A Simulation-Based Evaluation Approach for Digitalization Scenarios in Smart Supply Chain Risk Management

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Abstract

To increase the security of modern, volatile supply chains a proactive risk management based on real-time risk related information transparency is required. At this time, none or only limited empirical/objective information about digitalization benefits for supply chain risk management is available. A method is needed, which draws conclusion on the estimation of costs and benefits of digitalization initiatives. The paper presents a flexible simulation-based approach for evaluating digitalization scenarios prior to realization. The evaluation approach is integrated into a framework and its applicability will be shown in a case study of a German steel producer, evaluating digitalization effects on the Mean Lead time-at-risk.

Keywords: Supply chain risk management, Smart supply chain risk management, Digitalization, Simulation, Industry 4.0.

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1 Introduction

Several industrial trends (e.g. outsourcing, just-in-time deliveries, shorter product life cycles) led to an increase in supply chain (SC) vulnerability over the last years [51]. This can be seen in many example cases, like Ericsson [12, 51], Toyota [55], Land Rover [67] and other Japanese automotive companies and computer manufacturer [13]. A supply chain disruption and a resulting glitch can have serious cascading effects on all supply chain members. Not only a negative performance impact but also a negative economic impact. Three different empirical studies of Hendricks and Singhal show the negative effect of supply chain glitches (supply and demand mismatch) on operating performance, on shareholder wealth and on long-term stock price [29–31]. They also found out that it does not matter who caused the glitch, what the reason was or what industry a firm belongs to. The glitches are associated with negative operating performance across the chain [31].

Supply chain risk management (SCRM) became a critical supply chain management (SCM) discipline in the past due to the increasing number of events causing supply chain disruptions and to lower the impact of such supply chain glitches [35]. [21] have empirically shown the benefit of information sharing of supply chain members to understand the different risks which could have an impact on the supply chain [21]. Though a SC wide proactive risk management based on risk related information transparency is required to increase the security of supply, decrease safety stocks and to lower costs for manufacturer and their customers [11, 14]. While supply chain risk (SCR) information has been identified as crucial, the importance of a company's information processing capability to its SCRM effort has received little attention in the literature [22]. [22] have shown in an empirical study the positive effect on a firms operational performance by an improved capability in processing supply chain risk information, which comprises supply chain risk information sharing and analysis [22]. The integration of modern technologies into supply chains leads to a smart supply chain management, which combines multiple independent data analytics models, historical data repositories, and real-time data streams [75]. Through this embedded intelligence, supply chain management moves from supporting decisions to delegating them and, ultimately, to predicting which decisions need to be made [10]. Using this available data from digitalized supply chain processes in SCRM leads to a smart SCRM (SSCRM). A system which processes SCR information helps firms to respond in a timely manner – however, there is a need to test whether the benefits outweigh the implementation costs [23]. The problem at this time is, none or only limited empirical/objective information about digitalization benefits is available – a method is needed which allows estimation of costs and benefits of digitalization initiatives [4]. This paper presents a simulation-based approach for assessing process oriented digitalization scenarios (DS) as part of creating a SSCRM. The method should either be used with expert opinions or objective information (when available) to estimate potential benefits. Additionally a methodological framework will be presented which helps practitioners to develop such DS based on a previous SCR evaluation.

In Section 2, a research overview will be described. In Section 3 a framework and its new assessment method will be developed, and applied at a German steel producer in Section 4. The results will be shown in Section 5 and the paper ends with a final discussion and managerial implications in Section 6.

2 Research Overview

2.1 Supply Chain Risk Management

SCRM can be seen as an emerging critical and cross-functional discipline between SCM, corporate strategic management and Enterprise Risk Management (ERM) [35, 81]. In the literature the definition of “supply chain risk” and SCRM is not unified [18, 64]. According to [36], definitions of “supply chain risk” can be found at [8, 19, 39, 72, 80]. Most of the proposed definitions do not span across the entire chain [36]. Due to that, the authors of this paper define supply chain risk accordingly to the work of [36] as “the likelihood and impact of unexpected macro and/or micro level events or conditions that adversely influence any part of a supply chain leading to operational, tactical, or strategic level failures or irregularities”. Additionally the authors differ between three supply chain risk elements in accordance to [37]: risk sources, risk events and risk effects. Also according to [36], definitions of SCRM can be found at [26, 38, 39, 51, 68, 70]. In their literature review, 36 [36] stated that the proposed definitions focus on specific elements of SCRM and do not span the SCRM processes completely or differ in their SCRM methods and types of events. Given this, the authors also follow [36] in their definition of SCRM as “an inter-organisational collaborative endeavour utilising quantitative and qualitative risk management methodologies to identify, evaluate, mitigate and monitor unexpected macro and micro level events or conditions, which might adversely impact any part of a supply chain”. When a company knows its supply chain risks, principal SCRM strategies are available: avoid (eliminate), reduce (removing the risk source, changing of likelihood and/or consequences), transfer (by contract, insurance, physical transfer or sharing) or accept (retain) the risks [49, 57].

2.2 Digitalization and Industry 4.0

The usage of available real time (risk) information throughout the SC can be seen as one way of influencing a risk probability (avoiding) or risk impact (reduce risk effects). It also makes risk transferring easier with the help of smart contracts. The integration or creation of Cyber-Physical-Systems (CPS) in existing or new supply chain processes leads to a convergence of the physical world and the virtual world (process digitalization) [73]. "CPS integrate computation with physical processes, and provide abstractions, modelling, design, and analysis techniques for the integrated whole" [74] Beside the term *digitalization* there are other definitions in the literature with a similar meaning [33]. Especially the term *Industry 4.0* or *Industrie 4.0* (I4.0) is widely used in German speaking literature and slowly makes its way into Anglo-Saxon literature (Industrie 4.0 as well as Industry 4.0) (e.g. [73] or [58]). [56] have performed a structured literature review and have shown that the biggest impact from I4.0 technologies and concepts is to be expected especially for the procurement, production and distribution activities in the supply chain. They have built up their literature review on articles which mostly can be found in scientific magazines and lower-rated journals as well on studies published by companies or research institutes – especially from the German literature [56]. This is because the whole topic of industrial digitalization or I4.0 is still today an emerging, under-developed and highly diverse research field [24, 56]. To give direction for practitioners and researchers, "work-cluster" for transforming value creating activities into the I4.0 are formalized within the "Dortmund Management-Model for Industry 4.0" by Henke [69]. More information about I4.0 and its components can be found in the literature [3, 6, 69]. For this paper, the term *digitalization* is defined as a necessary condition on the road to I4.0 and will be used synonymously at some points. The main drivers for the digitalization of supply chain processes are typically an increase in flexibility and reaction rate of industrial/logistic systems [69]. Another perspective is to improve the supply chain robustness by using this available data from digitalized supply chain processes and CPS in SCRM, leading to a smart SCRM. Making the supply chain smarter from a risk management perspective can be described as "SCRM digitalization", thus as "the integration of technology (sensors, actors, connectivity, analytics) along supply chain processes to improve supply chain risk identification, analysis, assessment, mitigation and monitoring through processing real time supply chain risk information – which comprises supply chain risk information sharing and analysis" [59].

