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Adequate Flexibility Potential to handle Supply Chain Uncertainties

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Risks and uncertainties (e.g. IT-system failure or demand fluctuation) threaten the performance of supply chains. This paper gives insight into the planning of flexibility potential as a crucial tool for managing the consequences of operational and disruptive uncertainties. A simulation study of lot-sizing decisions in a two-stage decentralised supply chain is used. The modelled supply chain faces operational as well as disruptive uncertainties. It is analysed how capacity and/or stock flexibility on each stage cope with unexpected events. The location of flexibility within the supply chain is key for its ability to handle uncertainties. The paper shows that stock flexibility can substitute capacity flexibility to a certain degree. However, disruptive uncertainties cannot be handled by stock flexibility alone. Therefore, trade-offs in flexibility potential have to be considered. In contrast to other studies, this simulation models operational and disruptive uncertainties in three areas: internal processes, supply side and demand side. Also flexibility management in a decentralised decision making process is analysed. Contrary to the lean thinking approach it is shown that inventory plays an important role in managing uncertainties. Therefore, management should use the right amount of inventory to create flexibility depending on the individual risk situation.

Keywords: Uncertainty; Supply Chain; Flexibility; Simulation Study

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1 Introduction

Globalisation, digitalisation and new technologies change the processes of value creation. As a result, global and complex supply chains can be observed (Meixell and Gargeya, 2005). The scale of these value creating networks makes them vulnerable (Peck, 2005; Peck, 2006). They are not only affected by unexpected events geographically near to the final consumer but also by incidents that occur on the other side of the world (Simangunsong et al., 2012). Examples for such events are the eruption of the volcano Eyjafjallajökull on Iceland in 2010 or an earthquake in Taiwan (Papadakis and Ziemba, 2001). In addition to those low-probability/high-impact risks operational uncertainties jeopardize supply chains (Tang and Tomlin, 2008; Sodhi and Tang, 2012). The focus on efficiency has led to supply chains which are not able to compensate even small disorders like delayed delivery or fluctuation in production rates and consumer demand (Craighead et al., 2007).

The literature on supply chain risks and uncertainties mentions different approaches to handle unexpected situations. Thus, a supply chain should be robust, resilient and agile (Naylor et al., 1999; Christopher and Peck, 2004; Klibi et al., 2010). The importance of each aspect depends on the individual circumstances of a supply chain (Cabral et al., 2012). However, all three concepts need flexibility to be utilised (Zitzmann, 2014; Zitzmann, 2016). It is the key ability to handle risks and uncertainties in supply chains and to use opportunities which emerge from unexpected situations.

Regarding flexibility management and flexibility in supply chains many research questions can be explored (Stevenson and Spring, 2007). The focus of this paper is to look into planning flexibility potential. In particular, we aim to give answers on the following questions: Where in the supply chain is flexibility needed? How can capacity and stock flexibility substitute each other?

This article is structured as follows. First, we provide background information on risk and uncertainties in supply chains as well as on flexibility and its creation. Subsequently, in the methodology section a simulation study is introduced. Section 4 presents the results of the simulation study and discuss its implications. The final section summarises the findings of the paper.

2 Review of Relevant Literature

This paper builds on existing literature regarding risks and uncertainties as well as flexibility in the context of supply chains. First, the terms risk and uncertainty will be distinguished in section 2.1 as they are often used interchangeably. Afterwards, section 2.2 will consider the complex concept of flexibility, especially flexibility in supply chains. How flexibility can be created will be the subject of section 2.3

2.1 Risk and Uncertainties in Supply Chains

Making decisions under uncertainty is part of every management process and therefore in supply chain management as well. Uncertainty can be described as inability to predict something (Milliken, 1987). The term risk is often used interchangeably with uncertainty, but they differ. Figure 1 shows two opinions how the terms can be distinguished. In both cases, uncertainty encompasses more than risk. According to decision theory, risk and uncertainty can be differentiated according to their predictability. If it is possible to quantify a probability of occurrence, it is called risk; if not it is called uncertainty (Knight, 1971). The second approach, which will be followed in this paper, considers the consequences of uncertainty. If they are positive, they are called chances; if they may be negative, then they are risks (Simangunsong et al., 2012).

The literature review of Simangunsong et al. (2012) identifies 14 sources of uncertainties in supply chains which can be classified into three groups: within an institution of a supply chain, within the regarded supply chain, or external to the value creating network. Chopra and Sodhi (2004), Jüttner (2005), Tang and Tomlin (2008), Sodhi and Tang (2012) as well as Tiwari et al. (2015) also identify these sources of uncertainties for supply chains.

