Monetary Quantification of Supply Risks of Manufacturing Enterprises - Discrete Event Simulation Based Approach

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Abstract

Various approaches exist to quantify risks in supply chains. However, two aspects in risk assessments are not usually considered: monetarized risk quantification and use-case dependent model complexity. Monetarily quantifying risks means quantifying root-cause and severity of each single risk and aggregating these risks into an aggregated risk value. Thereby information uncertainty, complex interrelations and dynamic influences need to be considered. Depending on a use-case’s goal information or process models need to be created at different levels of detail. This paper presents a Discrete Event Simulation (DES) approach providing all necessary features to monetarily quantify risks independent of the depth of information and thus allow adjusting the model dependent on the use-case. It provides graphical modeling language equipped with risk assessment probes enabling to capture all risk-relevant aspects. Based on this instrumented model, the framework is then able to compute and report about monetary risk quantification using an efficient DES engine driven by a Monte-Carlo procedure. Within this paper applicability of such an approach shall be assessed in use-case specific processes characterized by determined risks and parameter settings.

Keywords: monetary risk quantification; discrete event simulation, monte carlo simulation, use-cases

1. Introduction

Today’s manufacturers face an increased exposure to supply chain risks. Ever-expanding product complexity and increasing cost pressure force manufacturers to focus on their core competences. In conjunction with decreasing lead times and low inventory this results in increasing vulnerability of supply chains. Several recent publications deal with supply chain risk management (SCRM) [e.g. 1,2,3,4,5,6,7]. However, a gap and potential in developing quantitative models to make well-grounded decisions in managing risk has been identified [8]. In particular, existing approaches do not enable monetary supply risk quantification. Quantitative, monetary assessment of risk is required in order to be able to verify economic feasibility of risk management activities and thus to underpin and legitimate corporate decisions by balancing expected yields and risks [9]. In particular, an approach is required allowing performance optimized trade-offs between logistics-, manufacturing-, and risk-costs. Therefore, VON CUBE ET AL. developed a risk assessment model and software-based tool allowing monetary assessment of procurement risks using Monte Carlo Simulation (MCS) [10]. It uses a static risk model that does not account for different system states at different points in time. Furthermore, its scope is limited to the assessment of risk related to merely one procurement good at each simulation run. Entire process chains cannot be analyzed limiting the concept’s usability in industrial application.

Hence, our goal was to develop a comprehensive quantitative supply risk assessment approach, which supports decision makers in the field of procurement and production logistics in designing cost optimal processes under consideration of firm’s exposure to supply risk. In order to
Supply risk quantification requires a comprehensive understanding of system processes in order to be able to determine risk induced costs. Therefore processes subsequent to the point of failure occurrence and their interrelations need to be analyzed. In our approach we applied a DES solution to simulate procurement activities, production, transportation, assembly and storage processes. DES is defined as “modeling of systems in which the state variable changes only at a discrete set of points in time” [14]. Time is hence abstracted as specific time points where the occurrence of an event (e.g. arrival of ordered goods) marks the transition of the system into another state (e.g. new inventory level) [15]. DES is suitable for reasoning about discrete entities moving through a network of stations, compete for resources and are subject to stochastic stopping times [16]. Fig. 1 illustrates the basic concept of our approach. In the following, the conceptual scope as well as the basics of risk quantification will be presented prior to introducing our supply risk quantification methodology.

2. Conceptual Approach

2.1. Scope of risk and risk quantification

Most commonly risk can be distinguished between cause-oriented and effect-oriented perspectives [17,18,19,20]. Cause-oriented definitions consider uncertainty of information validity as the root-cause of risk and define risk as measurable uncertainty [21]. Effect-oriented understandings of risk generally consider risk as the chance of missing targets [20]. To properly manage risk a combination of both understandings is required. Hence, risk in the present context is defined as the chance of missing targets due to uncertainty regarding occurrence probabilities of future events. Supply risks are the noticeable consequences of all upstream risk events and express themselves as deviations from the expected quality of delivered parts, deviations from the scheduled date of delivery of ordered lots, deviations from the planned quantity of delivered goods, and deviations from the planned prices of procured goods. As monetary effects of the latter risk category can directly be determined and does not influence logistics performance, solely delay, quantity, and quality risks are taken into account. Supply risks can basically leads to three major risk consequences of financial loss:

- Stock-out costs,
- Costs for excess inventory, and
- Failure costs

Stock-out costs comprise of opportunity costs for lost production volumes, hence lost sales, and possible contractual penalties. Costs for excess inventory occur in case of early deliveries. Failure costs comprise costs for potential machine outages caused by faulty parts, costs for potential rework processes, and possible reliability claims. The total supply risk costs equal the sum of the three individual cost factors. Additionally, process and inventory costs, as well as operational logistics indicators are provided in order to provide all necessary information to assess and improve process performance.

