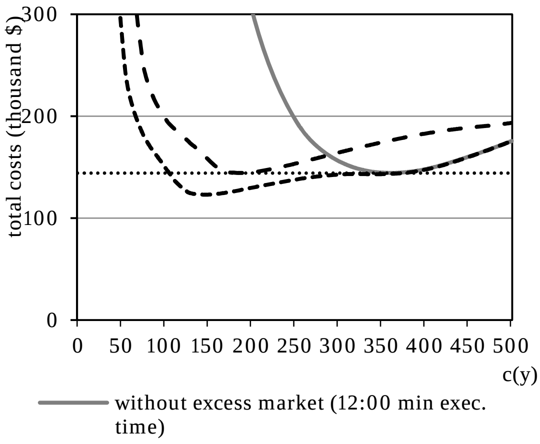

Figure 7. Increased Execution Time

Table IV provides details on the differentiation advantages illustrated in Fig. 6 and 7 by specifying the total costs of scenarios 2 and 3, their cost components, and the shifting of the cost advantage (shown in brackets) compared to the basic setting with ECM access (scenario 1). It considers the costs for the in-house unit, the costs for excess capacity, compensations, and penalties. For the sake of completeness, the setting without ECM access (benchmark) is shown in the far-right.

Cost component	**Improved SLA of 10:54 min (scenario 2)**	**Increased exec. time of 16:13 min (scenario 3)**	**Basic setting w/ ECM (scenario 1)**	**Basic setting w/o ECM (benchmark)**
Optimal In-house Capacity [units]	154	189	147	362
In-house Capacity Costs [USD]	53,900 (+2,450)	66,150 (+14,700)	51,450	126,700
Excess Capacity Costs [USD]	41,410 (+442)	42,195 (+1,227)	40,968	0
Compensations & Penalties [USD]	48,982 (+18,418)	35,947 (+5,383)	30,564	17,592
Total Costs [USD]	144,292 (+21,310)	144,292 (+21,310)	122,982	144,292

Table 4. Summary of costs and cost components for different scenarios

In scenario 2, the PSP can offer a more attractive SLA and, at the same time, face higher compensation payments due to the reduction in the agreed-upon SLA timeframe. Thus, most of the cost advantage of ECM integration is passed on to the retailer. However, the PSP has to consider possible negative side effects on customer (i.e. retailer) perception caused by increasing SLA-violations, which are not included in our model. Accordingly, the improved SLA of 10:54 minutes represents the absolute minimum of the processing time and does not contain any concrete action recommendation. In scenario 3, longer execution times for special requests require more in-house capacity, and compensation payments between the PSP and the retailer increase. However, as the PSP's in-house unit is given more time to focus on non-standard procedures, processing quality can be increased. Though quality and customer satisfaction are, as indicated, not captured in our model, we assume that increased processing times can be utilized to respond individually to customer needs, thereby strengthening customer relationships. Thus, the differentiation strategy of scenario 3 can constitute a significant competitive advantage for the PSP, as it may increase customer satisfaction as well as the retailer's prospects for customer retention.

IV.1.5 Conclusion, Managerial Implications, and Further Research

Amid the challenges for service providers in cost-driven value chains and the research gap described above, this paper examines the potential of IT-enabled ECM to create *competitive advantages* in e-business value chains for *inhomogeneous* services. Having discussed the information and integration capabilities necessary to utilize excess capacity, we considerably extended the model of Dorsch and Häckel [41] and focus on the capacity optimization problem of a BPSP within a three-stage supply chain. We ran a discrete-event simulation with input data from a possible application scenario to analyze the model and derive interpretable results relevant to our research question.

We answered our research question by analyzing the competitive advantages that can be realized through an IT-enabled ECM for the processing of cost-driven inhomogeneous service requests. First, we identified a remarkable *cost advantage* in using the ECM to process a certain portion of incoming requests, as the capacity of the in-house unit can be reduced without negative effects on service levels, reducing overall operating costs. Our analysis reveals a cost advantage even if the portion of special requests is rather high (i.e., if the portion of incoming requests suitable for handling by third-party providers is low). Nevertheless, the extent of this competitive advantage is rising significantly with the increasing service homogeneity. Building on this *cost advantage*, we examined the possibilities of gaining a *differentiation advantage* (i.e., improvements in service levels and service quality without raising prices). We showed that reduced processing times can be guaranteed and executions times (and thus quality) increased at equal costs, leading to a competitive advantage.

Based on these results, we can derive the following *managerial implications*:

- First, our results suggest that high upfront investments in information and integration capabilities might pay off in the mid to long run due to the economic potential of using excess capacity. The quantitative results of our model show the potential value of such investments and therefore determine an upper bound for investment spending.

- Furthermore, our model provides a sound basis for analyzing the economic advantages of various differentiation strategies. As discussed, the BPSP can, for instance, offer improved service levels and/or higher service quality without raising prices. Our model allows a thorough evaluation of these different business strategies, which might strengthen a BPSP's competitive position.
- As discussed in the introduction, an IT-enabled ECM is most suitable for standardized services rather than complex or non-standardized services. Regarding the processing of these, we propose that a BPSP should carefully evaluate whether investments in the further standardization of services may enable the usage of external service providers such as IT-enabled ECM and whether the resulting economic potential would justify such investments.
- Furthermore, as discussed, the extent of the competitive advantages of an IT-enabled ECM is highly dependent on the inhomogeneity of the service. As a consequence, a BPSP may also consider investments into a further homogenization of the service (e.g., by improving the usability of input forms, thus enhancing the data quality of the incoming service requests) to strengthen the potential competitive advantages.
- To look ahead, a BPSP might also consider establishing new business models connected to excess capacity that consider offering non-SLA backed capacity only or operating as excess capacity brokers or market makers. Highly standardized services, especially those spanning multiple business sectors, may offer strong potential for such business models.

Although our model implies several managerial implications, it also has limitations based on its assumptions, which offer opportunities for future research. We relied on the simplifying assumption of an *exogenous market*, in which the amount of the available excess capacity is not affected by the actual demand of the BPSP or any other market user. Moreover, the interdependencies between peak times both for the BPSP and the market players were not considered. Consequently, modeling an endogenous market may be a promising subsequent step from an *analytical point of view*. Additionally, from an *empirical point of view,* the lack of knowledge concerning the interdependencies between the strategy of a single player and an endogenous ECM should be addressed by appropriate field studies. Moreover, our model focuses on cost minimization, which seems a reasonable first step, as our study is concerned with the analyses of cost-driven services. Nevertheless, our analyses of possible differentiation advantages are limited to a discussion of the differentiation strategies that build on cost advantages and that can be realized without raising prices. Extending the model by incorporating price-demand functions (and thus considering revenue aspects) would facilitate a further analysis of various competitive differentiation strategies and their economic potential.

Aside from these potential starting points for further research, our paper contributes to the knowledge on the competitive advantages that can be realized through IT-enabled ECM within a BPSP`s value chain for the processing of cost-driven inhomogeneous service requests. Our research provides valuable insights for both researchers and managers engaged in business processes and service management.

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IV.2 Research Paper 5: "Assessing IT Availability Risks in Smart Factory Networks"

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Abstract: *Emerging smart manufacturing technologies combine physical production networks with digital IT systems resulting in complex smart factory networks, which are especially vulnerable to IT security risks like IT component non-availabilities. In order to secure their production facilities, companies need to employ extensive IT security measures. However, complex network structures and inherent dependencies of smart factory networks complicate corresponding investment decisions and rise the need for appropriate decision support. We develop a risk assessment model that supports companies in the investment decision process by identifying and evaluating the most critical areas of the information network while considering the underlying production network. At this, IT availability risks are quantified by means of graph theory, matrix notation, and Value-at-Risk. Our model provides a structured approach and considers network structures and interdependencies. The in-sights gained by our model present a profound economical basis for investment decisions on IT security measures. By applying our model in an exemplary real world setting, we analyze different IT security measures and their risk reduction effect.*

Keywords: *Smart Factory, Cyber-Physical Systems, Risk Assessment, IT Availability Risks, Risk Quantification, Network Structure Analysis, Investment Decision Support*

IV.2.1 Introduction

The *Internet-of-Things* (IoT) and C*yber-Physical Systems* (CPS) are key elements of the emerging technologies that are currently transforming our economy. In a report on technological trends, McKinsey ranks IoT third, behind the mobile Internet and the automation of knowledge work (Manyika et al. 2013). Thereby, so-called *smart factories* are one of the most promising application areas of IoT and CPS, as they lead to tremendous advancements and paradigm shifts in manufacturing (Lasi et al. 2014). At this, CPS combine physical production with digital information by connecting networked embedded systems. This highly automated and intelligent manufacturing environment enables a flexible production of individualized goods while increasing efficiency at the same time (Lucke et al. 2008; Radziwon et al. 2014). Besides these benefits, the criticality of information and communication infrastructures increases the smart factory's vulnerability to IT security risks. This involves especially IT availability risks, which become one of the most critical threats for organizations (Amiri et al. 2014).

CPS control themselves autonomously and communicate in a decentralized way (Yoon et al. 2012). They consist of embedded systems connected over the Internet or other network infrastructures to form dynamic, intelligent, and self-controlling networks (Broy et al. 2012; Schuh et al. 2014). Within these networks, smart objects, i.e. intelligent machinery and products, control and monitor the production process collaboratively through the use of sensors and actuators and machine-to-machine communication. Thereby, they optimize themselves and the production process (Hessman 2013; Schuh et al. 2014; Yoon et al. 2012).