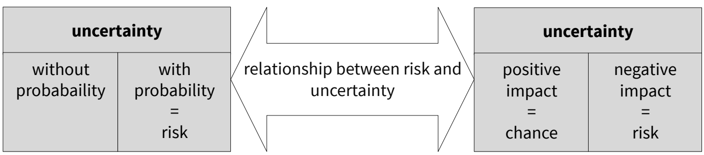

Figure 1: Relationship between risk and uncertainty

The focus of this paper is flexibility in supply chains and its ability to handle uncertainties, and not about reducing uncertainties, as it is done in (supply chain) risk management. Therefore, more important than the sources of uncertainties are their impact on the supply chain. According to their magnitude it can be distinguished between operational and disruptive uncertainties (Chopra and Sodhi, 2004; Tang, 2006; Tang and Tomlin, 2008; Sodhi and Tang, 2012):

Operational uncertainties are inherent fluctuations in the processes of a supply chain, e.g. uncertain customer demand, variations in production rate or delays in transportation. Uncertainties are operational when fluctuations are limited to a certain range around an average value.

Disruptive uncertainties refer to events with major impact on the supply chain. These are natural or man-made disruptions that happen rarely like earthquakes, floods, terrorist attacks or machine breakdowns. Their consequences for the supply chain are massive and cannot be predicted to a certain degree.

Operational as well as disruptive uncertainties can result from the sources mentioned previously and can affect the flow of goods, information and finance within a supply chain. This paper considers the flow of goods and how flexibility can handle the impact of emerging uncertainties. Usually, no organisation exists that manages the whole supply chain. Therefore, decisions about flexibility management are made on the institutional level (Lummus et al., 2003). Taking this viewpoint, supply chain uncertainties have impact on three different areas: the supply side, the process of value creation within the regarded institution itself and the demand side (Chopra and Sodhi, 2004; Tang and Tomlin, 2009). Even a single source of uncertainty can lead to consequences in more than one area, e.g. the breakdown of a machine is an uncertainty located within the manufacturing process. When it happens in the regarded institution, it affects the process of value creation. The supply process is affected when the breakdown occurs at the side of a vendor. Natural disasters which are external uncertainties often affect all three areas of uncertainty impact. An earthquake may not only destroy factories as well as streets and therefore, endanger the supply and manufacturing process, it also affects the demand side.

2.2 Flexibility in Supply Chains

According to Garavelli (2003), “[…] flexibility reflects the ability of a system to properly and rapidly respond to changes, coming from inside as well as outside the system […]“. As supply chains are the considered system in the context of supply chain flexibility, this definition shows that flexibility is a suitable instrument to handle uncertainties which may be internal or external to a supply chain (Tang, 2006). Flexibility is topic in economic and organizational literature as well as in the context of manufacturing (Sethi and Sethi, 1990; Jain et al., 2013). So far, a holistic flexibility theory does not exist (Yu et al., 2015). Sánchez and Pérez (2005), as well as Garavelli (2003), summarize the aspects of flexibility according to six dimensions. These include functional, hierarchical, measurement and strategic aspects as well as the time horizon and the object of change. Different approaches exist on how flexibility may be achieved. The models of Vickery et al. (1999) and Duclos et al. (2003) are the most common concepts (Singer, 2012). Due to a more process orientated view, the latter is more suited when looking at supply chains.

The dimensions of Duclos et al. (2003) as well as the attributes of other approaches (Pujawan, 2004; Kumar et al., 2006; Stevenson and Spring, 2007; Manders et al., 2017), describe features of a flexible supply chain. They also explain what these dimensions are used for, yet no guideline is given how planning flexibility works and how the right scale of flexibility is established. Also, these categorisations and frameworks do not solve some of the major issues in managing flexibility. There is still the problem that no independent measure for flexibility exists (Stevenson and Spring, 2007). Due to multiple dimensions, indicator systems have to be applied to measure flexibility. These indicators cannot be used universally but rather have to be developed for each regarded system individually. Therefore, they are subjective and situational (Gerwin, 1993; Koste et al., 2004). Additionally, it is not possible to determine the benefit of flexibility in advance (Jain et al., 2013). Only in retrospect the contribution of flexible components to the supply chain performance can be evaluated.

flexibility potential	
strategic flexibility = redundant capacity	operational flexibility = redundant stock