2.3 Contribution to the Research Field

In the literature, various frameworks for leading digitalization initiatives in companies are available – all with a different focus and some lacking methodological support for evaluating developed scenarios. General I4.0 frameworks with no relation to risk management or SCRM can be found at [9, 33, 47, 61]. The principal structure of all frameworks is: (1) capturing of the current situation, (2) derivation of scenarios for potential processes, (3) evaluation of scenarios, and (4) road mapping. While the frameworks of [47] and [9] have no evaluation phase, the framework of [33] uses a qualitative and subjective scoring for assessing scenarios and the framework of [61] includes earlier work of [62]. The developed Extended Performance Analysis (EPA) of [62] links non-monetary and non-directly measurable digitalization effects with monetary effects, over cause-and-effect chains. Their method will be discussed at a later point in this paper. Due to its focus on monetary effects of DSs it serves as a basis for the developed simulation-based evaluation method. SCRM and digitalization related frameworks can be found at [41, 60]. [41] have developed a four-phase framework for digitalizing processes from a risk management perspective. Their method has a focus on potential risks through the implementation of digitalization technologies. There is also a lack of evaluating the benefits of digitalization. Due to that, [60] have developed a five-phase framework for process oriented digitalization leading to SSCRM. The main weaknesses of their method are a superficial description of suitable methods for the different framework phases, especially for "risk digitalization" and "digitalization scenario evaluation", and they focus only on supply chain risk identification. However, due to its focus on process oriented SCRM improvement through digitalization the framework of [60] serves as a basis and will be enhanced with concrete methods and the simulation-based evaluation method will be integrated into the framework (see next chapter). Right now there is no known publication with a holistic method for SCRM DS development and assessment, which focuses on improving SCRM in general through digitalization. Due to the increasing globalization and complexity of the network structures of companies, predicting various scenarios can make a valuable contribution for future planning [27]. In this context, a scenario is understood as a representation of different futures [7]. Due to distrustful results and the lack of quantitative data, a trend towards a combination of quantitative and qualitative methods can be observed. The increasing dynamics of research objects can no longer afford purely quantitative methods [27]. Thus in this paper a hybrid methodology consisting of qualitative and quantitative aspects will be developed.

3 Method Development

The overall process is based on a framework from [60], supplemented by various research methods and extended for digitalizing SCRM in general (Figure 1). They have combined major components of the planning process which tend to be found in most planning process models [1] and have originally

Phase	Objectives	Methods
1. Process identification/ specification	• Structured description and visualization of the supply chain process • Definition of process condition measures (PCM) (performance indicators for Phase 4 and 6)	• Process inspection • Process model • Expert interviews • Workshops
2. Risk identification	• Identification of risk elements (sources, events and effects) for each process	• Collection methods • Search methods (analytical/creative)
3. Risk analysis	• Cause-effect analysis of identified risks (sources, events and effects) • Determining of direct impact of risks on process condition measures	• Process model and inspection • Expert interviews • Supply Chain Risk Map
4. Risk evaluation	• Simulation model development and validation • Aggregated evaluation of risks	• Monte Carlo Simulation • Discrete Event Simulation
5. Risk digitalization	• Selection of relevant processes based on their risk potential • Development of digitalization scenarios for selected processes	• Workshops • Industry 4.0 Design Principles
6. Digitalization scenario analysis	• Effect identification of digitalization scenarios on processes • Impact quantification of digitalization scenarios on processes • Aggregated evaluation of identified risks with changed simulation parameters (based on the impact of the digitalization scenarios)	• Extended Performance Analysis • Expert interviews • Secondary data about digitalization effects (if available) • Monte Carlo Simulation • Discrete Event Simulation

Figure 1 Framework for SCRM Digitalization.

made them up for a planning process for digitalizing only the supply chain risk identification. The extended framework consists of six phases (Figure 1): Process identification/specification; Risk identification; Risk analysis; Risk evaluation; Risk digitalization and Digitalization scenario analysis.

3.1 Phase 1: Process Identification/Specification

At first target processes (TP) and risks (separated into risk elements like sources, events and effects [37]) have to be identified using data collecting methods like process observation, expert interviews and secondary company data [53]. This is followed by a process visualization. Numerous models for illustrating business processes have been developed in the past but based on a comparative study only the process chain model of [43] was especially developed for illustrating, designing and analysing logistic processes [52]. The basic element of this model is a general process chain element, which is initially described by processes which help making goal oriented transformation to an object [52]. Each process chain elements is influenced by the internal structures, processes, resources and steering modes as well as by the exchange with the environment via a source and a sink [52]. Each element also has a set of key performance indicators (KPI) describing its state: throughput time, technical capacity, work-in-progress, costs and schedule adherence [43, 78]. Because a process chain element is always setup the same, independent from the level of particularization, it can be constructed for various levels of detail. An enterprise can be conceptualized en bloc as one process chain element or it can be broken down into various highly detailed levels [52]. The right level of detail must be estimated by the user. For this work, the authors focus only on four of the five KPIs and thus will neglect the schedule adherence for the following method. Based on the collected company information a process chain plan of material flow, information flow and/or financial flow can be modelled and used for the risk identification process in the next phase.

3.2 Phase 2: Risk Identification

The main goal of this phase is to find, recognize and describe risk elements in terms of risk source, event and effect [37]. Typical approaches for identifying risks for every defined process from the first phase are: risk checklists, expert interviews and workshops (i.e. [28]). Which methods should be used depends on the use case scale and also on how many risks should be identified. Sometimes it can be hard for experts to distinguish between the aforementioned risk elements (source, event, effect). In this case, it is practical to collect all information from the interviewees and do clustering within the risk analysis of the third phase. Also usually applied risk mitigation actions should be collected for the later analysis.

3.3 Phase 3: Risk Analysis

In the next phase the processes and risk elements have to be put into relation by creating cause-and-effect chains (CEC), based on the Fault-Tree logic (e.g. [44]). The CEC will be constructed for each process and later be merged to create an overall risk map. The information for the analysis has to be gathered from the results of Phase 2. If the experts were not able to distinguish between the three risk elements, a practical approach is an iterative analysis. The moderator who collected the risk information in Phase 2 first tries to construct CEC by himself and then brings the results into a discussion with the experts to validate the results. When the moderator has to create the CEC it is useful to start with potential risk sources. The risk sources have per definition no predecessor risk element (attention: this statement is only valid while focusing on only one process chain element – when creating the risk map later, risk sources of one element could also have predecessor risk elements in other parts of the process chain). After thinking about what of the experts descriptions could be a source, the moderator has to think about what descriptions could be possible events, resulting from these sources. In practice there is no limit of risk events between risk sources and risk effects – it depends on the expert's description level of detail. It is also possible that one source can lead to different following events. After connecting risk effects and sources, the next step is to select the corresponding mitigation actions mentioned by the experts. The last step is to define the resulting effect on the process chain element, depending on the chosen mitigation action. For this step, some clarifications are necessary:

- The effects are measured on the aforementioned KPIs of the methodology by [43] and whenever an object leaves the process chain element [78].
- Also only the direct effects of a risk have to be considered and not succeeding effects. For example: Due to a risk event a transport service provider has less transport capacity available, which leads to a rise in lead-time – in this case only the reduced capacity has to be considered, because the rise in lead time will later automatically considered within the simulation (risk evaluation).