This new paradigm of manufacturing brings a variety of benefits, like increased flexibility and productivity, optimized processes, improved capacity utilization, reduced lead times, and enhanced energy and resource efficiency (Chui et al. 2010; Radziwon et al. 2014; Schuh et al. 2014; Shrouf et al. 2014; Yoon et al. 2012). Furthermore, these benefits contribute to the smart factory's ability to custom produce highly individualized products in low batch sizes in a considerably short time-to-market at costs comparable to mass production (Lasi et al. 2014). This is of central importance for companies in all manufacturing industries, since intelligent automation technologies become a basic prerequisite for the future competitiveness, as customer expectations shift toward mass customization, ever shorter innovation cycles, and customer participation models (Lasi et al. 2014; Yoon et al. 2012).

Smart objects rely on communication and real-time information synchronization and thus depend on the underlying IT systems, which are mandatory for the reliable functioning of the production infrastructure (Yoon et al. 2012; Zuehlke 2010). Due to this dependency, short-term non-availabilities of IT systems can interrupt the functioning of the dependent production infrastructure (Lee 2008; Lucke et al. 2008; Zuehlke 2010). These failures are especially problematic considering that smart factories are no longer isolated and closed systems like conventional, self-contained production facilities, but highly connected with both internal and cross-company networks, including suppliers, customers, and vendors (Smith et al. 2007; Yoon et al. 2012). Thus, local failures can cause disruptions in entire value networks.

Accordingly, the increasing interconnectedness of modern manufacturing processes leads to new IT security related vulnerabilities (Amin et al. 2013). Simple technical failures as well as intentional attacks on the IT systems, e.g. targeted denial-of-service attacks, can cause the non-availability of IT components, affecting the functionality of the production network and reducing its productivity (Amin et al. 2013; Lucke et al. 2008; Zuehlke 2010). Therefore, IT availability risks pose a significant threat potential to smart factories. This threat potential is illustrated by numerous examples. The German Federal Office for Information Security (abbreviated as BSI) mentions in its status report on information security that hackers attacked a steel plant by intruding its office network. After advancing into the production control network and attacking the control components of the blast furnace, the blast furnace was in an “undefined status”, and it was impossible to shut it down in a controlled manner. As a result, the blast furnace and other parts of the plant were severely damaged (BSI 2014). This illustrates that, due to the ongoing interconnectedness, IT security is of critical significance even in traditional production facilities. Another example is the Stuxnet worm attack of 2010, which aimed at industrial control systems in high-security infrastructures like atomic plants. Stuxnet showed that the interconnectedness of applications presents a serious security issue and demonstrated that even the control system’s disconnection from the Internet as well as personal access restrictions are insufficient as protection for industrial control systems (Karnouskos 2011). In order to respond to these threat scenarios, companies have to employ IT security measures to secure their CPS infrastructure against IT availability risks. Appropriate IT security measures include, but are not limited to, redundancies through backup components, industrial hardware with integrated IT security mechanisms, intrusion detection systems, or appropriate service-level agreements (Byres and Lowe 2004; Cardenas et al. 2008; Yadav and Dong 2014; Zambon et al. 2007).

The corresponding investment decisions on IT security measures have to be based on a profound economical basis (Cavusoglu et al. 2004). Therefore, costs, benefits, and risk aspects of IT security measures have to be evaluated to enable investment decisions that are in line with the concept of value based management aiming at long-term economic growth (Gordon et al. 2003; Huang 2010). For this purpose, the most critical areas of the IT system have to be identified and evaluated in a structured approach in order to invest available funds in the most effective way (i.e. reducing IT availability risks to the best possible extent). Thereby, the analysis has to consider the diverse and complex network structures and dependencies between the physical production world and the digital IT systems of the smart factory. In order to develop a structured approach for the identification and evaluation of the most critical areas in regard to IT availability risks, we formulate the following two research questions:

RQ1: How can a smart factory network consisting of dependent and connected production components and IT systems be modeled and formalized?

RQ2: How can IT availability risks of IT systems in a smart factory network be quantified in order to identify the most critical nodes?

The remainder of our paper is organized as follows. Section 2 gives an overview of existing literature regarding smart factories and corresponding IT availability risks and outlines the research gap. In section 3, we outline the basic idea and describe the model developed to address the research questions raised. Section 4 evaluates the developed risk assessment model with an exemplary application and sensitivity analyses. Finally, section 5 gives a conclusion and points out limitations and further research.

IV.2.2 Literature Overview and Research Methodology

Given the innovative nature of IoT in manufacturing, scientific literature is currently emerging to address this issue (e.g. see Fleisch and Thiesse 2007; Haller et al. 2009; Iansiti and Lakhani 2014; Turber and Smiela 2014). Besides scientific literature, there are numerous studies and application-oriented examples of research institutes exploring and describing the implementation of smart manufacturing technologies (e.g. see Hessman 2013; Lucke et al. 2008; Radziwon et al. 2014; Yoon et al. 2012; Zuehlke 2010). In practice, we can observe that partial technological solutions like RFID are already widely implemented. However, the comprehensive implementation of smart manufacturing technologies in production facilities remains object to laboratory research facilities like *SmartFactory^{KL}* or pilot facilities like Siemens Electronic Works facility (Hessman 2013; Zuehlke 2010). Based on *SmartFactory^{KL}*, Zuehlke (2010) describes that a “factory-of-things will be composed of smart objects which interact based on semantic services”. Radziwon et al. (2014) defines the smart factory as a “manufacturing solution that provides such flexible and adaptive production processes that will solve problems arising on a production facility […]". Yoon et al. (2012) describes a "factory system in which autonomous and sustainable production takes place". And Lucke et al. (2008) envisions the smart factory as a "real-time, context-sensitive manufacturing environment that can handle turbulences in production using decentralized information and communication structures for an optimum of production processes".

These definitions reflect the specific characteristics of smart factories, like their modular design enabling functionalities like flexibility, reconfigurability and adaptability (Radziwon et al. 2014; Zuehlke 2010). This enables the smart factory to respond to circumstances and turbulences in the real-time production, e.g. the short-term non-availability of production components (Lucke et al. 2008). Within the smart factory network, smart objects equipped with embedded systems and built-in intelligence represent central components. These embedded systems consist of computing hardware and software. Together with sensors and actuators, smart objects are able to control themselves autonomously and to connect over a network infrastructure in order to form collaborative production infrastructures and to exchange information (Yoon et al. 2012; Zuehlke 2010).

Although smart objects control and optimize themselves autonomously, central IT systems are required for planning and coordination of the decentralized smart objects. For example, central IT systems can provide parameters and framework conditions for the autonomous control and optimization of smart objects (Schuh et al. 2014). However, the prevailing hierarchical structure of the respective IT systems and services gradually dissolves. IT systems are rather integrated vertically to enhanced standardized IT services in correspondence to a service-oriented architecture (SoA). Furthermore, IT systems are horizontally connected with other internal and external networks to facilitate information exchange and collaboration within the supply network. The necessary infrastructure is usually company-specific and can either be on-premise, cloud-based or a hybrid form of both (Colombo et al. 2013; Karnouskos and Colombo 2011; Shrouf et al. 2014; Yoon et al. 2012; Zuehlke 2010).

Nevertheless, the functioning of the physical production process depends on the functioning of the IT services. As Amin et al. (2013) state, CPS face new IT security threats, which stem from four channels: (1) software bugs and hardware malfunctions, (2) open Internet protocols and shared networks, (3) numerous parties involved, and (4) a large number of field devices that can be accessed. Based on these threat channels, events including intentional attacks, e.g. denial-of-service, and random failures, e.g. malfunctions, can cause the non-availability of IT services (Amin et al. 2013). This non-availability, i.e. the inaccessibility and non-usability of a service upon demand, poses a significant threat to the smart factory due to its real-time constraint (Cardenas et al. 2008; Lee 2008). Further, the smart factory's interconnectivity and IT-based integration with its supply network pose, besides the benefits through improved collaboration, increased IT security risks, since former protective barriers are at least partially removed (Smith et al. 2007). Modern industrial control systems are, for example, connected to the office network and external systems for information exchange and are no longer completely isolated through "air gaps" (Byres 2013). A study by Byres and Lowe (2004) also indicates this increased vulnerability and reveals that security incidents increasingly stem from external sources (70%) compared to internal sources (30%). Amongst others, they mention the increasing interconnection of critical systems and resulting interdependencies as a reason for this development.

Considering this threat scenario, companies need to mitigate risks through appropriate IT security measures. The first step in this process is the risk assessment, which can be performed by various methods (Savola 2007) and differentiated into qualitative and quantitative approaches (Rainer et al. 1991). Qualitative methods use descriptive variables to evaluate likelihood of occurrence and impact of an IT non-availability (Aagedal et al. 2002; Caralli et al. 2007). Quantitative methods rather deploy mathematical functions and quantitative data (Karabacak and Sogukpinar 2005; Suh and Han 2003; Sun et al. 2006). For example, the risk assessment framework developed by Jaisingh and Rees (2001) uses the quantitative risk measure Value at Risk (VaR). Thereby, the VaR derives "the worst loss due to a security breach over a target horizon, with a given level of confidence". The derived information can then be used to achieve a trade-off between risk reduction effects and cost of security measures. Furthermore, there are methods combining both qualitative and quantitative elements (Rainer et al. 1991; Yadav and Dong 2014). Besides these methodical approaches, the risk assessment also has to consider specifications of its respective application field. For example, the risk assessment method developed by Zambon et al. (2007) considers the IT architecture as well as dependencies between IT constituents based on a time-dependency model for business processes.

However, this method does not consider dependencies between production processes nor other aspects of production networks, which would be necessary for smart factory networks. Thus, we formulate the following requirements for an appropriate risk assessment approach for smart factory networks: First, the network structures and the modular production infrastructure, including interdependencies within the production process, have to be considered. Second, the network structure of the IT system, including dependencies between

IT components, has to be considered. And lastly, losses in the production process caused by IT non-availabilities have to be quantified and assigned to IT components. To the best of our knowledge, there is no risk assessment approach meeting these requirements. Therefore, we develop a structured approach to answer the research questions raised. Our approach uses graph theory and matrix notation methods, as they are widely utilized methods for the analysis of complex and interdependent networks. For example, Wagner and Neshat (2010), Faisal et al. (2006), and Buldyrev et al. (2010) use graph theory and matrix notation to analyze risk in supply chains and critical infrastructures in regard to vulnerability, risk mitigation, and cascading failures in interdependent networks.