Figure 2: Flexibility potential

Planning flexibility on a strategic level means creating potential through additional capacity in the regarded system. Thus, we describe it as capacity flexibility. It may be established by an additional production line, spare transportation vehicles or a multiple instead of a single sourcing concept. Alternative or additional to strategic flexibility capabilities flexibility potential can also be created on the operational level. This operational flexibility is established through stock flexibility (Vickery et al., 1999; Wang, 2008). Thereby, a certain amount of inventory is hold on purpose to react to uncertainties. Safety stocks are an example of flexibility created by inventory. Thus, flexibility potential can be created by capacity or stock potential as shown in Figure 2. What kind of flexibility is more useful in a supply chain to handle uncertainties and where it should be established is considered in the simulation study in section 3 and 4 of this paper.

3 Simulation

As we look at situations where operational as well as disruptive uncertainties may occur at multiple places within a supply chain an analytical analysis is not possible. To investigate if capacity and/or stock flexibility are adequate approaches to handle uncertainties in supply chains we therefore conducted a simulation study. The supply chain considered in the study is introduced in section 3.1, whereas, the modelling of strategic and operational flexibility in the supply chain is explained in section 3.2.

3.1 Two-stage Supply Chain as Object of Analysis

A two-stage supply chain is the object of the simulation. Its structure is based on the supply chain introduced by Banerjee (1986). The author analysed joint lot-sizing in a producer-retailer relationship. This case will be modified to the purpose of the simulation study. Figure 3 summarises the structure of the modelled supply chain. Additional to Banerjee's case a transportation process is added. Hence, the modelled supply chain includes three processes: The first one is the production of goods at the place of the producer that is followed by the transportation process. Thereby, the finished goods are carried from the warehouse of the producer to the warehouse of the retailer. The third modelled process of the supply chain is the customer demand which is satisfied at the place of the retailer. In this supply chain the producer as well as the retailer determine their individual lot size which will then be produced and transported. The planning as well as the execution process is rolling and consists of six periods. In each period with the length of a month decisions about production and order sizes have to be made. In all three processes of the supply chain operational and possibly disruptive uncertainties exist. The study analyses the effect of capacity as well as safety stock to handle such uncertainties.

Operational uncertainties are modelled with the help of probability distributions. In all three processes – production, transport and demand – the production and transport performance or request for goods can differ from the average rates. In production as well as in transport triangular distributions are used. Table 1 presents the basic parameters with operational uncertainties used for the simulation model.

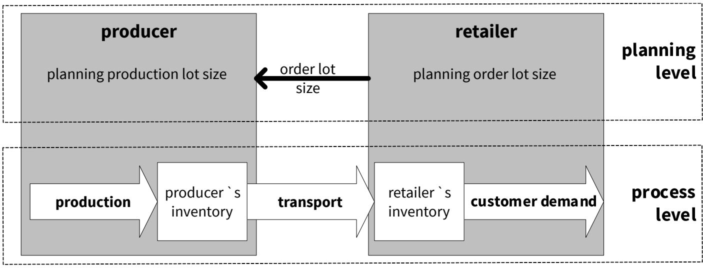

Figure 3: Supply chain of the simulation study

Table 1: Model parameters including operational uncertainties

Parameter	Value (Explanation)
Production time	Triangular distributed, mode 36 minutes/piece, lower bound 32.4 minutes/piece (-10 %), upper bound 54 minutes/piece (+50 %)
Warehouse capacity (producer or retailer)	unlimited
Transportation time	Triangular distributed (-10 %/+50 %): mode 120 hours, lower bound 108 hours, upper bound 180 hours/piece (e.g. 1 month for carrying goods from Asia to Europe by ship)
Demand	Normal distributed: mean 100 pieces/month, S.D. 20 pieces/month, lower bound 0 pieces/month

Additional to operational uncertainties disruptive events are possible in some simulation models. They are also modelled in all three processes. Within production and transport disruptive uncertainties will lead to an interruption of the respective process. The nature of unexpected events is that their occurrence cannot be predicted. Nevertheless, they happen. Table 2 explains possible disruptive events for the different supply chain processes.