- It is also possible that multiple effects occur. For example: Due to bankruptcy of a service provider the company has to switch to another provider which is more expensive and is more slowly in transportation – in this case there are two parallel effects with a rise in cost and a rise in lead-time which both have to be considered.

After creating the local CEC, they will be validated together with the experts and changes have to be implemented. When all local CEC are validated they will be connected and integrated into a global risk map. This should also happen in a workshop together with experts to easily identify risk dependencies between process chain elements. The final risk map contains all observed processes, related risks and inter-process risk dependencies.

3.4 Phase 4: Risk Evaluation

For the aggregated risk evaluation a Discrete Event Simulation (DES) will be combined with a Monte-Carlo-Simulation (MCS), based on a methodology by [78]. Also other simulation types should work, like System Dynamics, as long as the risk value distribution can be implemented via a MCS. The DES simulates the regular material flow, based on the information from *Phase 1* and the MCS is responsible for the consideration of risks and allows for a supply chain risk evaluation based on the Loss-Distribution-Approach (LDA) [63]. The probability of occurrence for each initial risk source and the impact for its corresponding risk effect(s) has to be quantified. For the LDA risks will be quantified in terms of probability distributions. Based on operational risk literature [63] there are typically three sources to use for risk quantification: (1) company data; (2) external data and (3) expert knowledge (self-assessment). Self-assessment should be used if there is no or insufficient data available. In this case the approach by [71] is recommended. At first experts will be asked how often a certain risk occurs (during a time period or during order processing – depends on the case). Based on the literature [15], if a risk occurs only once within a given period, the probability of occurrence can assumed to be Binomial distributed – otherwise Poisson distributed. Second, the risk impact has to be quantified. Due to the superficial description in [78] and also in [71] the authors suggest the following approach for risk impact quantification (discussed with risk management experts in academia and approved in the case study): To fit expert knowledge to probability distributions usable within the simulation, the statistics software “R” is suggested, together with the package “rriskDistributions” [5]. The package helps to identify a suitable distribution based only on two quantile values gathered from the experts. Usually company experts are no experts in statistics thus are unable to give detailed information about risk distributions [65] – however they are able to give at least information about the median risk impact (happens in 50% of the cases) and the pretty much worst impact they have experienced (considered as the 95% or 99% quantile). After selecting an appropriate distribution, the software will also give the user the relevant parameters for the simulation. The described approach allows assessing the impact of multiple risks at the same time on single company process KPIs as well their impact on the whole system. At the end of *Phase 4* the current situation is clear – the crucial supply chain processes and risk sources have been identified.

3.5 Phase 5: Risk Digitalization

In *Phase 5* DSs for risk containing processes have to be drafted. For this a methodology by [9] will be used. Their work describes a meta-model for the transformation of organizations towards I4.0 and combines existing change management processes [46] with identified I4.0 design principles [33] to develop DSs [9]. Their approach gives no information about the qualification and number of participates in the workshops for risk digitalization. However, these two aspects are decisive for the quality of the workshop results. It is important that both experts from in the research field, manager as well as creative employees from the shop floor participate in the workshop. The number of participants should not be too high, as otherwise the creativity of each individual will suffer, and the opinion leader of the group usually prevails. If more participants are desired in the workshops, they should be divided into several small groups [34]. Furthermore, the developed methodology by [9] does not mentioned the summary and documentation of the workshop results. However, since this is important for the presentation of the consensus of the group participants and the analysis of the DS, the authors suggest a proposal in form of a profile with different categories. The digitalization profile categories (DPC) for SCRM are explained in the following:

- <u>Process name, participant and objective (DPC1):</u> In this category, the focused process with its objective is stated and which organizational areas and employees are involved.
- <u>Identified risks (DPC2):</u> The risks that relate to the focused process are listed in this category. Thereby the identified risks from *Phase 2* are considered.

- Target situation with I4.0 technologies (DPC3): Technologies according to I4.0, which are used in the new process flow, are summarized in this category and how they are related to the identified risk elements.

3.6 Phase 6: Digitalization Scenario Analysis

The approach of [9] as well as the framework of [60] lacks a methodological support for evaluating the benefits of such scenarios especially with regard to SCRM DSs. To overcome this lack, a hybrid qualitative-quantitative approach has been developed. It merges previous ideas of [62] who have developed a method called *Extended Performance Analysis* (EPA) for evaluating RFID investments with the described risk assessment method from *Phase 4*. [62] link non-monetary and non-directly measurable digitalization effects through RFID implementation with monetary effects, over CECs. Because the risk evaluation and scenario development happens along SC processes, the DS assessment should follow this approach to be consistent. With this requirement, the method of [62] needs several extensions. A further critique is that the authors have used CECs with subjective assumptions regarding the interdependencies between the initial (non-monetary and non-directly measurable) process-effects of DSs and propagating (non-monetary but directly measurable, or monetary) effects. [62] also only use monetary values to describe the effects which is not sufficient in the context of I4.0 and SSCRM. To make it more suitable for the framework, this paper combines their approach with a DES model. DES is recognized in the literature as a valuable tool to test proposed strategies in an unpredictable environment (e.g. multi-tiered supply chains) [76]. By using a DES, each DS can be evaluated dynamically in the simulation and the (validated) simulation model objectifies the CECs due to its close to reality behaviour. Instead of assuming all effects and correlations the simulation will use the (predicted or known) initial effects of a scenario (i.e. less breakdowns due to more information transparency) and simulate/calculate the propagating effects accordingly to the defined and validated simulation rules (i.e. reduced unplanned maintenance stops and thus reduced maintenance costs and less delay) (Figure 2). Additionally a Monte Carlo Simulation (MCS) is implemented, which helps to diminish the inherent uncertainty in the decision making process and achieves results closer to reality [79]. For the MCS experts will guess in workshops a parameter range for each potential initial effect on specific processes and their risks, define a probability distribution and the MC samples the possible combinations

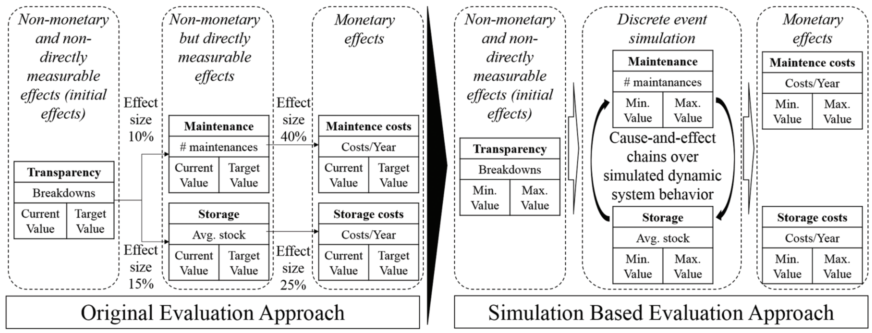

Figure 2 Comparison between original and simulation-based evaluation approach.

of parameters in proportion to their probability of occurring [48]. By combining a DES with the EPA, a process oriented assessment method for DSs (*Phase 5*) has been developed, which delivers less subjective results due to the defined simulation rules and the implemented MCS for the initial effects. The developed method also allows to assess DSs simultaneously with risks, which will not be directly affected by the DS and also with potential risks arising from the SC digitalization. The output comparison serves as a decision support.

