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A Simulation-based Analysis of Supply Chain Resilience

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The increased interest in supply chain risk management (SCRM) is not only a consequence of recent natural disasters, but moreover the recognition that even small incidents can have a severe impact on the entire supply chain (SC). Instead of making high investments in eliminating every potential risk, it is much more appreciated to incorporate the concept of resilience in supply chain design and operations that provides the ability to reduce the consequences of disruptions and to reduce the time to recover normal performance. However, as resilience significantly increases the ability to adapt quickly and efficiently to changes in the environment, it comes along with an increase in costs in most cases. Moreover, achieving resilience in supply chains and agile response requires a holistic approach, which contributes to the complexity of decision making processes in supply chains. Since most of the researches has been discussed the resilience of supply chains from a qualitative point of view in the literature, there is a lack of research concerning the resilience from a quantitative perspective. In this context, the main purpose of this paper is to provide a simulation-based decision support framework for assessing supply chain resilience and evaluating the cost and resilience trade-off with different mitigation strategies in an uncertain environment. The decision framework incorporates the supply chain resilience metrics and argues their relationship to the impacts of those disruptions on the performance and to the time required for recovery.

Keywords: Supply Chain Resiliency, Simulation, Flexibility, Supply Contract

1 Introduction

Companies operating in today's business environment face various uncertainties that make it difficult to operate successfully as supply chain disruptions are occurring regularly (Glendon and Bird 2013). With the advancement in communication and transport technology enabling an international alignment, global supply chains were found to be a competitive advantage. As companies have been focusing on the reduction of costs and a fundamental growth, the access of cheap labor and raw materials, better financing opportunities, larger product markets, arbitrage opportunities and the attraction of foreign capital are a key to success (Manuj and Mentzer 2008). Likewise, the increased use of outsourcing of manufacturing and services to foreign suppliers intends to create cost advantages and enables the companies to focus on their core-competency (Norman and Jansson 2004).

The opportunities created by the globalization of supply chains are often accompanied by new supply chain challenges. Longer transport distances and lead times have been accepted to benefit from lower labor costs. The disadvantage of global supply chains is therefore the exposure to intercontinental risks and disruptions. As the network extends over the entire globe, the amount of links interconnecting a wide network of companies is growing numerously. The links are prone to disruptions, bankruptcies, breakdowns, and disasters, increasing the possibility for an unplanned event (Manuj and Mentzer 2008). More partnerships, as occurring in supplier relationships, can also lead to a loss of visibility, higher complexity, and less control for the focal firm in cases of disruption (Christopher

2011). Furthermore, as supply chains become more global, they are becoming more vulnerable to business disruptions and hence, they are usually slow to respond to changes (Tang and Tomlin 2008).

Between 2009 and 2011 the number of supply chain disruptions has risen by 465%, interrupting the flow of merchandise and leading to costs of \$350 billion (Langley 2012). An excellent example that shows how an enterprise suffers from a significant disruption is Ericsson's crisis in 2000: a fire broke out at Ericsson chip supplier plant leading to a production standstill of 2 weeks that finally caused an estimated loss of 400 Million Dollars because Ericsson had no backup sources. Similarly, Toyota was forced to shut down 18 plants for almost two weeks because of the fire in 1997 at Toyota's brake valve supplier. The costs caused by the disruption were an estimated \$40 million per day (Norrman and Jansson 2004).

The examples mentioned above show that even small incidents can have a severe impact on the whole supply chain. The challenge in risk management today is to avoid such incidents or reduce their negative impacts. Instead of making high investments in eliminating every potential threat, it is much more appreciated to increase the resilience of the supply chain to adapt quickly and efficiently to changes in the environment. Building a resilient supply chain is related to development of responsiveness capabilities through flexibility and redundancy (Rice and Caniato 2003). Recent studies found out that organizations with higher levels of flexibility are more capable of responding to unexpected events compared to inflexible supply chains (Swafford et. al. 2006). However flexibility comes along with an increase in costs in most cases as it increases the ability to adapt to changes. Thus, a match between flexibility and environment uncertainty