Table 2: Model parameters regarding disruptive events

Event	Probability	Impact
Production interruption	0.1 %/hour	Interruption for a uniformly distributed length of at least one day (6 working hours) up to 10 days (60 working hours)
Transportation interruption	0.1 %/hour	Interruption for a uniformly distributed length of at least one day (6 working hours) up to 10 days (60 working hours)
Unexpected demand peak	0.05 %/hour	Uniformly distributed demand from 120 % up to 200 % of the actual demand of the period
Unexpected demand drop	0.05 %/hour	Uniformly distributed demand from 0 % up to 80 % of the actual demand of the period

We assume minimum costs for the retailer at an order size of 80 pieces/shipment. Depending on the disposable inventory in its warehouse and the expected demand in two months the retailer will therefore order nothing or a multiple number of the lot size every month. The order must be placed two months in advance because of the production and transport time. The producer uses the order quantities of the retailer and its own disposable inventory to decide if production is necessary or not. When production is started the production lot size is 200 pieces.

3.2 Modelling Flexibility Potential in the Supply Chain

Flexibility potential can be created at four points in the observed supply chain. In two cases it is capacity flexibility and the others are stock flexibility, which are implemented in the simulation model according to Table 3.

The first point for capacity flexibility is the place of the producer. If uncertainties occur the flexibility potential can be used to compensate them. The transportation process is the second point where capacity flexibility can be integrated in the process. Stock flexibility can be created in both, the producer's and the retailer's warehouse. In this case a certain level of additional inventory is defined. It is used as safety stock to handle unexpected events and uncertainties. The producer as well as the retailer have to consider the defined level of safety stock within their planning process. That is done by reducing the disposable inventory by the amount of additional inventory.

Table 3: Flexibility potential in the simulation model

Event	Probability	Impact
Production	Reduction of production time by 33 % = average production capacity increases to 300 pieces/month (additional production lines and work force)	Safety stock: 20 % of the average demand (= 20 pieces)
Transportation	Reduction of transportation time by 33 % (faster ship or use of an alternative means of transportation)	–
Demand	–	Safety stock: 20 % of the average demand (= 20 pieces)

Producer and retailer can use capacity and stock flexibility. Nevertheless, it is also possible to use just one kind of flexibility potential or none at all. Therefore, 16 alternative combinations of creating flexibility potential are possible in the observed supply chain. For each of them a simulation model was created. Additionally, we distinguish between situations where only operational uncertainties exist and such where operational as well as disruptive uncertainties occur. This differentiation leads to additional simulation models. The models -1- to -16- are regarding operational uncertainties alone, whereas the models -17- to -32- consider operational as well as disruptive uncertainties. Each model will run for 10,000 iterations. Supplementary to the 32 supply chain configurations we model a supply chain with no flexibility potential and no uncertainties. This deterministic model (-0-) is used to verify the correct modelling.

4 Results and Findings

To analyse what kind of flexibility is best to handle uncertainties in the regarded supply chain and at which process it should be created a performance index is needed. As the purpose of a supply chain is to match supply with customer demand we will use hours with out-of-stock situations at the retailer as performance indicator for the whole supply chain. The simulation calculates the performance within six periods which are 720 working hours (6 hours per day). We use this time as basis to calculate the service level. As the focus of the study is on the benefit and location of flexibility, we do not consider the costs of implementing flexibility (Tang and Tomlin, 2008).

Since there are no uncertainties in the deterministic model -0- the demand can always be satisfied (service level = 100 %). Such a situation with no uncertainties is not possible in a real world supply chain.

Section 4.1 presents the performance of the supply chain with uncertainties. The implications of the results are explained in section 4.2.

4.1 Simulation Results

Figure 4 shows the performance of the supply chain with operational uncertainties (flexibility configurations -1- to -16-) The amount of hours with out-of-stock situations given in Figure 4 is the mean of 10,000 iterations.

With a mean of 70 hours of out-of-stock situations, the performance of a supply chain with operational uncertainties and no flexibility at all (-13-) is the lowest. Thus, the service level is 90 %. The highest service level of 97 % can be achieved in the models -7-, -8- as well as -11- and -12-. These configurations have in common that capacity flexibility in the transportation process and stock flexibility at the retailer exists. This is the first indication that the other forms of flexibility are not as important. Especially stock flexibility of 20 % at the producer has low benefit to handle uncertainties in the supply chain. The service level of model -14- which simulates a situation where only this kind of flexibility exists is just 1 % above model -13- with no flexibility at all.

Comparing simulations with and without stock flexibility at the place of the producer but otherwise similar configurations (e.g. -1- with -2-, -3- with -4- or -15 with -16-) confirms the small benefit of stock flexibility at the producer.