4 Framework Application at a German Steel Producer

The method validation took place at a German steel producer. Continuously growing service expectancy and increasingly complex customer requirements for individualization present new challenges for companies in the age of digitalization [42]. Particularly the companies in the German steel industry are in demanding times. Produced overcapacities especially of China and declining sales on world market caused decreasing sales prices, resulting in sales losses as well as value decline in warehouses for steel companies [25, 77]. Steel can be seen as the most important engineering material in use today and its versatility, strength, toughness, low cost and wide availability are unmatched [2, 16, 54]. So steel producers are an inseparable part of several complex supply chain networks and they deliver key resources for different manufacturing industries [60]. The steel industry is typically characterized through volatile lead times, leading to problems with on-time-delivery, expensive ad-hoc solutions and ultimately in sales losses. Risks such as failure of transport and/or work aids in the delivery process lead to significant problems with the customer [38]. In order to meet the market challenges in terms of price, quality and delivery service, producers in the steel sector have to be proactive in identifying potential risks in the supply chain. Out of this, the high consideration relevance of steel producers is justified. The digitalization of processes in supply chains assures to face the current challenges. For this reason, it is important to reduce potential supply chain risks for the improvement of lead time fluctuation and customer's satisfaction.

4.1 Process Identification/Specification

Critical supply chain processes have been identified within expert interviews [53]. For simplification, the paper focuses on one process, involving the transport of cold strips (coils) to succeeding aggregates. Modelling is carried out accordingly to the process chain model of [43]. Corresponding to [43] processes can be characterized by five different process condition measures: lead time, capacity (resources), inventory, on-time delivery and processing costs [43]. The hot strip is stained and rolled by a cold rolling mill before the coils are transferred to an intermediate buffer point by an automated conveying line. An overhead crane picks up, transports and stores the coils in a warehouse. An external transport service provider transports the coils to the next location. The removal and loading are carried out by the same crane (Figure 3).

4.2 Risk Identification

In accordance to [28], the process owner were asked in interviews about a representative/important sub-process and its risks. The process owner has identified the "Pick-up, transport and storage coil via overhead crane" as the TP because the highest risk in this transportation scenario is the failure of the overhead crane. Consequently, the following aggregates cannot be supplied due to a rise in lead time. After choosing a representative process they were asked about possible risks. Because it was difficult for the process owners to differentiate between risk sources, events and effects as well as to stay focused

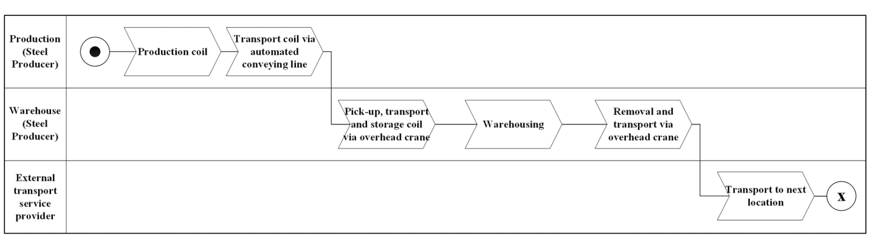

Figure 3 Identified and modelled supply chain process.

on only the TP they were asked to tell anything regarding risks and possible mitigation actions for the overall process. For this example relevant mentioned risk elements were:

- Crane unavailable
- Staff shortage
- Crane defect
- Delay
- Waiting for substitute personnel
- Waiting for reparation

4.3 Risk Analysis and Evaluation

The overall risk analysis and evaluation approach are based on work by [78] and [45]. The authors put all risk elements (*source, event and effect*) into relation and validated the CECs with process owners (Figure 4). Due to the strict focus on the mentioned TP and for simplification, all risk elements with a relation to other processes have been neglected. In the defined TP the two identified inherent risk sources have in the end a risk effect on the throughput time of the TP, due to the chosen mitigation action (Figure 4).

After creating the CEC a single risk assessment took place. Therefore historical data from a six months period in 2016 was available and helped to determine both risk probabilities ([number of directly affected orders]/[all orders during this period]). For both risk impacts no data was available and experts were asked. The above-described method for transforming expert knowledge into distributions has been used (see Section 3.4). For each impact on the process condition measures the experts estimated a median value (lower bound, mentioned in Figure 4) and a worst case value (upper bound, mentioned in Figure 4) and a distribution and its parameter values for the simulation have been derived.

Afterwards the described scenario has been modelled in a DES, combined with a MCS [78]. Typically, a MCS is used to test risky scenarios and their consequences in a *Value-at-Risk* framework [17, 66]. In this publication it is shown how the identified risks and also later the DS will affect the mean lead time. Thus the risk and SCRM DS assessment KPI will be *Mean Lead time-at-Risk*. After validating and running the simulation the results represent an aggregated evaluation of the risk affected current situation. For better comparison, the results can be found in Section 5.

4.4 Risk Digitalization

In order to counteract the identified risks, a DS for the described transport process has been developed with a focus on minimizing risk by using I4.0 technologies. For the creation of the DS, the developed design principles