Generally, risk should be modeled in form of probability distributions [22]. As risk is defined as the deviation from a planned value, statistical measures can thus be applied to operationalize and compare the possible magnitude of such deviations [22]. In our application we use the Value-at-Risk (VaR) and the Conditional-Value-at-Risk (CVaR) as target risk measures. The VaR is a common risk measure defined as the amount of loss not being exceeded with a certain probability during a defined period [23]. It thus does explicitly not consider rare, extreme events as the tail of a distribution is “cut off”. Therefore, the CVaR is additionally provided as it equals the expected value of loss under the condition that the VaR is exceeded [23]. Hence, those measures facilitate a comprehensive illustration of the possible range of risk impacts.

2.2. Modeling and Simulation Framework

The core element of our supply risk assessment solution is the developed graphical process modeling and simulation framework. All main elements of manufacturing processes are represented in our simulation meta-model, which allows
defining concrete models that are simulated in a DES engine [13]. Basically, four steps are necessary to analyze and evaluate the supply risk exposure:

1. Definition of the analysis purpose and risk identification
2. Risk-oriented process modeling and specification of input data
3. Simulation and risk assessment
4. Definition of risk mitigation and scenario analysis

First of all, the analysis purpose and the object of examination have to be defined by the user. This could either be a specific product or a group of products with their relevant procured components. Furthermore, it needs to be defined which risks to consider and which target measures to include. A preliminary study indicated that enterprises consider supply risk, quality risk and supplier risk as most important [24].

Subsequently, the production system with its relevant elements and their relations is specified in the phase of process modeling. In that phase, examined storage, production, transportation, and assembly processes are defined modeled by logically combining provided standard building blocks. A user-friendly “drag and drop” interface is provided for maximal usability. For this step it is particularly important to define a proper level of detail, which needs to be defined, based on the data available and the analysis purpose [25]. The whole process is actually driven by the definition of risk measurement probes that determine the necessary and sufficient level of detail of the model. For each relevant process step, input variables and parameters, such as processing times need to be defined. Additionally, order schedules, the expected demand and procurement data (order quantities, replenishment times, delivery dates) are specified in the phase of model quantification. Supplier behavior is of stochastic nature hence the intervals between incoming lots and respective lot sizes are quantified as probability distributions which represent quantity and delivery date risks. Furthermore, quality risks are modeled by specifying the ratio of defective parts and its variation per lot. PRINTZ ET AL. introduce a cybernetic approach supporting in defining suitable occurrence probability distributions for supply related risks [26].

In step three, the actual simulation of the created model is conducted. A simulation engine uses the input data of the model to run DES algorithms. Material and information flows through the system are simulated over time whereat the simulated time period is adjustable and depends on the simulation objective. Stochastic variance and uncertainty of input data is considered by applying MCS generating a set of representative sample of possible outcomes. During the simulation inventory levels, stock-out durations, machine downtimes, and reliability measures are retrieved to compute expected losses, production and inventory costs, and logistics performance measures, such as service level or order throughput times.

If the risk exposure exceeds the acceptable level, the user can decide on appropriate mitigation measures and test their effectiveness by conducting scenario analyses before implementation. Support is also provided to help determining adequate risk control parameters.

3. Use Cases

In the following we will demonstrate how our solution can be applied to support decision making under risk. For that purpose two examples have been modeled and analyzed. The chosen cases are simplified and anonymized versions of actual industrial applications and illustrate the range of different problems for which the developed solution can provide helpful support. As our own software solution is not yet completely developed in terms of result analysis, MATLAB® and its DES toolbox SimEvents® have also been applied to build the process models and run the simulations. This is considered a valid way to test the general concept applicability, to gain insight about strengths and weaknesses of our approach, and to derive aspects we need to include in our own software tool.