In order to identify and evaluate the most critical IT components, we use the research paradigm introduced by Meredith et al. (1989). This approach structures research into a "continuous, repetitive cycle of description, explanation, and testing". By going through these stages in an iterative process, the description and explanation of an observable economic fact in a structured manner is possible. First, we (formally) describe cause-and-effect-relationships that determine the threat potential of an IT component (e.g. the basic structures and dependencies of smart factory networks). Since new findings cannot always be derived from practical observations, we use a formal deductive modeling approach. Afterwards, we discuss and explain the derived findings and try to give (practical) recommendations. An exemplary application indicates the utility of our risk assessment model and serves as a starting point for its empirical validation. However, the testing of the findings shall be subject to future case study research.

IV.2.3 Risk Assessment Model

The risk assessment model presented in this paper identifies the most critical IT components of a smart factory's information network in regard to IT availability risks by quantifying the corresponding threat potentials. In the following subsection, we describe the model's procedure as shown in Figure 1. First, we present an abstraction of the smart factory's general setting with its basic structures and relations (1). Afterwards and based on this abstraction, we describe our risk quantification algorithm. At this, we model and formalize the smart factory structure by means of graph theory and matrix notation (2). Subsequently, the threat potential of each IT component is quantified (3).

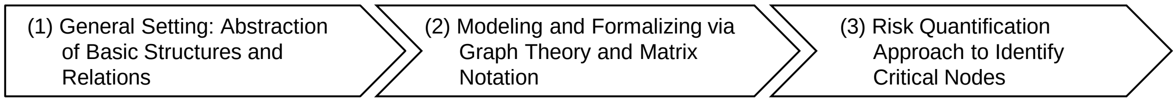

Figure 2. Methodical Procedure of the Model Development

The basic idea of our risk assessment model is to analyze the threat potential posed by the non-availability of an information network's IT component to the production network of a smart factory. This threat potential arises as the functionality and productivity of the production network depend on the reliable functioning of the information network. In order to quantify the resulting threat potentials, we apply graph theory and matrix notation as well as VaR. The results gained by our model are of central importance since available funds for IT security measures have to be invested in the most efficient way in correspondence to value-based management principles.

IV.2.3.1 General Setting

The basic structure of the smart factory consists of two connected networks, the production network and the information network, as illustrated exemplarily in Figure 3.

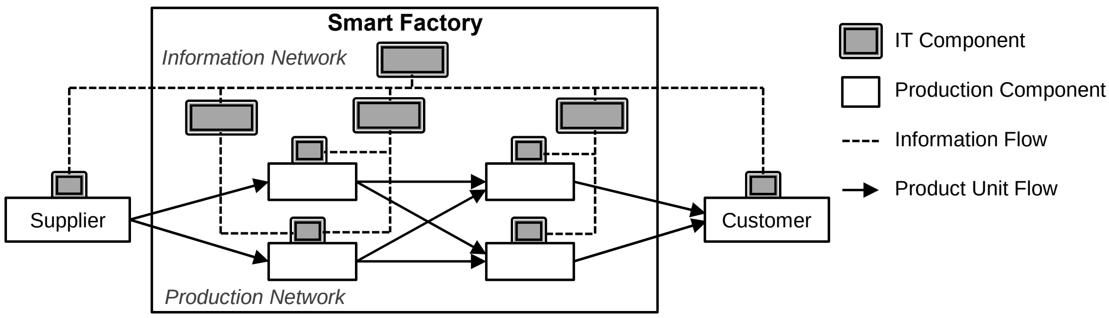

Figure 3. Simplified Structure of the Smart Factory

First, there are different smart manufacturing machines in the production network performing various production procedures. They process the products and are organized in process steps whereby a process step contains machines with identical capabilities. The manufacturing machines are equipped with *embedded systems*, which consist of an electronic hardware (e.g. microchip) and a software component. The embedded systems enable the manufacturing machines to control themselves autonomously (up to a certain point) and to synchronize process information via the information network. For this purpose, the *information network* consists of components performing different IT services crucial for the reliable functioning of the smart factory. These IT services range from machine control and manufacturing execution to enterprise level and machine communication applications. The different applications may be hosted on on-premise hardware or are obtained as cloud-based solutions. The respective IT infrastructure is also considered as an IT service. As a result, a hierarchical structure emerges inducing *functional dependencies* between the IT components. These functional dependencies exist either *directly* between two IT components (e.g. applications depend on the server) or *indirectly* over at least one other IT component (e.g. an embedded system depends on the server over an application hosted on that server). A company may also include *redundancies* within the information network through backup components to secure certain IT services and to prevent single-point failures. If all IT services operate reliably, the smart manufacturing machines are able to coordinate themselves in a highly flexible and adaptive manner. This includes, for example, the adjustment of the product flow in case of a manufacturing machine's non-availability. In addition to the manufacturing components, there are suppliers vertically and horizontally integrated into the supply network and customers receiving the completed products. Both are defined as parts of the production network due to their importance and since local interruptions affect the smart factory. Considering the integration of external partners into the IT system of a smart factory, both suppliers and customers are connected through external data interfaces.

Given the dependencies within and between these networks, a diverse and complex *dependency structure* emerges in which the production components depend on several components of the information network in regard to their functionality. This dependency structure is of central relevance for our model, because it provides the basis for the quantification of the IT component's availability risks. Based thereupon, we analyze the consequences of an IT component's non-availability by deriving the unprocessed units, which occur in a fixed time period. By analyzing the resulting risk values of all IT components, we are able to prioritize the IT components regarding their threat potential to the production network.

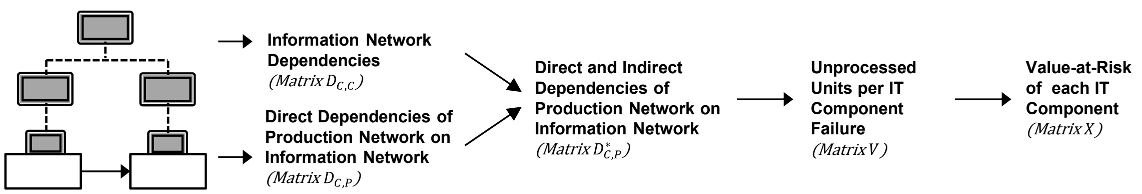

Figure 4. Operational Steps of the Risk Assessment Algorithm

In the following subsection, we outline the algorithm and its assumptions (see Figure 4) in more detail. First, we formalize and model the basic structures of the smart factory and its networks by means of graph theory and matrix notation. The resulting dependency structure of the smart factory lays the ground for the risk quantification based on VaR, which will be discussed in the subsection afterwards.

IV.2.3.2 Modeling of the Smart Factory

In the following, we describe, model, and formalize the two connected and dependent networks of the smart factory. Thereby, we elaborate on the underlying assumptions in regard to the basic structures and characteristics of both networks, their components as well as their connections and dependencies.[1]

A1: The production network $\boldsymbol{P}$ consists of a finite set of smart production components $\boldsymbol{p_i}$ with $\boldsymbol{i = 1, \dots, m} \in \{\mathbb{N}\}$ (nodes) performing specific production procedures and a finite set of arcs (edges) connecting the production components.

The smart production components p_i perform production procedures in order to process a *product unit* $u \in \{\mathbb{N}\}$ and are assigned to a *process step* l with $l = 1, \dots, L \in \{\mathbb{N}\}$ in correspondence to their respective production task. The suppliers and customers are modeled to be part of the production network and are also denoted as production components p_i. The production capabilities of production components are identical within a process step l, but differ between process steps. Regardless of the process step, each production component p_i has a given *capacity* $q_i \in \{\mathbb{N}\}$ to process a given number of units u in the considered time period. In combination with the current *capacity utilization* $\bar{\bar{q}}_i \in \{\mathbb{N}\}$ of a production component, the *idle capacity* $\bar{q}_i \in \{\mathbb{N}\}$ of a production component can be derived by equation (1).

$$\bar{q}_i = q_i - \bar{\bar{q}}_i \; with \; \bar{\bar{q}}_i \leq q_i \tag{1}$$

If a process step l consists of more than one production component, product units can be flexibly routed to any of the assigned production components under consideration of the respective idle capacities. Therefore, the utilization of the smart factory and the individual production components are important factors determining the smart factory's flexibility and adaptability.

A2: The information network $\boldsymbol{C}$ consists of a finite set of IT components $\boldsymbol{c_s}$ with $\boldsymbol{s = 1, \dots, k} \in \{\mathbb{N}\}$ and a finite set of arcs connecting the IT components.

The IT components c_s of the information network C perform various IT services s. Thereby, each IT service is provided by one IT component and may be backed up by a redundant IT component denoted as $c_{s.2}$. Depending on the specific layout of the information network, different types of IT components like hardware components, software modules, embedded

[1] The reader might find it helpful to reference to Figure 5 on page 145 while reading the following subsections to better comprehend the used notations.

systems, and external data interfaces can be included. This flexibility enables the adaption of the algorithm to any information network layout (e.g. on-premise vs. cloud-based) without changing the algorithm's overall approach.

Considering the layout and hierarchical structure of the information network and its IT services, there are direct functional dependencies between the IT components, e.g. the dependency of an application on the server on which the application is hosted. The binary *information network dependency matrix* $D_{C,C}$ defined by equation (2) represents all direct functional dependencies.

$$D_{C,C} = \begin{bmatrix} d_{c_1,c_1} & \cdots & d_{c_1,c_k} \\ \vdots & \ddots & \vdots \\ d_{c_k,c_1} & \cdots & d_{c_k,c_k} \end{bmatrix} \tag{2}$$

The numerical value of the binary variable $d_{c_s,c_s} \in \{0; 1\}$ expresses whether there is a direct functional dependency between two IT components or not.