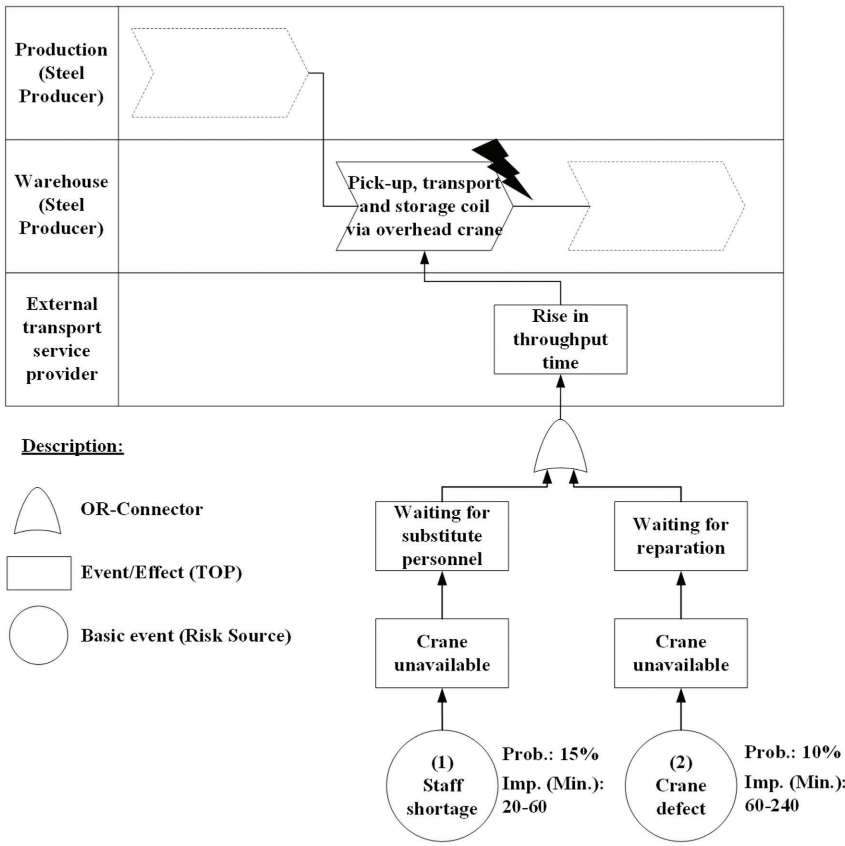

Figure 4 Cause-and-Effect relationships of risk sources, events and effects.

by [33] are used in a workshop accordingly to the methodology by [9]. Two groups, each with six workshop participants were formed. The group members were both process owners from the departments of production, warehousing and transportation (DPC1) as well as employees from a research institute to promote the flow of creativity on the subject of I4.0. Each group developed ideas to a DS. The results were combined into a scenario, which addresses the identified process risks and reduces their impact. Due to the limited focus on the TP (DPC1), only the relevant details of the scenario will be outlined. The main purposes were to reduce problems with staff shortage and sudden crane defects happening in the past (DPC2). In the DS, the coil is transported and stored by an autonomous overhead crane, equipped with predictive maintenance capabilities. The data for the storage location

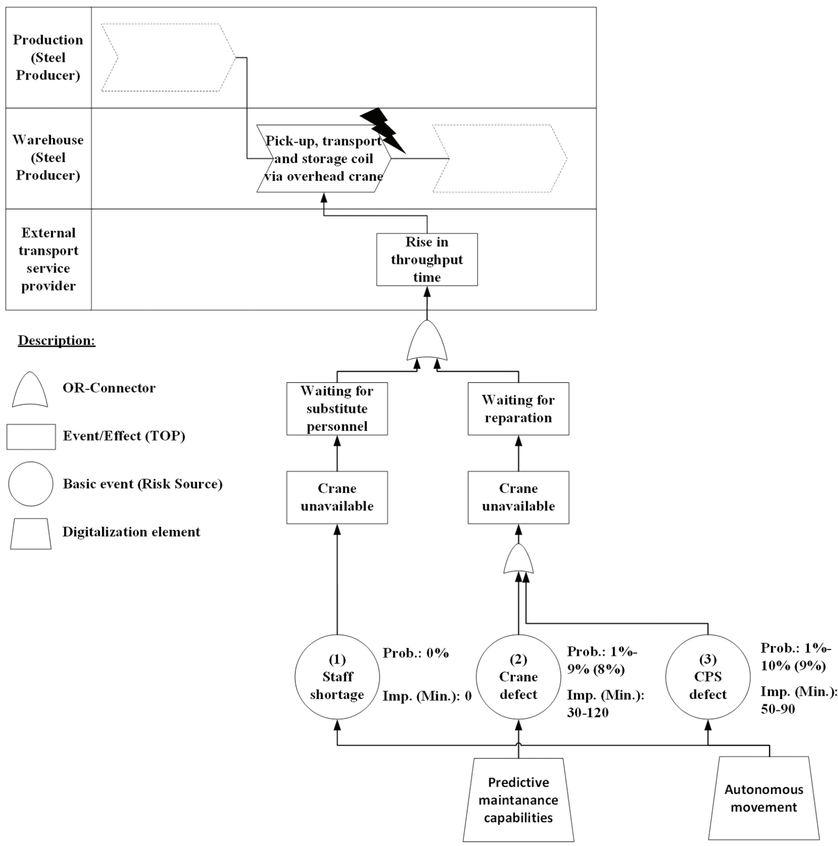

Figure 5 Extended CEC with estimated changes in risk values.

will be transferred wirelessly from the databases to the crane and real-time status information from the crane sensors will be transferred back into the database. All data is gathered and analysed by Big Data analytics, which allows identification of unwanted system patterns in real-time (DPC3). The documented scenario elements have been implemented in the CEC for better assessment of the potential effects and to show additional risks (Figure 5).

4.5 Digitalization Scenario Analysis

The simulation is an important and common method, particularly in the context of digitalization or I4.0. It can be used as an auxiliary tool to evaluate different scenarios without realizing them. This allows predictions and can increase decision support [40]. The initial effects of a DS are probably not completely determined quantitatively at the time of evaluation (uncertainty exists) – experts mostly will have to guess how a scenario will become manifest in the initial effect numbers. For the MCS experts have guessed in workshops a parameter range for the potential initial effect on each risk (Figure 5). Later these ranges have been implemented into the simulation model.

Probabilities: As mentioned, there is no scenario data available and experts had to estimate the DS impact on the parameters. Because of the missing data the authors decided to use a triangle distribution for the probabilities, accordingly to the literature [20]. To reflect the sceptical attitude of the experts towards digitalization, the mean value has been defined only 1% better than the max. (Worst-case) value (mean value in brackets in Figure 5).

Impacts: For the DS, the personnel shortage risk is not relevant anymore but an additional risk of defect of the cranes smart capabilities arises. The experts estimated this value based on their experience regarding IT system defects of other machines. The reduction of the “crane defect” impact results from the fact that often times half of the downtime comes from contacting and waiting for the reparation equipment/team to appear. With smart capabilities the team can be informed when the system detects an imminent defect. The distributions have been derived based on the same method described in the risk assessment phase.

The input data and simulation results of the DS can also be found in the next section.

5 Simulation Results

Before the actual evaluation took place, the number of MCS replications had to be determined. Therefore, the simulation results for 10, 100, 200, 500, 750 and 1000 replications have been compared. Because there was no significant change in the results after 500 runs for this small case, the number of replications for the evaluation had been set to 500. This approach goes along with the literature [50]. With the collected risk input values in Table 1 the simulation has been run for a risk-free, current and digitalization scenario. The results can also be found in Table 1.