Simulation model	Capacity flexibility– producer	Capacity flexibility– transport	Stock flexibility – producer	Stock flexibility – retailer	Out-of-stock situations	Service level
-1-	X				65	91 %
-2-	X		X		63	91 %
-3-	X			X	27	96 %
-4-	X		X	X	26	96 %
-5-		X			45	94 %
-6-		X	X		43	94 %
-7-		X		X	23	97 %
-8-		X	X	X	21	97 %
-9-	X	X			42	94 %
-10-	X	X	X		45	94 %
-11-	X	X		X	21	97 %
-12-	X	X	X	X	23	97 %
-13-					70	90 %
-14-			X		67	91 %
-15-				X	31	96 %
-16-			X	X	30	96 %

Figure 4: Supply chain performance with operational uncertainties (mean out of 10,000 simulation runs)

The same can be said about capacity flexibility of the producer. Comparing the models -2- with -14-, -4- with -16- or -6- with -10- the service levels are identical. These configurations only differ in the regard of capacity flexibility at the producer. In models that have this flexibility the amount of out-of-stock hours is lower. Therefore, it can be noted that capacity flexibility helps to handle uncertainties. However, the benefit is equally small like the one of stock flexibility at the producer. In both cases the reduction of out-of-stock hours does not affect the service level. It only changes compared to a supply chain with no flexibility potential.

The kind of flexibility that increases supply chain performance the most is stock flexibility at the retailer. In this simulation model (-15-) a service level of 96 % can be achieved. That is just 1 % below the highest level of models that consider operational uncertainties alone.

The results of the supply chain with operational as well as disruptive uncertainties simulated in the models -17- till -32- can be seen in table 4.2. Again, with one exception the service level does not change when stock flexibility at the producer exists or not (e.g. comparing -17- with -18; -19- with -20- or -31- with -32-). This statement also applies to the comparison of a situation with no flexibility potential and stock flexibility at the producer alone. Overall, the analyses of situations with operational and disruptive uncertainties together confirm the findings regarding stock flexibility at the producer that were made by analyzing service levels when only operational uncertainties exists. The results of table 4.2 also confirm that the capacity flexibility in transport together with stock flexibility at the retailer lead to the highest service levels (95 % or 94 %). Regarding capacity flexibility at the producer the results of table 4.2 differ from them in table 4.1. The performance of models without this flexibility potential (e.g. -29- till -32-) is nearly as good as in models with capacity flexibility at the producer (-17- till -20-). Therefore, it can again be noted that capacity flexibility at the producer does not play an imported role by handling uncertainties.

Simulation model	Capacity flexibility– producer	Capacity flexibility– transport	Stock flexibility – producer	Stock flexibility – retailer	Out-of-stock situations	Service level
-17-	X				97	87 %
-18-	X		X		94	87 %
-19-	X			X	52	93 %
-20-	X		X	X	51	93 %
-21-		X			74	90 %
-22-		X	X		69	90 %
-23-		X		X	46	94 %
-24-		X	X	X	41	94 %
-25-	X	X			63	91 %
-26-	X	X	X		63	91 %
-27-	X	X		X	40	94 %
-28-	X	X	X	X	39	95 %
-29-					104	86 %
-30-			X		98	86 %
-31-				X	58	92 %
-32-			X	X	57	92 %

Figure 5: Supply chain performance with operational and disruptive uncertainties (mean out of 10,000 simulation runs)

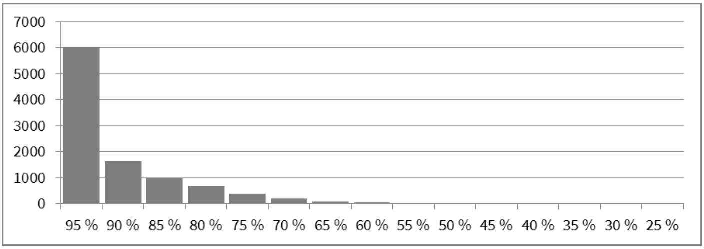

Figure 6: Achieved service level in 10,000 simulation runs in a supply chain with operational uncertainties and no flexibility

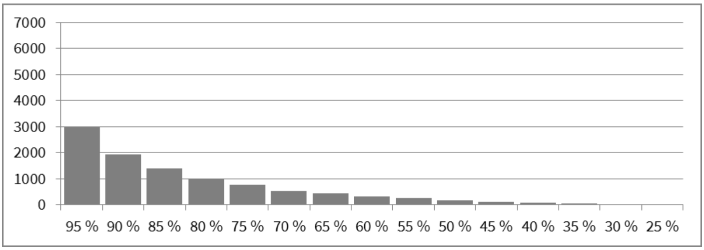

Figure 7: Achieved service level in 10,000 simulation runs in a supply chain with operational and disruptive uncertainties and no flexibility