A3: Production components depend either directly or indirectly on IT components in regard to their functionality.

As already described, the smart production components' ability to synchronize information via the information network C is an essential requirement for the reliable functioning of the production network. The resulting *direct functional dependencies* of the production components on IT components are expressed by the binary *direct functional dependency matrix* $D_{P,C}$ defined by equation (3).

$$D_{C,P} = \begin{bmatrix} d_{c_1,p_1} & \cdots & d_{c_1,p_m} \\ \vdots & \ddots & \vdots \\ d_{c_k,p_1} & \cdots & d_{c_k,p_m} \end{bmatrix} \tag{3}$$

Thereby, the binary variable d_{c_s,p_i} equals one for the dependency relationship between production components and their respective embedded system, since the embedded systems establish the necessary connection to the information network and are the interface between the smart production components and the digital information flow. For all other IT components, variable d_{c_s,p_i} equals zero since production components are not directly connected with them. However, production components can still depend *indirectly* on those IT components, since the IT services provided by those IT components are not available if the IT components are not available. This is due to the transitivity of IT component failures, meaning that, for example, the failure of a server affects production components through the triggered failure of a software application (Zambon et al. 2007). Further, existing *redundancies* in the information network have to be considered since redundant IT components prevent single-point failures of backed up components and hence, influence the dependency structure of the smart factory (Cardenas 2008, p.3). In order to consider both direct and indirect functional dependencies as well as redundancies in the information network, we apply a set of matrix calculations based on methods of matrix algebra, which will not be explained in full detail, but be briefly described in the following.

First, we determine all direct and indirect functional dependencies within the information network by raising matrix $D_{C,C}$ to higher powers according to the algorithm by Festinger, Perry and Luce (Festinger 1949) and by combining the resulting matrices in the binary matrix $\overline{D}_{C,C}$. Now, multiplying matrix $\overline{D}_{C,C}$ with the *direct functional dependency matrix* $D_{C,P}$ delivers all indirect functional dependencies of production components on IT components (matrix $\overline{D}_{C,P}$). Adding the matrices $D_{C,P}$ and $\overline{D}_{C,P}$ results in the *direct and indirect functional dependency matrix* $\overline{\overline{D}}_{C,P}$ containing both the *direct* and *indirect* functional dependencies of production components on IT components. Now, we adjust matrix $\overline{\overline{D}}_{C,P}$ for possible redundancies by further matrix calculations based on the IT services performed by the respective IT components. The resulting *dependency matrix* $D^*_{C,P}$ defined by equation (4) contains all direct and indirect functional dependencies of production components on IT components and considers redundancies in the information network. Thereby, the binary variable $d^*_{c_s,p_i} \in \{0; 1\}$ equals one if there is a direct or indirect functional dependency, otherwise $d^*_{c_s,p_i}$ equals zero.

$$D^*_{C,P} = \begin{bmatrix} d^*_{c_1,p_1} & \cdots & d^*_{c_1,p_m} \\ \vdots & \ddots & \vdots \\ d^*_{c_k,p_1} & \cdots & d^*_{c_k,p_m} \end{bmatrix} \tag{4}$$

The *dependency matrix* $D^*_{C,P}$ is a central artifact of our algorithm and essential for the following risk quantification approach since it enables the consideration of the smart factory's diverse and complex dependency structure.

So far, the explanations referred to the production network (A1), the information network (A2), and their components. Further, the functional dependencies between the two networks were described (A3) and the *dependency matrix* as a central artifact was derived. These steps lay the ground for the risk quantification approach, which identifies and evaluates the critical IT components in regard to IT availability risks.

IV.2.3.3 Risk Quantification Approach

The risk quantification approach determines the unprocessed units caused by the non-availability of an IT component on the basis of the smart factory's dependency structure. The resulting *VaR values* represent the central results of our model and enable the identification of the most critical IT components. The following section elaborates on the risk quantification approach and its assumptions in more detail.

A4: The non-availability of an IT component restricts the productivity of dependent production components.

Since technical failures and attacks result in the non-availability of the affected IT component, we assume that an IT component fails completely and do not consider partial functionality restrictions. Accordingly, a failing IT component is not able to provide its IT service and restricts dependent production component's productivities leading to decreased production capacities. Thereby, we observe the consequences of an IT component's non-availability in a fixed time period and assume, that the IT component failure occurs at the beginning of the considered period and lasts until its end. The production components' restrictions differ for each IT component and can range from a partial capacity reduction (e.g. through a restricted automation) to a complete failure. The restriction degree of each IT component is expressed by the *restriction degree variable* $\bar{r}_{c_s} \in \{0; 1\}$. Although it would be possible to differentiate the restriction degree of an IT component on a more detailed level for each production component, we assume that an IT component's restriction degree is identical for all production components for reasons of complexity reduction. Multiplying the values of the *dependency matrix* $D^*_{C,P}$ with $\bar{r}_{c_s}$ according to equation (5) derives the *restriction variable* $r_{c_s,p_i} \in \{0; 1\}$ expressing the degree of productivity restriction of a production component p_i if an IT component c_s fails.

$$r_{c_s,p_i} = \bar{r}_{c_s} * d^*_{c_s,p_i} \tag{5}$$

If a productivity restriction occurs, $0 < r_{c_s,p_i} \leq 1$, otherwise $r_{c_s,p_i} = 0$. If the reduced capacity is less than the utilization, i.e. the restriction cannot be absorbed by idle capacity, the productivity restriction causes *initially unprocessed units* v_{c_s,p_i} at the production component p_i as calculated by equation (6).

$$v_{c_s,p_i} = \max\left(\bar{\bar{q}}_i - q_i * \left(1 - r_{c_s,p_i}\right); 0\right) \tag{6}$$

A5: Initially unprocessed units v_{c_s,p_i} caused by the restriction of an affected production component can be (partially) compensated by other production components.

The compensation of initially unprocessed units v_{c_s,p_i} is enabled through the ability of the smart factory to flexibly combine the production components to temporary production lines. However, the compensation is only possible if compensating production components possess the same production capabilities and hence, belong to the same process step l as the affected production component. Further, compensating production components must have idle capacity left. The *compensable units* w_{c_s,p_i} provided by a compensating production component are calculated as described by equation (7).

$$w_{c_s,p_i} = \max\left(q_i * \left(1 - r_{c_s,p_i}\right) - \bar{\bar{q}}_i; 0\right) \tag{7}$$

After deriving the initially unprocessed units and the compensable units on the production component level, we aggregate both values separately for each process step l. By subtracting the compensable units $w_{c_s,l}$ from the initially unprocessed units $\bar{v}_{c_s,l}$ on the process step level according to equation (8), the *unprocessed units* $v_{c_s,l}$ per process step l after the compensation effect can be derived.

$$v_{c_s,l} = \max\left(\bar{v}_{c_s,l} - w_{c_s,l}; 0\right) \tag{8}$$

A6: Unprocessed units $v_{c_s,l}$ at a process step l cause a continual production failure in following process steps due to the lack of workable units.

As we assume that each unit of process step $l+1$ requires one unit from the preceeding process step l, production failures are passed through all subsequent process steps. This production failure cycle continues until the last process step is reached. Further, the number of unprocessed units might increase in later process steps if the IT component's non-availability also affects that process step. Accordingly, we transfer the unprocessed units $v_{c_s,l}$ to following process steps with further matrix calculations. The *resulting unprocessed units matrix* $V^*_{C,L}$ defined by equation (9) represents all unprocessed units $v^*_{c_s,l}$ per process step l after consideration of the compensation effect and the continual production failure.

$$V^*_{C,L} = \begin{bmatrix} v^*_{c_1,1} & \cdots & v^*_{c_1,L} \\ \vdots & \ddots & \vdots \\ v^*_{c_k,1} & \cdots & v^*_{c_k,L} \end{bmatrix} \tag{9}$$

A7: Unprocessed units $v^*_{c_s,l}$ at a process step l cause monetary losses.

The losses caused by unprocessed units reflect the value added during the production process in the respective process steps. They are assigned proportionally to each process step according to the respective activities performed in each process step. Process step specific loss values are necessary since different *impact locations* of IT component failures cause different effects in the production network. For example, a production failure in the first process step means that there are no processed units at all. In contrary, a production failure in an advanced process step means that there are at least semi-finished units, which present a value since their time-to-market is shorter due to their advanced production state. The information about process step specific loss values is available through accounting and performance measurement methods like activity-based costing (Cooper and Kaplan 1991). Based thereupon, we apply the VaR to quantify the consequences of an IT component's non-availability in the considered time period (Duffie and Pan 1997). Thereby, the loss values are not fixed and may vary due to market-induced interference factors and random effects like price and demand fluctuations. Therefore, we assume that the losses are normally distributed with an expected loss value μ_l and a standard deviation σ_l per unprocessed unit u for each process step l, expressed in monetary units (in \$). The use of a normal distribution is justifiable, since variations of the value added are driven by market parameters causing both positive and negative deviations. However, other distributions like the log-normal distribution can be used if the normal distribution is not appropriate in a specific application scenario. The definition of a confidence level $(1-\alpha)$ takes the risk attitude of the company into account. In most cases, there exists no sufficient historical data basis to derive the loss values and standard deviations solely by means of statistical analysis methods. Therefore, the loss extends and probabilities have to be estimated by experts (Gordon and Loeb 2002; Hovav and D'Arcy 2003; Mercuri 2003). Additionally, the excessive amounts of production related data can be used to support these expert estimations (Lucke et al. 2008). With this information, the VaR of each IT component c_s for each process step l denoted as $x_{c_s,l}$ can be derived by equation (10) with $N_{(1-\alpha)}$ being the $(1-\alpha)$ quantile of the normal distribution.

$$VaR = x_{c_s,l} = \left(\mu_l * v^*_{c_s,l}\right) + N_{(1-\alpha)} * \left(\sigma_l * v^*_{c_s,l}\right) \tag{10}$$

The *risk value matrix* $X_{C,L}$ defined by equation (11) represents all VaR-values of each IT component c_s for each process step l.

$$X_{C,L} = \begin{bmatrix} x_{c_1,1} & \cdots & x_{c_1,L} \\ \vdots & \ddots & \vdots \\ x_{c_k,1} & \cdots & x_{c_k,L} \end{bmatrix} \tag{11}$$

The row sums $\sum_{l=1}^{L} x_{c_s,l}$ of matrix $X_{C,L}$ show the total VaR caused by the non-availability of an IT component c_s. Ranking these values derives a priority order in regard to the IT component's threat potential. This represents the central result of our risk assessment model quantifying the consequences of an IT component's non-availability.