The results show that even the expert’s conservative expectations of the DS can have a mitigating effect on the rise in lead time through risk. Within the DS the *Mean Lead time-at-risk* has not been higher than 7893 sec. (132 min.), with a 95% confidence level. The results can be used subsequently to calculate

Table 1 Simulation input and results

		No Risk	Current	Scenario
Staff shortage	Probabilty (%)	0	15%	0
	Impact (Min.)	0	20–60	0
CPS defect	Probabilty (%)	0	0	1%–10% (9%)
	Impact (Min.)	0	0	50–90
General defect	Probabilty (%)	0	10%	1%–9% (8%)
	Impact (Min.)	0	60–240	30–120
Mean Lead time-at-risk (Sec.)		7680	8393	7893
Mean Lead time-at-risk (Min.)		128	140	132
Change		–	9%	3%

the positive financial impact of the DS, which in return can be compared with expected investment costs.

6 Conclusion and Further Research

The paper presents a flexible simulation-based approach for assessing process oriented DSs based on customizable KPIs and prior to realization, which can either be used with expert estimations or objective information to estimate potential benefits. The assessment approach is integrated into a framework and its applicability could be validated within a case study of a German steel producer. As a result, the expected *Mean Lead time-at-risk* could be quantified. The positive evaluation helped selecting the scenario for implementation and it shows the positive effect of digitalization on SCRM.

6.1 Limitations and Further Research

When applying the framework, the user has to be aware about its limitations. The simulation-based evaluation approach probably needs more user competence regarding DES and it needs time to complete all steps of the framework. There is a need in comparing the proposed method and the original approach by [62] regarding necessary effort and result accuracy. Due to the positive scenario evaluation at the German steel producer and a following realization, the shown case study can serve as a pilot study to benchmark subsequent studies on the implemented DS. A comparison of the pilot study with the subsequent study results (predicted benefit vs. real benefit) allows further research on the reliability of either the expert predictions or the proposed evaluation method in general. This helps to improve the proposed method and evaluate its usefulness. Another potential for further research is an improved method for DS development within the context of SCRM. The suggested transformation method by [9] served as a basis for industry workshops at the German steel producer. Due to a superficial description of how such transformation workshops should be set up and proceed, the authors had to improvise beforehand and during the workshop. The developed method has been used for assessing process oriented SCRM DSs. Further research is required to find out if the approach can be used for assessing process oriented DSs with no focus on SCRM. For example: the evaluation of potentials in collaborative planning and control processes in supply chains through digitalization. There is also a need in identifying suitable approaches, formalizing the impact estimation of digitalization effects on risk parameters. It is also worthwhile to test the presented approach with other types of simulations then DES. Especially System Dynamics can be an appropriate tool for larger problems because of better runtime performance and when the evaluation shall be more strategic and less detailed.

6.2 Managerial Implications

The described framework allows practitioners to derive individual and process oriented DSs for a smart SCRM, and the subsequent assessment of such scenarios. The smart SCRM mentioned here is a good basis for a proactive SCRM which in the literature is discussed on a conceptual basis for many years (e.g. [32]) but up to now it has rarely been realised in business practice. In the age of Big Data, digitisation and autonomisation today we have sufficient data as well as the technologies (such as Blockchain), which can allow a proactive management of such data along supply chains. The transparency in value-added networks exists end-to-end so that in the future risks can be avoided or reduced at an earlier stage than today. For a practical application of such a SSCRM it is also necessary that there is a structured approach from application-oriented research to core elements of a cycle of SSCRM.

References

[1] Alexander, E. R. (1992). *Approaches to Planning: Introducing Current Planning Theories, Concepts, and Issues*. Luxembourg: Gordon and Breach Publishers.

[2] Ashby, M. F. (2009). *Materials and the Environment: Eco-informed Material Choice*. Oxford: Butterworth-Heinemann.

[3] Bauernhansl, T., ten Hompel, M., and Vogel-Heuser, B. (eds) (2014). *Industrie 4.0 in Produktion, Automatisierung und Logistik. Anwendung – Technologien – Migration*. Wiesbaden: Springer Fachmedien.

[4] Becker, W., Ulrich, P., Botzkowski, T., and Eurich, S. (2016). "Controlling von Digitalisierungsprozessen – Veränderungstendenzen und empirische Erfahrungswerte aus dem Mittelstand," in *Industrie 4.0 als unternehmerische Gestaltungsaufgabe. Betriebswirtschaftliche, Technische und Rechtliche Herausforderungen*, ed. R. Obermaier (Wiesbaden: Springer Gabler), 97–118.

[5] Belgorodski, N., Greiner, M., Tolksdorf, K., and Schueller, K. (2017). *Package 'rriskDistributions'.*

[6] Bischoff, J., Taphorn, C., Wolter, D., Braun, N., Fellbaum, M., Goloverov, A., et al. (2015). *Erschließen der Potenziale der Anwendung von 'Industrie 4.0' im Mittelstand. Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie (BMWi)*. Mülheim an der Ruhr: agiplan GmbH.

[7] Blomgren, H., Jonsson, P., and Lagergren, F. (2011). "Getting back to scenario planning: strategic action in the future of energy Europe," in *Proceedings of the 2011 European Energy Market* (Zagreb: IEEE), 792–801.

[8] Bogataj, D., and Bogataj, M. (2007). Measuring the supply chain risk and vulnerability in frequent space. *Int. J. Prod. Econ.* 108, 291–301.

[9] Bücker, I., Hermann, M., Pentek, T., and Otto, B. (2016). "Towards a methodology for industrie 4.0 transformation," in *Proceedings of the 19th International Conference: Business Information Systems*, Leipzig, Germany, July, 6–8, 2016, eds W. Abramowicz, R. Alt and B. Franczyk (Cham: Springer International Publishing), 209–221.

[10] Butner, K. (2010). The smarter supply chain of the future. *Strategy Leadersh.* 38, 22–31.

[11] Chatfield, D. C., Kim, J. G., Harrison, T. P., and Hayya, J. C. (2004). The bullwhip effect. Impact of stochastic lead time, information quality and information sharing: a simulation study. *Prod. Oper. Manag.* 13, 340–353.

[12] Chopra, S., and Sodhi, M. S. (2004). Managing risk to avoid supply-chain breakdown. *MIT Sloan Manage. Rev.* 46, 53–61.

[13] Chopra, S., and Sodhi, M. S. (2014). Reducing the risk of supply chain disruptions. *MIT Sloan Manage. Rev.* 55, 73–80.

[14] Christopher, M., and Lee, H. (2004). Mitigating supply chain risk through improved confidence. *Int. J. Phys. Distrib. Logist. Manag.* 34, 388–396.

[15] Cottin, C., and Döhler, S. (2013). *Risikoanalyse. Modellierung, Beurteilung und Management von Risiken mit Praxisbeispielen: Studienbücher Wirtschaftsmathematik*. Wiesbaden: Springer.

[16] Cullen, J. M., Allwood, J. M., and Bambach, M. D. (2012). Mapping the global flow of steel: from steelmaking to end-use goods. *Environ. Sci. Technol.* 46, 13048–13055.