has to be found in order to create a cost-effective flexibility configuration (Merschmann and Thonemann 2009). This match is difficult to find in the first place as companies are struggling to determine the consequences of uncertainty and therefore the required degree of flexibility. As a result, there is a need for an approach to be capable of assessing risk exposure in order to implement the suitable extent of resilience, so that organizations can survive in a competitive business environment and succeed their strategies under uncertainty. This paper presents a simulation-based quantitative approach for assessing supply chain risks and evaluating the cost and resilience trade-off with different mitigation strategies in an uncertain environment. To be able to develop a decision support system, we propose a simulation-based framework that incorporates concepts of resilience into the process of supply chain risk management and design. In this context, resilience is defined as the ability of a supply chain system to reduce the time to recover normal performance under disruptions. To illustrate how the developed simulation model can be utilized to determine the resilience in the supply, a case study is presented.

2 Supply Chain Resilience

The high number of sources of complexity exposes the network to an increasing level of uncertainty, and the uncertainty level exposes the network to numerous kinds of events that may disrupt the course of their business. These events are usually random and have a probability of occurrence. They are disruptive, have a relevant impact on the performance and they are sometimes difficult to anticipate. Hence, risk is defined as an uncertain

event or a set of circumstances which, should it occur, will have an effect on the achievement of one or more objectives (Tuncel and Alpan 2009). Uncertainty can also be declared as the risk causing factor, which forms a changing environment, in which risky events may occur. Any risky event is defined as an event that is not known for sure ahead of time, but the risk itself is defined as the potential harm that may arise in future due to some present processes or some future events (Klimov and Merkurjev 2008). In particular, resilience has been used as an important characteristic to handle uncertainties in a supply chain and to respond to such major supply chain disruptions. In the literature, several terms are linked with resilience, such as, agility, flexibility, and robustness. According to Ponomarov and Holcomb (2009), resilience is "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at desired levels of connectiveness and control over structure and function". In contrast, robustness refers to the ability to endure changes in the environment without adapting (Asbjornslett 2008). Asbjornslett states that a robust system has the ability to absorb a disturbance while retaining the same previous state whereas a resilient system has the ability to adapt and achieve a new stable state. According to Swafford et al. (2006), agility refers "the supply chain's capability to adapt or respond in a speedy manner to a changing marketplace environment". Agility is unplanned and unscheduled adaption to unforeseen and unexpected external circumstances (Goranson 1999). In contrary, flexibility is scheduled or planned adaption to unforeseen and expected external circumstances. The concepts of flexibility and agility are therefore tightly coupled with supply chain resilience. Wieland and Wallenburg

(2013) for example divide supply chain resilience into agility, resulting from visibility and speed, and robustness, resulting from anticipation and preparedness. Christopher and Peck (2004) define agility as the third element of supply chain resilience. According to Longo and Ören (2008), the most important elements affecting supply chain resilience are: flexibility, agility, velocity, visibility and redundancy. Based on the literature review, Lotfi et al. (2013) illustrate some overlapping and non-overlapping practices/initiatives across robustness, agility and resilience.

Consequently, resilience can be achieved through robustness, flexibility and agility. In the context of robustness redundant capacity that may or may not be used is installed. It is additional capacity that would be used to replace the capacity loss caused by a disruption. In this regard, flexibility entails redeploying previously committed capacity (Rice and Caniato 2003). Moreover, instead of raising the claim of being prepared for every situation by creating a robust supply chain through comprehensive planning, it is much more appreciated to increase the flexibility of the supply chain to adapt quickly and efficiently to changes in the environment, because frequent plan adjustments in the analysis would be necessary in times of increasing environmental dynamics (Bretzke 2010). Sheffi and Rice (2005) claim that enterprises can increase their resilience by developing flexibility in supply and procurement. In other word, supply flexibility plays a critical role in supply chain resilience.