The described risk quantification approach of our model enables the consideration of diverse and complex *network structures* and *dependencies* between the production network and the information network of the smart factory (A4). Further, the model considers with the compensation effect (A5) and the continual production failure (A6) two key characteristics of a smart factory: the flexible combination of production components and the unit flow dependencies within the production network. By determining the resulting unprocessed units and by quantifying the corresponding financial damage based on VaR (A7), the model derives a *risk value vector* with risk values for each IT component. This information enables the management to identify the information network's components most critical to the production network and to ground corresponding investment decisions regarding IT security measures on a profound basis.

IV.2.4 Exemplary Application

In the following chapter, we demonstrate the applicability of our risk assessment model in an exemplary smart factory producing customized sports shoes. Afterwards, we conduct sensitivity analyses in regard to the capacity utilization and the impact of varying loss potential estimations in order to evaluate the basic effects of two major influencing factors. Finally, we analyze the risk reduction effects of different IT security measures by comparing the model's results based on the *with-and-without-principle*.

IV.2.4.1 Exemplary Smart Factory Setting

The smart factory in our application example is an automated production facility for the custom production of sports shoes.[2] The factory produces sports shoes, which are customized by customers online in regard to shoe type as well as fabrics and colors of each shoe part. In order to produce the shoes in the shortest time possible, the company is deploying smart

2 The smart factory example is geared to the research project "SPEEDFACTORY" funded by the German Federal Ministry of Economics and Energy (2015).

manufacturing technologies in the factory. This enables the highly flexible custom production of sport shoes in a batch size of one at costs comparable to mass production. The exemplary setting of the smart factory is illustrated in Figure 5. The customer (p_7) customizes a sports shoe on the online platform of a sports goods manufacturer. Once completed, the order is transmitted automatically to the smart factory through a data interface (c_{11}). In correspondence to the specifications of the customers, the necessary semi-finished parts are ordered automatically from the supplier (p_1). For this purpose, the supplier is connected with the smart factory through another data interface (c_5). Once the raw materials are received, smart manufacturing machines first stitch the parts of the shoes together (p_2, p_3 and p_4) and then conglutinate the stitched parts (p_5 and p_6). All machines, i.e. sewing machines and conglutination machines, are equipped with embedded systems (c_6, c_7, c_8, c_9 and c_{10}) connecting the machines with the information network and enabling their communication.

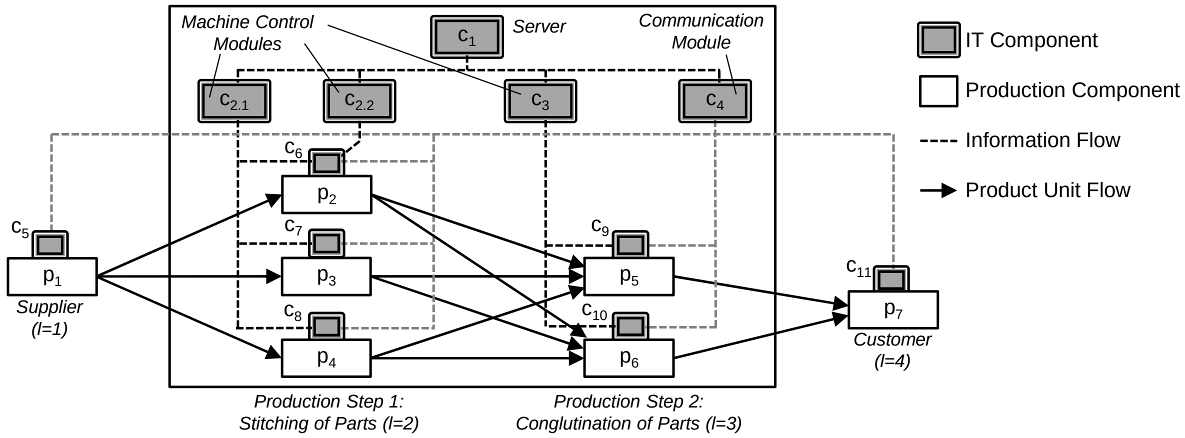

Figure 5. Exemplary Smart Factory

The information network contains a communication module (c_4) facilitating the information synchronization between the smart manufacturing machines and providing all required parameters for the optimization. By synchronizing status information like utilization, idle capacity and orders in the queue, the smart manufacturing machines optimize the product flow through the production process. Further, there are machine control modules ($c_{2.1}$, $c_{2.2}$ and c_3) for the manufacturing machines controlling and monitoring the production activities of the assigned machines. Thereby, sewing machine p_2 has a backup module ($c_{2.2}$) securing the main module ($c_{2.1}$). Accordingly, the backup module is an existing redundancy. All software modules are hosted on a company-own server (c_1) located on the premise of the smart factory. The assignment of the IT components to the respective IT services can be seen in Table 1.

IT Service s	1	2	3	4	5	6	7	8	9	10	11
Main IT component	c_1	$c_{2.1}$	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}
Backup IT component		$c_{2.2}$									

IT Comp. c_s	c_1	$c_{2.1}$	$c_{2.2}$	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}
Restriction Degree $\bar{r}_{c_s}$	100%	75%	75%	75%	75%	50%	50%	50%	50%	50%	50%	50%

Prod.Comp. p_i	p_1	p_2	p_3	p_4	p_5	p_6	p_7
Capacity q_i (units)	120	40	40	40	60	60	120
Utilization $\bar{\bar{q}}_i$ (units)	120	40	40	40	60	60	120

Process step l	1	2	3	4
Expected Loss μ_l ($)	5	10	10	15
Standard Dev. σ_l ($)	1.5	3	3	4.5

Table 1. Parameters of the Exemplary Application

The non-availability of IT component causes different restriction degrees at the dependent production components (see Table 1). Thereby, the non-availability of the server (c_1) causes a complete standstill of the dependent production components because all software services are interrupted. The non-availability of a software module causes a restriction of 75% because either the information synchronization is disrupted or machine control functions are no longer provided. However, emergency routines of the affected machines enable a partial continuity of the production process. The non-availability of an embedded system causes a restriction of 50% since the dependent production components' information synchronization is hampered. Lastly, the non-availability of a data interface causes a restriction of 50% because either the automated ordering process with the supplier is hampered and manual backup ordering processes performed instead do not achieve the same efficiency or the customer's ability to customize products is restricted. Once the production of an order is completed, the sports shoes are shipped to the customer. The smart factory has a capacity of 120 units and a utilization of 100%. The capacities, utilizations, and idle capacities of the production components are also shown in Table 1.

IV.2.4.2 Analysis of Basic Scenario

By applying our risk assessment model to the exemplary smart factory, we are able to identify the IT components most critical to the production network. First, the matrix calculations obtain all functional dependencies of production components on IT components. The derived *dependency matrix* $D^*_{C,P}$ is multiplied with the restriction degrees $\bar{r}_{c_s}$ shown in Table 1. Based thereupon, we derive the *unprocessed units* $v^*_{c_s,l}$ according to the risk quantification approach. In combination with the expected losses and standard deviations shown in Table 1, we calculate the threat potential based on the VaR for each IT component c_s with a confidence level $(1-\alpha)$ of 95%. The resulting *risk value matrix* $X_{C,L}$ shown in Table 2 presents the total threat potential ($\sum_{l=1}^{4} x_{c_s,l}$) posed by the non-availability of each IT component c_s.

IT Comp. c_s	c_1	$c_{2.1}$	$c_{2.2}$	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	Σ
VaR $x_{(c_s,1)}$ ($)	896	0	0	0	672	448	0	0	0	0	0	0	
VaR $x_{(c_s,2)}$ ($)	1,792	896	0	0	1,344	896	299	299	299	0	0	0	
VaR $x_{(c_s,3)}$ ($)	1,792	896	0	1,344	1,344	896	299	299	299	448	448	0	
VaR $x_{(c_s,4)}$ ($)	2,688	1,344	0	2,016	2,016	1,344	448	448	448	672	672	1,344	
VaR $\sum_{l=1}^{4} x_{(c_s,l)}$ ($)	7,169	3,136	0	3,360	5,376	3,584	1,045	1,045	1,045	1,120	1,120	1,344	29,346
Rank	1	5	12	4	2	3	9	9	9	7	7	6	

Table 2. Analysis Results and Risk Value Matrix

The derived information about the threat potential of the individual IT components and their rank in relation to other IT components support identifying the most critical IT components. Additionally, the results of our risk assessment model reveal the following insights:

- The server of the smart factory (c_1) causes the *maximum possible threat potential* with a VaR of $7,169, since its non-availability results in the complete standstill of the production network.
- The supplier data interface (c_5) ranks third and before the machine control modules (fourth and fifth) although the supplier data interface has a lower restriction degree than the machine control modules. This can be explained by the *impact location* of the failing IT components. The supplier data interface impacts already the first process step in contrary to the machine control modules, which impact later process steps. Therefore, an interesting insight is that the impact location in the production network is an important factor since the restriction of the supplier data interface causes production failures in all process steps of our exemplary smart factory. Further, the machine control module for the sewing machines has a partial backup, which reduces its threat potential.
- The embedded systems of the conglutination machines (c_9 and c_{10}) rank seventh and before the embedded systems of the sewing machines (c_6, c_7 and c_8) although they affect a later process step. This is due to the utilizations of the conglutination machines, which are with 60 units higher than the 40 units of the sewing machines and hence, lead to higher threat potentials.