3.1. Case A - Overview

The product under investigation is a relatively simple product consisting of three components, which are procured externally. The production process can be characterized as an order-driven, small batch, job shop production as depicted in Fig. 2.

Figure 2: Simplified simulation model use-case A

Materials A and B are delivered on a regular basis and kept on stock, whereas component C is ordered based on the current demand using a Kanban system. Whenever a new customer order arrives, inventory is checked. If enough parts are available, the order is released and the production process starts. If not, the order has to wait until new supplies arrive causing a delayed start of production and potentially delayed deliveries. Materials A and B are polymer materials stocked as mats out of which single components need to be cut in a first production step prior to assembling and processing all three components. Completed orders are directly shipped and no final products are kept in stock. In case of faulty deliveries in terms of quality and quantity, the entire lot is rejected and sent back to the supplier who provides a new lot as soon as possible. During the incoming goods inspection, all defective
parts are detected. Thus the only risk considered is untimely deliveries, which, however, can also be caused by quality and quantity risks. Quality induced costs (rework, machine repair, reliability claims) are hence not taken into account. Costs for excess inventory are considered negligible. Customer service is of special importance for company A. Order lead times should be as low as possible and should not exceed 4 days as otherwise penalties need to be paid.

The developed simulation tool has been applied in order to analyze logistics performance and risk costs to identify potential improvements. In our analysis we used input data characterizing the intervals between incoming orders and material throughput. For reasons of simplification, we assumed a constant volume of ten units per customer order. Supply risks have been considered using fictive probability distributions for inter-arrival times of delivered lots and estimated probabilities of lot rejection. Plausibility of input data has been tested to guarantee that no other risk factors than supply risks (e.g. order quantities exceeding production capacity and thus causing delays) were biasing simulation results.

3.2. Use-Case A – Analysis and simulation results

We conducted a total of 1000 simulation runs to cover the complete range of possible risk scenarios. Target measures should only include stock-out costs, inventory costs, the amount of delayed deliveries, and the average order throughput time per simulation run. The results are illustrated as frequency distributions in Fig. 3.

In a first analysis overall risk related costs due to delayed deliveries to customers amount to a mean value of €18,000, while the VaR for a confidence level of 95% results to about €25,000. The average lead time adds up to nearly 11 days being far off the desired 4 days and causing a high number of delayed orders. Worst case scenarios cause average lead times of more than 30 days. Inventory costs vary between €35,000 and almost €60,000.

In a second risk mitigation simulation analysis, we examined the impact of an increased safety stock level of component C and an increased order lot size of component A. The ordering threshold was raised from 70 to 100 units. The regularly ordered lot size was increased by five units to 35. Those parameter changes result in a significant decrease of the stock-out probability and hence drastically improve logistics performance. Average risk costs are reduced, while inventory costs do not significantly increase (Table 1).

Table 1: Simulation results use-case A

|                | Mean risk costs [€] | VaR<sub>0.95</sub> risk costs [€] | Mean inventory costs [€] | VaR<sub>0.95</sub> inventory costs [€] |
|----------------|---------------------|-----------------------------------|--------------------------|------------------------------------------|
| Simulation 1   | 17,969              | 24,676                            | 39,218                   | 46,648                                    |
| Simulation 2   | 5,555               | 24,543                            | 40,683                   | 47,065                                    |

3.3. Use-Case B – Overview

In contrast to Use-Case A, company B is a make-to-stock manufacturer, producing quantities based on demand forecasts. It is characterized by a high manufacturing depths resulting in an insignificant ratio of externally procured parts. The product type under investigation is a complex, multicomponent tool available in different variants. Required components and modules are manufactured at different sites and distributed to the final assembly locations. Within the production process a critical punching machine has been identified which produces a range of parts each of which are required for multiple different products. The punching machine is thus regarded as a “supplier” for follow-up process steps. It batch-wise produces parts which are then shipped to the designated production facility. Risk should be measured as the potential loss in sales, indicating by how much the total sales revenue decreases due to machine or process disruptions. Hence, it is assumed that each time a machine or a process is disrupted alternative costs result due to lost production volumes.