As the future performance of the entire supply chain depends significantly on the selected sourcing strategy and supplier management (Klug 2010), flexible supply contracts are presented next as a mitigation strategy in or-

der to create a resilient supply chain. Supply contracts coordinate materials and information flows between a supplier and a buyer. Different and often conflicting objectives can be accommodated through associating them with the right incentives (Tsay and Lovejoy 1999). In general, pricing, minimum purchase commitments, quantity flexibility, buy backs or return policies, allocation rules, lead time and quality can be issued in such contracts (Hennet and Arda 2008). Quantity flexibility can be specified in a supply chain contract that allows the buyer to adjust its order quantities after the initial order is placed. A buy-back contract (return policy) is a commitment by the supplier to buy back unsold inventory of the goods at the end of the selling season so as to induce the buyer to order more from the supplier (Hou et. al. 2010). Another form of flexibility in supply contracts includes capacity reservation, when the supplier is obligated to cover any request that remains within the upside limits (Cheng 2003). For undertaking the risk of guaranteeing to deliver any order amount desired by the buyer up to a reserved fixed capacity, the buyer offers guaranteed payment by making an obligation to buy a certain unit of capacity every day. Even if the buyer does not fully utilize the reserved capacity, he will pay for it (Xu 2006). Another proposed resilience strategy to mitigate disruption is multiple sourcing and safety stock (Iakovou et al. 2007). However, these strategies have not simulated or implemented under disruptions.

One challenge question in supply chain management is how to assess the resilience. A significant disruption initiated by a triggering event influences the company's performance in many ways. The process of a disruption can be categorized in different phases as it is illustrated in Figure 1. The impact

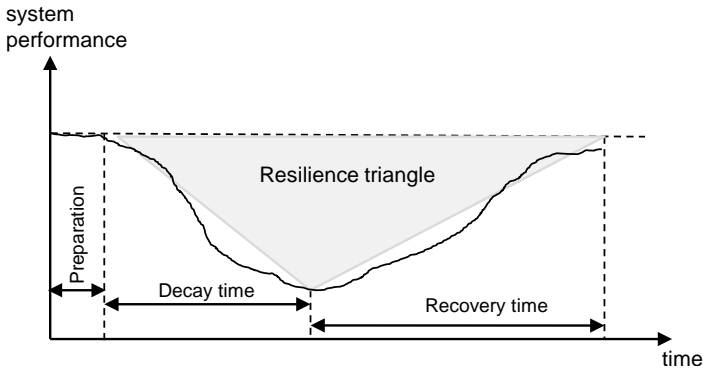


Figure 1 The stages of a disruption

is caused by a disruptive event, for instance the start of a labour strike or the explosion of a facility.

The normal operations are affected immediately, as contingency plans are implemented in the first place to prevent further damage. While some impacts are propagating through the value chain, the full impact is revealed by a short delay. During this time preparations for recovery typically start parallel in order to continue production and resume operations as soon as possible (Sheffi and Rice 2005).

3 Risk Assessment in Supply Chains by Using Simulation

A typical process of risk management is divided into four steps: risk identification, risk assessment, risk treatment and risk monitoring (Hallikas et. al. 2004). The aim of risk identification is to recognize the future uncertainties

and the potential risks surrounding the supply chain (Güller et al. 2015). The risk assessment stage defines the consequences of these risk events defined in the first step in order to give a clear view of all risks.

In the third stage, the most suitable mitigation options are to be implemented to reduce either the occurrence probability or the degree of severity of the pre-identified risks' consequences. The last stage of the process is the risk monitoring where risks are monitored to define variations in their probability or consequences (Hallikas et. al. 2004). Besides the definition and scope of risk management, it is also important to identify the measurement technique used in evaluating and assessing risk issues (Güller et al. 2015). In the literature, risks are measured based on qualitative and quantitative techniques. Measuring risk in a qualitative way is the most commonly used approach and only a quarter of the researches apply a quantitative method (Ghadga et. al. 2010). It is obvious that there is a lack of simulation-based quantitative approaches for assessing supply chain risks and analyzing supply chain resilience (Güller et al. 2015).

In the risk treatment phase, the improvement through reconfiguration of the supply chain cannot be examined with the common risk management methods, because a feasibility check is missing in the first place. In other words, the effect of possible mitigation strategies cannot be measured until they are selected during risk treatment and implemented in the real system. By estimating the potential costs and integrating them via the HTP-method, an approximate performance audit is feasible, when comparing them with the estimated impact of the risks. What remains characteristic for the qualitative methods are the vague results in the end as they are all based on subjective estimations instead of quantitative data. That is also

the main problem in risk monitoring and the reason why the requirement of control is not met at all. After the selected mitigation strategy is implemented, it is impossible to assess if the risk has been eliminated, because it remains unknown how the changed system will react to a risk event that has not occurred yet.