Of course, the complexity of the exemplary smart factory is limited and hence, the server's first rank rather obvious. However, smart factory networks in practice are far more complex and unmanageable since they consist of considerably more production components and IT components inducing a highly complex dependency structure. Further, we assumed a symmetric setting in regard to the production components' capacities within a process step, meaning that all production components of a process step possess identical capacities. This might also differ in practice since machines are constantly further developed and production facilities are usually grown over time resulting in a heterogeneous machinery pool. Nevertheless, the results and insights of our exemplary application clearly indicate the need for a structured approach for assessing the availability risks of individual IT components. With the information provided by our risk assessment model, the management of the focal company is able to discuss potential IT security measures and to ground the corresponding investment decision on a profound basis.

IV.2.4.3 Sensitivity Analysis

In order to evaluate the results and the basic effects of the two major influencing factors, i.e. the utilization and the loss potentials, we conduct sensitivity analyses in the following subsections. Thereby, we use the exemplary smart factory setting from our demonstration example above.

IV.2.4.3.1. Utilization Variation

For the utilization variation, we increase the utilization of all production components gradually from 1% to 100% and evaluate the effects on the VaR values of the IT components and the VaR sum. Thereby, the VaR sum $\sum_{s=1}^{k}\left(\sum_{l=1}^{L} x_{c_s,l}\right)$ of the *risk value matrix* $X_{C,L}$ makes no statement about the total threat potential of the information network since our model analyzes scenarios with individual IT component failures. However, the VaR sum can be used as an indicator for the vulnerability of the production network to IT component non-availabilities. All other parameters like restriction degrees and loss potentials are kept constant. The effects of an increasing utilization on the results of our model can be seen in Figure 6.

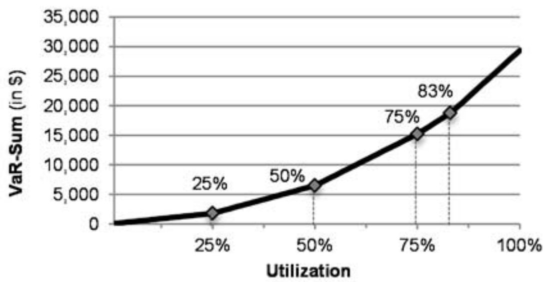

Figure 6. Utilization Variation - VaR-Sum

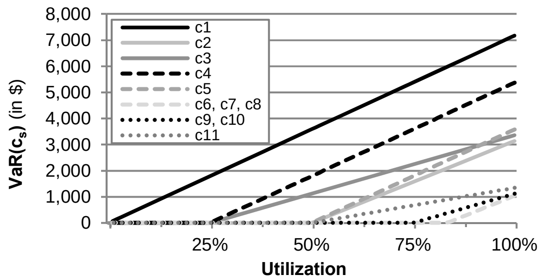

Figure 7. Utilization Variation - VaR(c_s)

Not surprisingly, the VaR sum increases with an increasing utilization since more units are in the production process. However, the slope of the curve is not linear and shows four kink points at which the slope increases. The kink points are caused by IT components whose non-availabilities have no effect up to a certain utilization threshold. This effect can be seen in more detail in Figure 7, which shows the curve of each IT component in dependency to the utilization. One reason for the kink points is a restriction degree <100%. Depending on their utilization, the restricted production components are still able to process some or even all product units with their reduced capacity. For example, the software modules (c_2, c_3 and c_4) have a restriction degree of 75%. Accordingly, the non-availability of the communication module (c_4) and the machine control module (c_3) has no effect until the threshold of 25%. Because of its partial backup, the machine control module ($c_{2.1}$) of the sewing machines causes no losses even until the threshold of 50%. The embedded systems have an even higher threshold. First, this is caused by their restriction degree of 50%, but also by the compensation effect for utilizations <100%. Accordingly, the threshold of the embedded system is 75% (c_9 and c_{10}) respectively 83% (c_6, c_7 and c_8). Thereby, the embedded systems of the sewing machines have a higher threshold because three machines are available for compensation within the stitching step in contrary to only two machines in the conglutination step.

These insights demonstrate the importance of the utilization as an influencing factor. We were able to show that the threat potential increases with an increasing utilization since risk reduction effects like the compensation ability decrease gradually. Considering the high utilization of smart factories through automation and optimization technologies as key benefits, the threat potentials posed by IT availability risks will be rather high in smart factories (Radziwon et al. 2014; Schuh et al. 2014).

IV.2.4.3.2. Loss Potential Variation

In addition to the utilization, we analyze the impact of loss potential estimations on the results of our model in the basic scenario of the exemplary smart factory. Thereby, we multiply the loss values μ_l and σ_l with a variable β in order to demonstrate the effects of an underestimation ($\beta < 1$) respectively an overestimation ($\beta > 1$). All other input parameters are kept constant. The effects of deviating loss potential estimations for different, rather high utilizations are shown in Figure 8 with $0.5 \leq \beta \leq 1.5$. The underestimation of loss potentials results in lower and the overestimation in higher threat potentials. Accordingly, the curves show an ascending slope. Thereby, the slope of a curve increases for higher utilizations. This shows that the underestimation or overestimation of loss values has a greater effect on the model's results in application scenarios with high utilizations. Therefore, considering the probably high utilization of smart factories, the accuracy of loss potential estimation is of crucial importance for the risk quantification in order to derive accurate results.

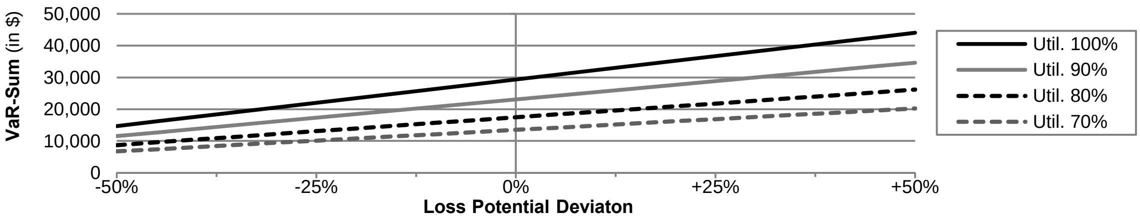

Figure 8. Impact of Deviating Loss Potential Estimation

Of course, there are other influencing factors besides the utilization and the loss potentials like the network structure of the smart factory and the restriction degrees of IT components. However, varying other factors does not change the fundamental tendencies and effects described in this section.

IV.2.4.4 IT Security Measure Analysis

In the following, we discuss and analyze different IT security measures for our exemplary smart factory by comparing the results of the risk assessment model based on the *with-and-without-principle*. For this purpose, we compare the VaR sum of our basic scenario ($29,346) based on the VaR sums of scenarios with additional IT security measures and apply the VaR sum as an indicator for the vulnerability of the production network to IT component non-availabilities. This determines the impact of an IT security measure on the vulnerability of the production network and hence, enables the risk-oriented evaluation of IT security measures. Accordingly, the results can be used as a basis for investment decisions.

Since our model is based on the smart factory’s network structure, it is highly suitable to analyze structure-based IT security measures like redundancies in the information network. However, we want to briefly mention other, process-based measures before. As we demonstrated as part of the sensitivity analyses, reduced loss potentials in specific process steps can reduce the overall threat potential. Thus, improving processes in order to reduce loss potentials is an effective way to reduce the overall threat potential. Since loss potentials are input parameters to our model, it is not possible to explain the cause-effect-chain of process-based measures and the reduced loss potentials as their effect. However, our model is able to show the impact of reduced loss potentials on the production network’s vulnerability to IT component non-availabilities if the reduced loss potentials are used as adjusted input parameters.

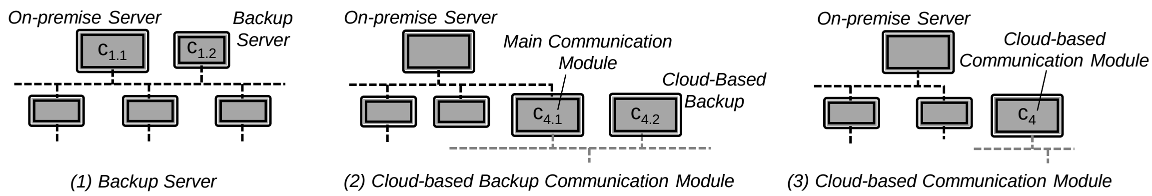

Figure 9. Exemplary IT Security Measures

Structure-based measures are highly effective IT security measures against IT availability risks including redundancies within the information network. Thereby, measures like backup IT components or cloud-based applications influence the dependency relations by preventing single-point failures of IT components. For example, the basic scenario of our exemplary application has a redundancy securing the machine control service for sewing machine p_2 due to the partial backup machine control module ($c_{2.2}$). Without the redundancy, the VaR increases to \$30,915. Accordingly, the partial backup component reduces the VaR sum by 5.1%. In the following, we add further IT security measures illustrated in Figure 9 to the information network in addition to the already existing partial backup component ($c_{2.2}$).