[17] Deleris, L. A., and Erhun, F. (2005). "Risk management in supply networks using Monte-Carlo simulation," in *Proceedings of the 37th Conference on Winter Simulation* (Orlando, FL: IEEE), 1643–1649.

[18] Diehl, D., and Spinler, S. (2013). Defining a common ground for supply chain risk management – a case study in the fast-moving consumer goods industry. *Int. J. Logist. Res. Appl.* 16, 311–327.

[19] Ellis, S. C., Henry, R. M., and Shockley, J. (2010). Buyer perceptions of supply disruption risk: a behavioral view and empirical assessment. *J. Oper. Manag.* 28, 34–46.

[20] Ezell, B. C. (2007). Infrastructure vulnerability assessment model (I-VAM). *Risk Anal.* 27, 571–583.

[21] Faisal, M. N., Banwet, D. K., and Shankar, R. (2006). Supply chain risk mitigation: modeling the enablers. *Bus. Process Manag.* 12, 535–552.

[22] Fan, H., Cheng, T. C. E., Li, G., and Lee, P. K. C. (2016). The effectiveness of supply chain risk information processing capability: an information processing perspective. *IEEE Trans. Eng. Manag.* 63, 414–425.

[23] Fan, H., Li, G., Sun, H., and Cheng, T. (2017). An information processing perspective on supply chain risk management. Antecedents, mechanism, and consequences. *Int. J. Prod. Econ.* 185, 63–75.

[24] Glas, A. H., and Kleemann, F. C. (2016). The impact of industry 4.0 on procurement and supply management: a conceptual and qualitative analysis. *Int. J. Bus. Manag. Invent.* 5, 55–66.

[25] Goh, J. H., and Kong, M.-K. (2016). The myth and reality of global steel overcapacity. *Asian Steel Watch* 01, 62–67.

[26] Goh, M., Lim, J. Y. S., and Meng, F. (2007). A stochastic model for risk management in global supply chain networks. *Eur. J. Oper. Res.* 182, 164–173.

[27] Göpfert, I. (ed.) (2016). *Logistik der Zukunft – Logistics for the Future*. Wiesbaden: Springer Link.

[28] Häntsch, M., and Huchzermeier, A. (2013). Identifying, analyzing, and assessing risk in the strategic planning of a production network: the pracitcal view of a German car manufacturer. *J. Manag. Control* 24, 125–158.

[29] Hendricks, K. B., and Singhal, V. R. (2003). The effect of supply chain glitches on shareholder wealth. *J. Oper. Manage.* 21, 501–522.

[30] Hendricks, K. B., and Singhal, V. R. (2005). An empirical analysis of the effect of supply chain disruptions on long-run stock price performance and equity risk of the firm. *Prod. Oper. Manag.* 14, 35–52.

[31] Hendricks, K. B., and Singhal, V. R. (2005). Association between supply chain glitches and operating performance. *Manage. Sci.* 51, 695–711.

[32] Henke, M. (2009). *Supply Risk Management. Planung, Steuerung und Überwachung von Supply Chains*. Berlin: Erich Schmidt.

[33] Hermann, M., Pentek, T., and Otto, B. (2016). "Design principles for industrie 4.0 scenarios," in *Proceedings of the 49th Annual Hawaii International Conference on System Sciences*, 5–8 January 2016, Kauai, Hawaii, eds T. X. Bui and R. H. Sprague (Piscataway, NJ: IEEE), 3928–3937.

[34] Herrmann, A., and Huber, F. (2009). *Produktmanagement. Grundlagen – Methoden – Beispiele*. Wiesbaden: GWV Fachverlage GmbH.

[35] Hillman, M., and Keltz, H. (2007). *Managing Risk in the Supply Chain: A Quantitative Study*. AMR Research Report.

[36] Ho, W., Zheng, T., Yildiz, H., and Talluri, S. (2015). Supply chain risk management: a literature review. *Int. J. Prod. Res.* 53, 5031–5069.

[37] ISO (2009). *Guide 73: Risk management – Vocabulary*. Geneva: Beuth.

[38] Jüttner, U. (2005). Supply chain risk management: understanding the business requirements from a practitioner perspective. *Int. J. Logist. Manag.* 16, 120–141.

[39] Jüttner, U., Peck, H., and Christopher, M. (2003). Supply chain risk management: outlining an agenda for future research. *Int. J. Logist. Res. Appl.* 6, 197–210.

[40] Kagermann, H., Wahlster, W., and Helbig, J. (2013). *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0. Final Report of the Industrie 4.0 Working Group*. München: acatech – National Academy of Science and Engineering.

[41] Kirazli, A., and Moetz, A. (2015). "A methodological approach for evaluating the influences of Industrie 4.0 on risk management of the goods receiving area in a German automotive manufacturer", in *Proceedings of the 22nd EurOMA Conference. Operations Management for Sustainable Competitiveness*.

[42] Krumeich, J., Jacobi, S., Werth, D., and Loos, P. (2014). "Big data analytics for predictive manufacturing control – a case study from process

industry," in Proceedings of the *2014 International Congress on Big Data (BigData Congress), IEEE*, 530–537.

[43] Kuhn, A. (1995). *Prozessketten in der Logistik. Entwicklungstrends und Umsetzungsstrategien*. Dortmund: Verlag Praxiswissen.

[44] Lee, W. S., Grosh, D. L., Tillman, F. A., and Lie, C. H. (1985). Fault tree analysis, methods, and applications – a review. *IEEE Trans. Reliabil.* 34, 194–203.

[45] Lingnau, V., and Jonen, A. (2007). "Kognitionsorientiertes risikocontrolling in der supply chain: supply chain risk map," in *Proceedings of the Risikomanagement in Supply Chains. Gefahren abwehren, Chancen nutzen, Erfolg generieren*, eds R. Vahrenkamp and C. Siepermann (Berlin: Erich Schmidt Verlag).

[46] Mento, A. J., Jones, R. M., and Dirndorfer, W. (2002). A change management process: grounded in both theory and practice. *J. Change Manage.* 3, 45–59.

[47] Merz, S. L. (2016). "Industrie 4.0 – Vorgehensmodell für die Einführung," in *Proceedings of the Einführung und Umsetzung von Industrie 4.0. Grundlagen, Vorgehensmodell und Use Cases aus der Praxis*, ed. A. Roth (Berlin: Springer-Verlag), 83–110.

[48] Milanovic, D. L., Milanovic, D. D., and Misita, M. (2010). The evaluation of risky investment projecs. *FME Trans.* 38, 103–106.

[49] Mullai, A. (2009). "Chapter 6: Risk management system – a conceptuatl model," in *Supply Chain Risk. A Handbook of Assessment, Management, and Performance: International Series in Operations Research & Management Science*, Vol. 124, eds G. A. Zsidisin and B. Ritchie (Boston, MA: Springer-Verlag), 83–101.

[50] Mundform, D. J., Schaffer, J., Kim, M.-J., Shaw, D., and Thongteeraparp, A. (2011). Number of replications required in monte carlo simulation studies: a synthesis of four studies. *J. Mod. Appl. Stat. Methods* 10, 19–28.