Discrete-event simulation exactly begins at this point where common qualitative methods struggle the most. It addresses the problem of quantitative data and also offers the opportunity to perform what-if analysis on the basis of a model of the real system. Therefore the findings of the observed behavior of the model can be transferred on the real system. This includes the assessment of the risk level, which can be measured precisely in terms of cost and performance data by simply implementing the risk event in the model. Besides, different mitigation strategies worked out by the operator can be implemented in the model as scenarios, supporting the operator with making a decision as the scenario with the best results in performance can be selected afterwards. By experimenting with different configurations of the supply chain in order to find the optimal mitigation strategy, the feasibility of different strategies also becomes apparent. Bottleneck analysis is particularly interesting in this context, because it indicates where work-in-process, information, materials etc. are being excessively delayed, causing an unstable environment. In summary, simulation as a quantitative method can particularly support the SCRM in the fields of risk assessment and risk treatment. The risk events and disturbances can be simulated virtually in a model environment in order to be able to compare the cost and performance data with and without mitigation strategies.

4 Simulation-based Decision Support Framework for Supply Chain Risk Management

The aim of this section is to build an approach that is capable of ensuring the correct solution in risk treatment based on a quantitative risk assessment. As discrete-event simulation does not support the entire SCRM process, methods in the field of risk identification and risk monitoring should be combined with simulation. Therefore, in order to guarantee the goals of SCRM throughout the simulation study, the very same process should be implemented in the simulation study process.

Risk identification is integrated in the first phase preparation of the simulation study. Both phases show similarities and harmonize well as it is important to first limit the scope of the system that is to be modeled. Furthermore, the critical parts of the supply chain are determined with the help of a portfolio in order to clarify the initial situation as it is important that the problem has been clearly understood. Now that the content of the future simulation model is known, cost and performance data is defined as the target system of the simulation study. Furthermore the goals of the simulation study are formulated and the questions that are to be answered as well as the data requirements are determined. Additionally to the common input, the probabilities, duration and manifestation of the risks have to be defined. Once the data is collected, analyzed and the random variables are determined as well as the distribution functions are fit and the constants are selected, the simulation model can be developed based on the supply chain map that was defined in the beginning.

With the completion of the simulation model, the actual simulation study can begin by defining a test plan. As the study is divided up into the two

parts assessment and treatment, the test plan also consists of the two parts that are defined separately. The research questions formulated in the preparation phase are usually investigated in the second part. In risk assessment, every risk is examined individually and if more than one risk factor exists, they should be studied individually as well. This is important as risk assessment is about determining the risk level of each individual risk in order to enable outright prioritization without interdependencies, so that conclusions can be drawn for risk treatment.

Risk assessment is about getting a feeling of how the real system currently reacts to certain planned events in different kind of ways. It is not about improving the system, but about determining the actual status as a preparation for the development of mitigation strategies. This is why the collected results should be evaluated with the help of graphical representations after the simulation runs have been carried out and before risk treatment takes place. That way, the simulation analyst gets a good overview on the different risks and it is easier to make comparisons. The most common graphical editing is to display the disruption curve with the help of the β -service level in a line graph, which is most suitable to illustrate the extent on the customer. Once the risks have been evaluated individually, whatever risks cause the longest delay, the worst service level or the most costs for example, are selected for risk treatment.