Installing a backup server (1) is an appropriate IT security measure since our model revealed in the exemplary application that the server (c_1) is the most critical IT component. As a result of this security measure, the VaR sum decreases to \$22,178, which equals a reduction of 24.4% in comparison to the basic scenario. The hereby occurring trade-off between the high investment volume and the risk reduction effect shows that our algorithm is of great value since it enables risk-oriented evaluation of investment alternatives and allows to ground investment decisions on a profound basis. The second measure is a cloud-based backup for the communication module (c_4) (2). Cloud-based applications are especially effective since they not just only remove the direct dependency of production components on the locally hosted, secured application. They also remove the indirect dependency of production components on the server if the production components do not depend on other applications hosted on that server. This is for example the case for the supplier (p_1) and the customer (p_7), whose data interfaces only depend on the server because of the communication module (c_4). Accordingly, the cloud-based backup communication module removes also the customer's and supplier's dependency on the server and reduces the VaR sum by 21.4% to \$23,704. The last measure analyzed is the complete switch of the communication module from a module hosted on a company-own server to a cloud-based module (3). As a result, the communication module depends no longer on the functioning of the server and hence, functional dependencies within the information network are removed. However, the production components still depend on the cloud-based communication module for the corresponding communication IT service since there is no redundant backup for that service. Accordingly, the VaR “only” decreases by 3.1 % to $28,450.

IV.2.5 Conclusion, Limitations, and Further Research

The increasing adoption of IoT-based technologies promises great potential and leads to a paradigm shift in manufacturing. The emerging smart factory networks are automated and flexible production facilities and able to economically produce individualized products in low batch sizes. However, the modular production infrastructure and the required IT systems result in a highly complex, interconnected, and interdependent network, which is increasingly vulnerable to IT availability risks. Considering this threat scenario, we develop a risk assessment model for the quantification and evaluation of IT availability risks in smart factory networks. Thereby, we first abstract the smart factory’s general setting with its basic structures and relations. Then, we model and formalize the smart factory based on graph theory and matrix notation and quantify the IT availability risk by applying the VaR. This structured approach identifies the most critical IT components and consequently offers a profound economical basis for corresponding investment decisions on IT security measures. Hence, the insights gained by our model provide practitioners with managerial implications regarding, for example, redundant IT infrastructure components like backup servers or cloud-based modules. We demonstrate the model’s applicability in an exemplary setting and evaluate the model by means of sensitivity analyses.

Our results show that the criticality of an IT component is determined by numerous factors: the dependency relationships to production components, the degree of productivity restriction caused by the IT component failure, the impact location of the IT component failure in the production process, the loss potentials in the respective process steps, the utilization of dependent production components, and the extend of the possible compensation effect. The variety of these influencing factors and their interplay clearly indicate the need for a risk assessment model enabling a structured analysis.

Nevertheless, there are some limitations to the results of our paper, which can be seen as potential areas for further research. First, we analyze the event of an IT component’s non-availability and its implications in a fixed time period. We are well aware of the fact that this approach ignores the possibility of recurring non-availabilities and varying failure durations. Further, we do not consider the possibility of negative, upward feedback effects within the information network. For example, a failing machine, which is not able to upload information due to its failing embedded system, in turn affects the overall system. Additionally, we apply our risk assessment model in an exemplary application to demonstrate its applicability and its basic functionality. For further evaluations, it would be beneficial to apply our model in a real world setting with real world data. Another area for further research is the trade-off between the risk reduction effects of idle capacity and the accompanying costs, which should be addressed by an optimization model building up on our risk assessment model. Additionally, investment decisions on IT security measures include other aspects like the overall investment budget and the correlation between the efficiency of a measure and the required investment volume, which are not addressed in this paper.

Despite these limitations, we strongly believe that the developed risk assessment model presents a first substantial step toward the profound management of IT availability risks in smart factory networks. This is of special importance since the continuous progression of IoT and CPS technologies requires the ongoing development of appropriate risk assessment methods.

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V Results and Future Research

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

V.1 Results

The main objective of this doctoral thesis is to contribute to the field of Finance and Information Management by focusing on the financial ex-ante valuation of IT projects. After discussing the significance and central role of modern IT for the economic success of companies, central challenges regarding the financial valuation of IT projects in an ex-ante perspective were presented. More precisely, these challenges concern (i) the valuation of intangible benefits, (ii) the consideration of interdependencies between IT projects, and (iii) the valuation of IT projects in digitized value networks. Regarding the first challenge, the research papers focus on analyzing and discussing the potentials and the applicability of financial approaches for the ex-ante valuation of intangible benefits (Chapter II). Regarding the second challenge, the research paper focuses on analyzing the influence of stochastic interdependencies on the risk position of IT projects and the associated investment decisions (Chapter III). Regarding the third challenge, the research papers focus on examining the valuation of IT projects in innovative IT-enabled business models in the service sector respectively in the manufacturing industry (Chapter IV). In the following, the key findings of the research papers that are included in this doctoral thesis are presented.

V.1.1 Results of Chapter II: The Value of Intangible Benefits in IT Projects

Chapter II focuses on the ex-ante valuation of IT projects and aims to develop insights for practice and research regarding the consideration of intangible benefits in financial valuation approaches. For this, Chapter II aims to provide a comprehensive state-of-the-art regarding the valuation of intangible benefits by analyzing the existing literature, and, moreover develops and discusses practice-oriented guidelines for companies and decision makers.

In Section II.1, research paper 1 provides a comprehensive literature review regarding the financial ex-ante valuation of intangible benefits in IT projects (Objective II.1). The results of the review show that many studies discuss the importance of intangible benefits or the challenges regarding their valuation. However, only very few studies focus on their financial ex-ante valuation and make efforts to include intangible benefits in financial approaches. In this context, the review analyzes and discusses commonalities and differences of the identified studies. Through this, the literature review identifies key factors and methodological starting points for a successful consideration of intangible benefits in financial approaches (Objective II.2). Regarding the identification of intangible benefits and the analysis of their causal relations to the financial bottom line, the majority of the examined studies is based on structured discussions (e.g. supported by checklists or benefit classification schemes) and the analysis of available company data. More elaborated methods such as activity-based approaches or system dynamics are only rarely used. Furthermore, the examined studies emphasize the importance of including different stakeholders in the analyses to consider the multifaceted value implications of IT projects. Based on the determined causal chains, the subsequent quantification is achieved through estimations by management, experts, or further stakeholders and supported by objective company data. The estimations are included in rather traditional financial methods of cost-benefit analysis that demonstrate to be appropriate given a mindful application and given a comprehensive consideration of the uncertainty associated with estimating the benefits. Moreover, the review finds that the studies mainly focus on the financial valuation of intangible benefits in the areas of *internal improvements* and *customers*. Finally, although intangible benefits are difficult to evaluate, the review underpins that an indirect financial ex-ante valuation of intangible benefits can be achieved through a structured and comprehensive analysis of the underlying causal chains.

In Section II.2, research paper 2 develops and discusses a practice-oriented process for the financial ex-ante valuation of intangible benefits for companies and decision makers (Objective II.3). The research paper shows how the financial implications of intangible benefits can be quantified through a detailed analysis of the underlying causal relationships. For this, the research suggests a structured evaluation process that comprises the process steps *identification*, *causal analysis*, and *quantification*. Based on that, the paper discusses corresponding core challenges, practical methodological approaches and key success factors. Through this, the paper supports a comprehensive and economically well-founded ex-ante evaluation of the highly relevant intangible value implications. In today's competitive environment, this is essential for companies of all sectors to ensure a focused allocation of available resources and a value-oriented IT management. To underline the applicability of the suggested approach, the experiences of a global technology group are demonstrated by means of a discussion of concrete IT projects. Furthermore, the paper concludes by providing recommendations regarding a company-specific implementation of the suggested valuation process.

V.1.2 Results of Chapter III: Risk Quantification of IT Projects in Consideration of Stochastic Interdependencies

Chapter III focuses on the quantification of risk by developing insights for practice and research regarding the consideration of stochastic interdependencies in the ex-ante valuation of IT projects and their impact on IT investment decisions. In order to determine the optimal allocation of investment budgets to investment alternatives, research paper 3 elaborates a comprehensive valuation approach that considers risk and return and especially stochastic interdependencies (Objective III.1). Accordingly, the paper proposes a valuation approach for IT projects that is in line with an ITPM on a mature, synchronized level and thus supports the aims of value-based management. The research paper analyzes the economic advantages of a well-founded synchronized valuation approach that takes an integrated view on risk and return in a portfolio context, and thus considers interdependencies between IT projects when valuating IT projects in an ex-ante perspective. Based on that, the research paper analyzes the impact of intertemporal as well as intratemporal stochastic interdependencies on IT investment decisions (Objective III.2). At this, especially a comprehensive simulation study is applied. The results of the simulation study underline the relevance of a synchronized ITPM approach, especially when the existing IT portfolio and the available IT investment alternatives of a company are rather heterogeneous regarding their risks and returns and particularly regarding their interdependency structures. Moreover, the research paper provides a stepwise approach regarding the implementation of a decision support system that is based on a synchronized ITPM, and thus provides guidelines for improving the maturity of a company's IT management (Objective III.3). Consequently, the research paper underlines the economic potentials of a well-founded financial ex-ante valuation of IT projects in consideration of stochastic interdependencies.

V.1.3 Results of Chapter IV: Valuation of IT Projects in Digitized Value Networks

Chapter IV focuses on the financial ex-ante valuation of modern IT projects in the context of IT-enabled digitized value networks. Consequently, Chapter IV examines risk and return aspects of IT projects that support the continuous and extensive transformation of value chains and business models enabled by the increasing advances in information and communication technology. In this context, Chapter IV on the one hand deals with IT projects within innovative business models in the *service sector* and on the other hand with IT projects fostering the transformation of value chains in the *manufacturing industry*.