Figure 4: Simplified simulation model - Use-case B

Consequently, the DES concept was applied to analyze the risk associated with a possible outage of the critical punching machine in terms of expected lost revenues. Analyses of
logistics performance, inventory levels, or lead times were not required. It is merely examined which and how many products are affected by different machine failure scenarios of different frequencies and durations. The simulation model is illustrated in Fig. 4. Basic input data is provided in Table 2.

Table 2: Basic input data use case B

| Input data                          | Values          |
|-------------------------------------|-----------------|
| Daily operating hours               | 24h             |
| Demand product A                    | 100,000 units/year |
| Market price product A              | €100            |
| Demand product B                    | 300,000 units/year |
| Market price product B              | €200            |
| Lot size per production order       | 100 units       |
| Processing time per lot             | 10.8h           |

Table 3: Simulation results use-case B

|                      | Mean loss in sales [€] | Std. deviation [€] | VaR of inventory costs [€] |
|----------------------|------------------------|--------------------|-----------------------------|
| Simulation 1         | 17,969                 | 24,676             | 46,648                      |

4. Discussion

In the previous sections the developed risk assessment concept was tested on two exemplary use-cases abstracted from actual industrial applications. Production processes of two different types of manufacturers and produced products have been modeled and analyzed regarding their exposure to different supply risks. These examples illustrate how the developed approach could be applied to assess an organization’s supply risk exposure to the demanded extent. In particular, the presented approach allows:

- Need-based process analyses due to model abstraction adjusted to the targeted risks and definable input and output information
- Decision making based on quantitative values under consideration of the entire range of possible risk scenarios

Customizable process models allow need-based analyses on different levels of detail. Besides production costs, inventory costs, and logistics indicators, supply risk costs are computed and visualized as distributions to capture a vast range of possible risk scenarios. Processes can thus be evaluated in terms of the three major targets of manufacturing: costs, time, and quality. Additionally, risk costs can be considered as a realistic estimation of the range of risk impacts is provided. In that way, optimal processes can be designed under consideration of the user’s readiness to take risk. Risk cost composition, moreover, is adjustable and can be limited to the factors of interest. In combination with customizable process models facilitating model building of varying levels of detail and scope, analyses can be adjusted to different analysis purposes and system characteristics.

However, capacity restrictions need to be taken into account in order to obtain unbiased results of expected risk costs. The mathematical model furthermore does not differentiate between stock-outs caused by supply risk or stock-outs occurring due to internal planning mistakes. Input data thus has to be carefully reviewed to be able to interpret simulation results. This is particularly true for input distributions as risk by definition is subject to uncertainty. Hence, simulation results do only provide an overview about the expected range of possible impacts but do not represent definite forecasts.

All in all, the developed approach facilitates a comprehensive analysis of an organization’s exposure to
supply risk and can be the basis for measure definition and may help to justify decisions or possible investments.

5. Conclusion

In this paper, we presented a flexible supply risk assessment approach using graphical process modeling and DES. Its applicability was demonstrated on two use cases before strengths and weaknesses were discussed. This approach addresses users in supply chain management, procurement, and business risk management.

The main objective of our research has been to develop a software based application allowing monetary supply risk quantification to support decisions makers in the field of procurement and production logistics. Applying a combined DES / MCS approach allows generating a holistic overview about the expected range of possible impacts of delay, quantity, and quality risks. Adequate mitigation measures can thus be defined and tested for economic feasibility under consideration under the user’s readiness to assume risk. Eventually, the main advantage of our solution is that our framework allows building of adjustable process models at the right level of detail to analyze the targeted risks and account for various types of manufacturers, strategies, policies, and analysis purposes. Yet, dynamically changing conditions, such as learning effects are not considered, as input distributions are static. Moreover, the scope is limited to risks along the supply chain. Interdependencies between supply, procurement, and demand risks have not yet been addressed.

Need for further research is seen in developing approaches providing support in specifying appropriate risk occurrence probability distributions, as uncertainty is high and the quality of simulation results strongly depends on the quality of defined model inputs. Using cybernetic business models could be a possible solution. Additionally, another idea is to additionally capture production and demand risks in order to consider the additional dependencies and provide a comprehensive overview of the entire risk situation in the context of production logistics.

The developed concept is currently being implemented in a custom software solution. An online web interface is accessible via [27] within the context of the research project SimQRi to provide a user-friendly graphic user interface and an efficient simulation engine allowing fast simulations.

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