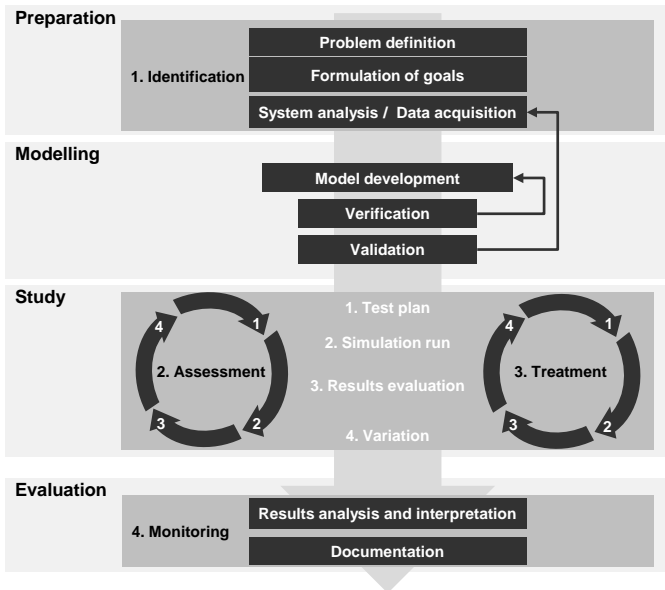


Figure 2 New SCRM simulation study approach

The goal of risk treatment is to find an overall optimum configuration of the supply chain in order to be able to handle the different risks in the best way. Similarly to risk assessment, it is recommended to also simulate the risk categories separately, but with all risk factors turned on. Additionally to these scenarios, the risk probability and duration should be varied, so that the effectiveness of the mitigation strategies can be fully assessed. More than in risk assessment, risk treatment is an iterative loop, because simulation is not a decision-making tool, but a decision support tool, which means that in order to find the optimal configuration, a loop has to be built

as described in Figure 2. Instead of the graphical analysis in risk management, it is advisable to evaluate the results with the help of total costs in order to find a global optimum, because nearly every KPI can be included. This is done with the help of penalty costs. As every scenario consists of different risks, this is done for all the scenarios defined in the test plan. As soon as a decision has been made for one solution in each scenario, risk treatment and the simulation study are over and the last phases evaluation and risk control begin.

In evaluation, the analysis and interpretation of every simulation result takes place. The result for every scenario or in the other words, the output data for every risk is analyzed. By comparing the results of the different risks, especially with regards to a scenario with the combined risks, conclusions are drawn with regards to the mitigation strategies and compressed statements are made. Hence, the interpretation is based on the detailed analysis of the varied parameter of the simulation model. The outcome is the determined configuration of the modeled supply chain that can be transferred to the real system.

In contrast to the qualitative methods, specific basic data can be stated like total costs, the required extent (e.g. number of supplier and quantity per supplier), savings and performance data (e.g. service-level, cycle time etc.) The acquired data also changes the purpose of the risk monitoring phase compared to the common approach, if the modeling of the simulation and the experimentation with the model has been done correctly up to here. Corrective actions will not be necessary as long as the simulation model operates in the scope of the real system, since the mitigation strategies have already been tested when experimenting with the model.

5 Case Study and Simulation Results

In the following, disruption curves due to supplier failure and demand volatility will be investigated exemplary. As a case study, the supply chain of an original equipment manufacturer (OEM) from the automotive industry in Germany is selected. The suppliers of the factory are spread all over the world. In the test plan, the scenarios are made up of different strategies such as JIT-Concept, inventory, multiple sourcing and flexible supply contracts. The JIT-concept is the base case of the model as waste is avoided through single sourcing and no inventory. The processes are efficient in order to cut down costs. The other configurations build in reserves in terms of inventory, multiple sourcing or standby suppliers (flexible supply contract). The flexible supply contract means that a certain amount of capacity is reserved each day, which can be used in case of a disruption, but that is paid for every day. First, the impact of demand volatility is shown. The total standard deviation was increased tenfold resulting in a higher number of extreme situations like days with almost no demand, or days on which demand is almost doubled with an overall average demand that stays virtually the same. In the base case JIT-deliveries, this does not lead to a significant drop in the service level as long as it does not happen several times in a row. But once the service level has dropped to zero, it will take time until the system has recovered itself depending on how much demand has to be covered at the bottom.