In Section IV.1, research paper 4 examines the potential of IT-enabled ECM for BPaaS providers in cost-driven e-business environments. The research paper presents an optimization approach based on queuing theory that focuses on analyzing the capacity optimization problem of a BPSP within a three-stage supply chain (Objective IV.1). The model is analyzed based on a discrete-event simulation with input data from a possible application scenario. Through this, the research paper allows to identify and analyze potential competitive advantages of IT-enabled ECM in e-business value chains (Objective IV.2). In this context, the research paper identifies a remarkable cost advantage as the in-house capacity can be reduced, and thus allows reducing overall operating costs. Building on this cost advantage, the paper examines the possibilities of gaining differentiation advantages (i.e., improvements in service levels and service quality without raising prices). The paper shows that reduced processing times can be guaranteed and the execution quality can be increased at equal costs, leading to a competitive advantage. Thus, the results suggest that high upfront investments in information and integration capabilities that enable the usage of ECM might pay off in the mid to long run. The quantitative results of the model quantify the potential value of such investments and therefore determine an indicative value for reasonable investments. Furthermore, the research paper provides a sound basis for analyzing the economic advantages of various differentiation strategies such as offering improved service levels and/or higher service quality without raising prices.

In Section IV.2, research paper 5 develops a risk assessment approach supporting companies in identifying and evaluating critical areas of the IT in smart factory networks (Objective IV.3). The paper models the smart factory's basic structures based on graph theory and matrix notation, and quantifies the IT availability risk by applying the concept of Value at Risk. The results show that the criticality of an IT component is determined by numerous factors, especially: the dependency between IT and production components, the impact location of the IT component failure, the degree of productivity restriction caused by the IT component failure, the loss potentials in the respective process steps, or the utilization of dependent production components. The variety of these influencing factors clearly indicates the need for a risk assessment model enabling a structured analysis. Moreover, the valuation approach also offers a profound economical basis for the analyses of corresponding investment decisions on IT security measures and their risk reduction effect (Objective IV.4). The applicability of the model is demonstrated in an exemplary setting. Consequently, the developed risk assessment model presents a first substantial step toward the profound management of IT availability risks in smart factory networks and provides a comprehensive decision basis for the ex-ante valuation of potential investments.

V.1.4 Conclusion

Summarizing the results of the research papers presented in Chapters II, III and IV, this doctoral thesis contributes to the existing literature in the field of Finance and Information Management by addressing different challenges regarding the financial ex-ante valuation of IT projects. Most notably, it complements previous research regarding the financial ex-ante valuation of intangible benefits, regarding the adequate quantification of risks resulting from interdependencies between IT projects, and regarding the valuation of IT projects in digitized value networks. However, despite the presented results, there remain challenges, which offer starting points for future research.

V.2 Future Research

In the following, potential starting points for future research are highlighted for each research paper included in this doctoral thesis.

V.2.1 Future Research of Chapter II: The Value of Intangible Benefits in IT Projects

In Section II.1, research paper 1 provides a comprehensive literature review aiming to identify and analyze previous studies that quantify intangible benefits through financial ex-ante valuation approaches. With regard to the widespread use of financial justification techniques in the budgeting processes of companies and with regard to the ever-increasing competitive pressure, this is a highly relevant topic. However, the limited number of studies identified in the literature review shows that this research area needs further attention. The literature review identified the following starting points for further research:

- The conducted literature review analyzed differences and commonalities of the examined studies, and, based on that, derived general recommendations for the ex-ante valuation of intangible benefits. However, as intangible benefits are manifold and many intangible benefits have not been thoroughly analyzed yet, future research should focus on examining *specific* intangible benefits in order to enhance our understanding of the underlying cause-and-effect relations between specific intangible benefits and the financial bottom line. For this, also ex-post examinations of IT projects will provide valuable insights. Moreover, existing multidimensional valuation frameworks that include a variety of non-financial or qualitative assessments for intangible benefits may be an excellent starting point to analyze specific cause-and-effect relations and make another step forward towards a financial valuation.

- The literature review shows that the analysis and consideration of related company data supports the identification and determination of detailed and well-founded causal chains and may enhance the validity of the financial valuation. With regard to the ever-increasing volume and the variety of today's data as well as the capabilities of modern data analytic systems, this is a promising starting point for future research. In this context, companies are no longer restricted to internal company or customer data, but may also be able to include unstructured external data. Consequently, future research should focus on improving the financial valuation of intangible benefits through the focused use of data analytics. Through this, the indirect financial impact of even complex changes of a company's value chain that are induced by an IT project can potentially be measured more easily and especially ever faster. Moreover, focused Big Data initiatives may enable to encounter new patterns that allow relating rarely examined intangible benefits to the financial bottom line.

In Section II.2, research paper 2 provides a practice-oriented valuation process that aims to support companies and decision makers regarding a comprehensive valuation of intangible benefits in IT projects. Nevertheless, the paper leaves the following central starting point for further research:

- The research paper provides a structured evaluation process and discusses corresponding core challenges, practical methodological approaches and key success factors. In doing so, the research provides general guidelines for the financial ex-ante valuation of intangible benefits. However, as intangible benefits are manifold and multifaceted, the detailed procedure and the suitable selection of concrete methods may vary between different (types of) intangible benefits. Consequently, future research should focus on specifying and adjusting the presented guidelines for the valuation of *specific* (types of) intangible benefits.

Summarizing, the presented research opportunities show that there are various starting points to further contribute to an improved understanding regarding the financial ex-ante valuation of intangible benefits, even though some research does already exist.

V.2.2 Future Research of Chapter III: Risk Quantification of IT Projects in Consideration of Stochastic Interdependencies

Research paper 3 analyzes the economic potentials of a mature, synchronized ITPM and shows the strong impact of intertemporal and intratemporal interdependency structures on IT investment decisions. With regard to the high complexity of present IT portfolios, the presented examinations underline the importance of a synchronized ITPM for the sustainable value creation of companies. Although the results allow for deducing several managerial implications, the presented model nevertheless shows some limitations that offer opportunities for future research:

- The model allocates an IT investment budget to two IT investment alternatives while considering the existing IT portfolio at the same time. However, companies usually face a large set of potential IT projects. Extending the presented synchronized ITPM approach regarding the consideration of an arbitrary number of IT investment alternatives in a portfolio context would be a promising next step. Furthermore, the approach could be extended to a dynamic optimization model to foster the applicability in real world settings.
- In the current model only portfolio effects regarding the risk of IT projects were taken into account. Portfolio effects regarding returns that, for instance, result from economies of scale or scope were not taken into account.
- From an empirical point of view, two main starting points are given: First, with detailed case studies relying on field data, the applicability of the model for different application scenarios can be validated, e.g. within different industries or for different types of IT projects. Second, another link for empirical research concerns the profound estimation of the model’s input parameters which is a particular challenge regarding the operationalization of the approach.

Summarizing, the presented research opportunities show that there are various starting points to further contribute to an improved understanding regarding the risk quantification in consideration of stochastic interdependencies between IT projects. A multitude of related and highly relevant issues needs to be addressed in future research.

V.2.3 Future Research of Chapter IV: Valuation of IT Projects in Digitized Value Networks

In Section IV.1, research paper 4 contributes to understanding the potential competitive advantages that can be realized through the usage of IT-enabled ECM within a BPSP`s value chain. In this regard, the research paper provides valuable insights for both researchers and managers engaged in the field of service management. However, the presented approach shows some limitations that present starting points for future research:

- The presented model relies on the simplifying assumption of an exogenous market. Consequently, the actual demand of the BPSP or any other market user does not affect the amount of the available excess capacity. Moreover, interdependencies between peak times for the BPSP and the further market players are not considered. From an analytical point of view, it would be a promising next step to model an endogenous market. Additionally, the lack of knowledge regarding the interdependencies between a single player's strategy and an endogenous ECM could be addressed by appropriate field studies.
- Moreover, the model focuses on cost minimization. This is reasonable, as the study focuses on the analyses of cost-driven services. Nevertheless, the analysis of possible differentiation advantages is limited to a discussion of differentiation strategies that build on cost advantages and that can be realized without raising prices. A further analysis of various competitive differentiation strategies and their economic potential could be facilitated by extending the model with price-demand functions (and thus by considering revenue aspects).

Research paper 5 presents a risk assessment model for the profound analysis and management of IT availability risks in smart factory networks. This is of special importance since the continuous interpenetration of the productions area by information and communication technology requires the active management of associated risks. Nevertheless, there are some limitations to the results of our paper, which can be seen as potential areas for further research:

- The risk assessment approach analyzes the non-availability of an IT component and its implications in a fixed time period. Consequently, the possibility of recurring non-availabilities and varying failure durations is ignored. The further development of a risk assessment approach allowing for the consideration of time-dependent availability failures would enable more comprehensive analyses of risks and IT security measures.

- In the presented research paper, the risk assessment model is analyzed within an exemplary application scenario to demonstrate its applicability and its basic functionality. For further evaluations of the approach, it would be beneficial to examine a real world setting with real world data.

Summarizing, the presented research opportunities show that there are various starting points to further contribute to an improved understanding regarding the valuation of IT projects in highly networked, digitized business environments. The examination of a multitude of related and highly relevant issues is still missing.

Taken together, the research papers presented in this doctoral thesis contribute to addressing some central challenges regarding the financial ex-ante valuation of IT projects. Though this doctoral thesis cannot answer all questions and challenges regarding the financial ex-ante valuation of IT projects, it complements previous work in this area. As IT plays a central role and will continue to be of tremendous significance for the economic success of companies, the comprehensive financial ex-ante valuation of IT projects is expected to remain a dynamic topic in research and practice. This is further leveraged by the on-going and ever-faster digitization of corporate businesses and value chains in all business sectors. In this connection, the hope is that this doctoral thesis can provide researchers and companies with helpful insights in this area to face the challenges of an ever-changing business environment.