[51] Norrman, A. and Jansson, U. (2004). Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident. *Int. J. Phys. Distrib. Logist. Manage.* 34, 434–456.

[52] Nyhuis, P. and Wiendahl, H.-P. (2009). *Fundamentals of Production Logistics. Theory, Tools and Applications*. Berlin: Springer-Verlag.

[53] Pawar, M. (2004). *Data Collecting Methods and Experiences: A Guide for Social Researchers*. New Delhi: New Dawn Press.

[54] Peters, K., Malfa, E., Colla, V., and Brimacombe, L. (2015). "Resource efficiency in the Strategic Research Agenda of the European Steel

Technology Platform," in *Proceedings of the 2015 World Congress on Sustainable Technologies (WCST),* IEEE, 34–39.

[55] Pettit, T. J., Crocton, K. L., and Fiksel, J. (2013). Ensuring supply chain resilience: development and implementation of an assessment tool. *J. Bus. Logist.* 34, 46–76.

[56] Pfohl, H.-C., Yahsi, B., and Kurnaz, T. (2015). "The impact of industry 4.0 on the supply chain," in *Proceedings of the Hamburg International Conference of Logistics (HICL) 21: Sustainability in Logistics and Supply Chain Management: New Designs and strategies*, eds W. Kersten, T. Blecker, and C. M. Ringle (Berlin: epubli GmbH), 31–58.

[57] Purdy, G. (2010). ISO 31000:2009 – setting a new standard for risk management. *Risk Anal.* 30, 881–886.

[58] Qin, J., Liu, Y., and Grosvenor, R. (2016). A categorical framework of manufacturing for industry 4.0 and beyond. *Proced. CIRP* 52, 173–178.

[59] Schlüter, F., Diedrich, K., and Güller, M. (2017). "Analyzing the impact of digitalization on supply chain risk management," in *Proceedings of the 2017 IPSERA Conference*.

[60] Schlüter, F., and Sprenger, P. (2016). "Migration framework for decentralized and proactive riskidentification in a Steel Supply Chain via Industry 4.0 technologies," in *Proceedings of the 5th International Symposium and 27th National Conference on Operational Research*, eds A. Spyridakos and L. Vryzidis, Athens, 85–91.

[61] Seiter, M., Bayerle, C., Berlin, S., David, U., Rusch, M., and Treusch, O. (2016). *Roadmap Industrie 4.0. Ihr Weg zur Erfolgreichen Umsetzung von Industrie 4.0*. Ulm: Tredition.

[62] Seiter, M., Isensee, J., and Rosentritt, C. (2008). "Evaluation of RFID investment – the extended performance analysis (EPA) approach," in *Proceedings of the RFID Systems and Technologies, 2008. 4th European Workshop on RFID Systems and Technologies*, June, 10–11, 2008, ITG-Fachbericht 209 (Berlin: IEEE), 1–6.

[63] Shevchenko, P. V. (2011). *Modelling Operational Risk Using Bayesian Inference*. Berlin: Springer-Verlag.

[64] Sodhi, M. S., Son, B.-G., and Tang, C. S. (2012). Researchers' perspectives on supply chain risk management. *Prod. Oper. Manage.* 21, 1–13.

[65] Steinhoff, C. (2008). *Quantifizierung operationeller Risiken in Kreditinstituten. Eine Untersuchung unter besonderer Berücksichtigung von Szenarioanalysen im Rahmen von Verlustverteilungsmodellen*. Göttingen: Cuvillier Verlag.

[66] Strong, R. A., Steiger, N. M., and Wilson, J. R. (2009). "Introduction to financial risk assessment using Monte Carlo simulation," in *Proceedings of the 2009 Winter Simulation Conference*, *(WSC 2009)*, (Piscataway, NJ: IEEE), 99–118.

[67] Tang, C., and Tomlin, B. (2008). The power of flexibility for mitigating supply chain risks. *Int. J. Prod. Econ.* 116, 12–27.

[68] Tang, C. S. (2006). Perspectives in Supply Chain Risk Management. *Int. J. Prod. Econ.* 103, 451–488.

[69] ten Hompel, M., and Henke, M. (2017). "Logistik 4.0 – Ein Ausblick auf die Planung und das Management der zukünftigen Logistik vor dem Hintergrund der vierten industriellen Revolution," in *Handbuch Industrie 4.0 Bd.4. Allgemeine Grundlagen*, eds B. Vogel-Heuser, T. Bauernhansl, and M. ten Hompel, (Berlin: Springer), s.l., 249–259.

[70] Thun, J., and Hoening, D. (2011). An Empirical Analysis of Supply Chain Risk Management in the German Automotive Industry. *Int. J. Prod. Econ.* 131, 242–249.

[71] van den Brink, G. J. (2005). "Quantifizierung operationeller Risiken – Ein Weg zur Einbettung in den Management-Zyklus," in *Modernes Risikomanagement*, ed. F. Romeike (Weinheim: Wiley-VCH), 255–268.

[72] Wagner, S., and Bode, C. (2006). An empirical investigation into supply chain vulnerability. *J. Purch. Supply Manage.* 12, 301–312.

[73] Wan, J., Cai, H., and Zhou, K. (2015). "Industrie 4.0: enabling technologies," in *Proceedings of 2015 International Conference on Intelligent Computing and Internet of Things (ICIT 2015)*, January 17–18, 2015, Harbin, China (Piscataway, NJ: IEEE), 135–140.

[74] Wan, J., Yan, H., Suo, H., and Li, F. (2011). Advances in cyber-phyisical systems research. *KSII Trans. Internet Inform. Syst.* 5, 1891–1908.

[75] Wang, L. and Ranjan, R. (2015). Processing distributed internet of things data in clouds. *IEEE Cloud Comput.* 2, 76–80.

[76] Wang, Q. (2008). A discrete event modelling approach for supply chain simulation. *Int. J. Simul. Model.* 7, 124–134.

[77] Wang, Y. (2016). "Steel industry overcapacity early warning research based on neural network," in *Proceedings of the 2016 International Conference on Smart Grid and Electrical Automation (ICSGEA)*, IEEE, 160–163.

[78] Yüzgülec, G. (2015). *Aggregierte Bewertung von Risikoursachen in Supply Chains der Automobilindustrie*. (Dortmund: Verlag Praxiswissen).

[79] Zio, E. (2013). *The Monte Carlo Simulation Method for System Reliability and Risk Analysis*. London: Springer.

[80] Zsidisin, G. A. (2003). A grounded definition of supply risk. *J. Purch. Supply Manage.* 9, 217–224.
[81] Zsidisin, G. A. and Ritchie, B. (2009). "Chapter 1: Supply Chain Risk Management – Developments, Issues and Challenges," in *Supply Chain Risk. A Handbook of Assessment, Management, and Performance*, eds G. A. Zsidisin and B. Ritchie (Boston, MA: Springer-Verlag, US), 1–12.

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