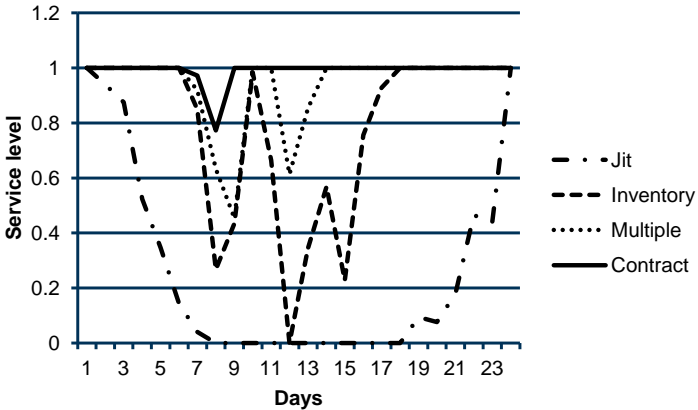


Figure 3 Disruption curves due to demand volatility

Figure 3 shows one of two longer disruption curves that occurred during the simulation run. This one occurred, because a very high demand had to be served in the beginning of the curve leading to eleven days with service level zero, because none of the products can be supplied on time. Unlike a disrupting event, the recovery phase depends on whether there will be additional days with very high unusual demand. As this is not the case during the last ten days of the curve, recovery can take place. With one day of inventory on hand, the disruption can be delayed until the seventh day. The spikes in the other curves come from peaks in the daily demand that were not visible during JIT-delivery, because the service level already dropped to zero. As the demand can be distributed on more than one

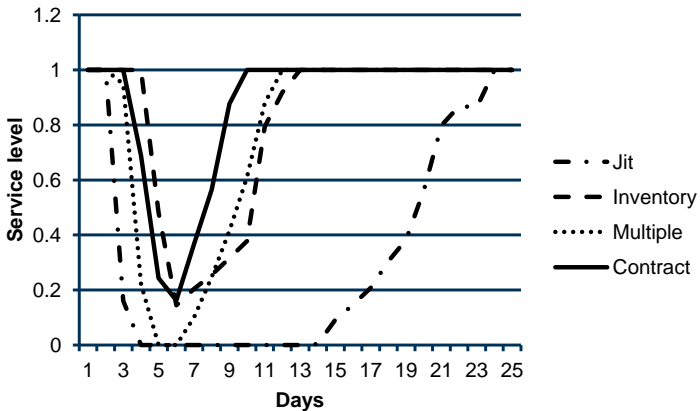


Figure 4 Disruption curves triggered by diminished capacity

supplier, the spikes in the service level are not as big, because additional capacity is available each day. The smallest drop in the service level is achieved through the flexible supply contracts. The impact of peaks in the daily demand is lessened through the flexible allocation of the backorders from the previous day on the standby supplier instead of maintaining the boundaries of common multiple sourcing, where backorders are not transferred from one supplier to another.

Figure 4 displays the different disruption curves according to the service level, when the capacity of a supplier for the steering columns is reduced by 50% for five days. The disruption happens on the second day of the curves resulting in an immediate drop to 20% service level in the base case on the next day. As there is 50% of the capacity left, the customer orders of the day of the disruption can be fulfilled the next day, so that they are still on time. All the other curves are shifted to the right and can recover faster.

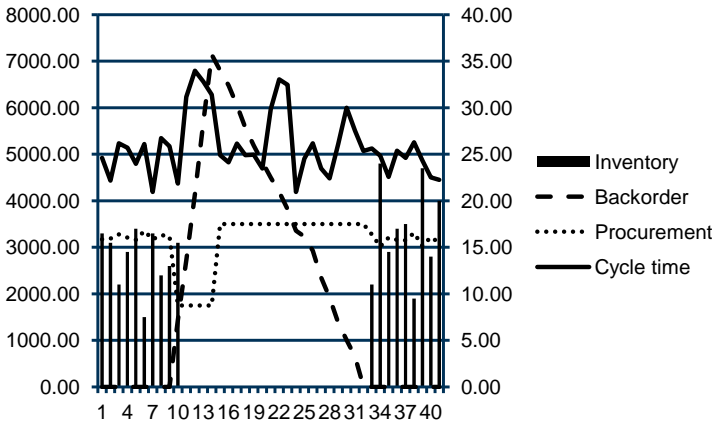


Figure 5 Performance data of a customer and supplier

With one day of inventory, the disruption can be absorbed for three days. Only the last two days make an impact resulting in a drop to 14%.

An explanation can be given by Figure 5 that describes causal relations of the individual performance data. It displays the level of inventory, the amount of backorders and the procurement volume of the disrupted supplier (all primary axis) and an exemplary cycle time for a customer (secondary axis). With the help of inventory, day one and two can be served completely as the supplier is able to supply one day of demand while the inventory is used up. On day three, only half of the demand can be satisfied, leading to a series of longer waiting times. As the modules supplied on the next day are used for the rest of the orders from last day, all customer orders are late from now on, because the backorders are building up until the capacity of the supplier resumes back to 100%.

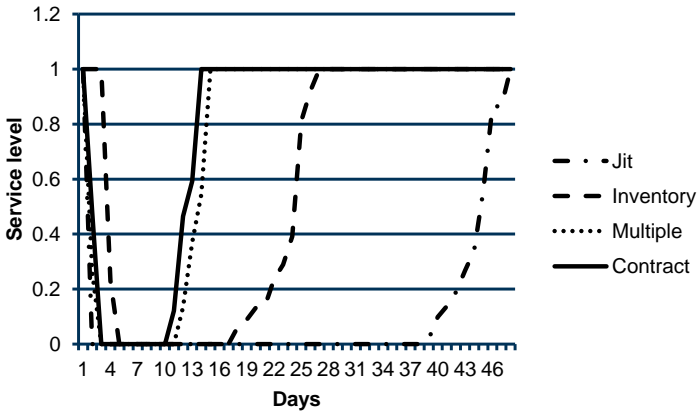


Figure 6 Disruption curves due to complete supplier failure

Since the supplier can only use the rest of the capacity that is not needed for new customer orders for the reduction of back orders, the curve only comes down slowly while maximum order quantity is ordered continuously for 16 days in a row. As this means that not enough modules are supplied (backorders still exist), it results in additional peaks in cycle time depending on which customer order has to wait for the modules. Only once the backorders are back to zero, the system returns to a normal state as inventory is building up again and the procurement volume only includes the daily demand. The effect is intensified in case of complete supplier failure, because there is no capacity available at all for five days (Figure 6). The configuration of the supply chain differs slightly compared to the diminished capacity in order to be able to cope with the increased impact. As only half of the capacity is disturbed in the first one, 10% are distributed to the continuing 2nd supplier compared to 25% in case of complete supplier failure.

Same goes for the flexible supply contract with 500 and 1000 reserved modules per day. This is the reason, why compared to the base case, the service level does not go down to 0% immediately on the day of the disturbance as some remaining capacity is left due to the second supplier to at least fulfill part of the customer orders on the second day. The additional capacity also helps the system to recover more quickly, because less back orders have to be caught up with. It is not sufficient though to keep up a low service level as the orders are processed later and later the longer the disturbance continues. Furthermore, the flexible supply contract has the advantage of fully distributing the demand flexibly on the available capacity. The two days of inventory help to absorb the impact as described before, but the recovery takes just as long as in the base case, because there is no additional capacity available. This also explains why five days of no capacity lead to 37 days with a service level of zero, as 46 days are needed to equalize the number of back orders, because new demand is continuously generated and no additional capacity is available.

6 Conclusion

The negative consequences which a company is confronted with in the course of an incoming supply chain risk depend on the features of the risk event on the one hand and on the design of the supply chain on the other hand. Both parameters have a significant impact on the vulnerability of a supply chain, which depends on numerous factors. Therefore, resilience is becoming an ever more important feature of supply chains to overcome their vulnerabilities and to react effectively to negative effects of risks.

Qualitative methods are not adequate, because they require an aggregation level that today's complex structures do not fit in. As a result, today's complex system has to be mapped in a simulation model in order to be able to perform a sufficient risk and resilience assessment.

As most of companies are struggling to perform simulation studies in practice due to the uniqueness and individuality of simulation technique, a new approach was specifically developed for SCRM. Simulation has been proven to be a suitable tool to analyze supply chain resilience to different strategies. Simulation is anticipating how the newly configured system will react to certain risk events within an experimental environment, which is the only alternative to an implementation in the real system and measuring the impact in the operative business. Herby, the difference of ignoring the risk and investing in mitigation strategies becomes apparent, which is not achievable in practice. If everything goes smoothly, the implication of risk will be absorbed by mitigation strategies and the benefits remain unclear. This is very useful as it enables performance audits and feasibility studies, which can be used in order to find a perfect match between resilience and uncertainty.

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