The simulation models -1- to -16- in Figure 4 consider only operational uncertainties. Therefore, it is expected that the amount of out-of-stock hours is lower than in the simulations models -17- to -32- of Figure 5 which consider operational as well as disruptive uncertainties. This can be confirmed. The service level of models with operational as well as disruptive uncertainties is about two till five percentage points below the one that can be achieved when only operational uncertainties. This is also illustrated by comparing Figure 6 and Figure 7 which show the achieved service levels of the supply chain with no flexibility within 10,000 simulation runs. When only operational uncertainties exist it is possible to achieve a service level of 95 % in 6,035 simulation runs (Figure 6). In one run the lowest service level of 44 % occurs. When operational as well as disruptive uncertainties exist a service level of 95 % can only be achieved in 2,983 runs (Figure 7). The lowest performance is a service level of 11 %. This shows that it is a huge difference if a mean service level of 90 % like in model -13- or of 86 % (model -29-) can be achieved.

4.2 Implications of Results

The simulation study shows how important it is to consider uncertainties in all stages of supply chains. The modelled uncertainties are independent from each other. However, at the final stage of a supply chain all effects of uncertainties may add up and interrupt customer satisfaction. The study shows that flexibility potential at the retailer is most effective. It is able to compensate not only uncertainties in demand but also in processes upstream. If sufficient flexibility potential is available here it can compensate nearly all uncertainties. In the simulation study, the stock flexibility at the retailer is not dimensioned to handle all uncertainties. But operational flexibility potential in the amount of 20 % from the average demand can already reduce out-of-stock hours tremendously. As stock flexibility as operational flexibility potential is the only way to handle short-term uncertainties at the end of a supply chain, it is highly important.

Capacity as well as stock flexibility at previous stages of the supply chain can handle uncertainties as well. But their effect is limited to uncertainties that occur at the place of the flexibility potential or upstream from it. Uncertainties downstream of flexibility potential cannot be handled by this capability. But it is still needed. It protects the final stage from situations where uncertainties of the whole supply chain add up. Such situations could only be managed by huge inventory levels which are undesirable considering cost efficiency and other supply chain objectives. However, medium levels are not able to handle situations where effects of different sources of uncertainties add up.

It can be noted that every kind of flexibility helps in handling uncertainties and will increase supply chain performance (Sánchez and Pérez, 2005). That is confirmed by the study. A small degree of flexibility can increase performance enormous when it is located at the right place. As Garavelli (2003) as well as Graves and Tomlin (2003) already pointed out it is not necessary to build total flexibility into a system. Crucial in handling uncertainties is stock flexibility (Tsay and Lovejoy, 1999). It is available immediately and has its biggest impact when located at the end of a supply chain. The respective models of the simulation study have the highest service levels.

5 Conclusions

This paper presented insights into handling uncertainties in supply chains with the help of flexibility. It regarded the effects of existing uncertainties. To overcome them a supply chain needs flexibility potential which has to be created proactive. As the study shows, the location of flexibility within the supply chain is key for its ability to handle uncertainties. The further down in the supply chain the potential is located the more effective it is in compensating uncertainties that occur somewhere in the value creation process. Nevertheless, flexibility only in the last stage of a supply chain is not sufficient to achieve the best performance regarding the matching of supply and customer demand. As uncertainties cumulate during the processes of value creation they may be too much to be handled at just one point in the supply chain. Therefore, flexibility potential should be established at the end of the supply chain but also at other critical processes.

Our study has a number of limitations. While the results of the simulation fit into existing literature on flexibility in supply chains the findings are limited to the observed two-stage supply chain. Analyses of different supply chain structures could validate and generalise our findings. Furthermore, strategic as well as operational flexibility is modelled by a certain amount of redundant capacity and additional stock. Different levels of flexibility were not considered. How variations in the level of flexibility potential influences the ability of handling uncertainties therefore still have to be studied. As investments in additional capacity are probably more expensive then into stock flexibility cost considerations may be another point of further research.

If management faces the challenge of handling uncertainties it therefore should first of all define levels of safety stock near the end customer. To a certain degree they have to abandon the lean thinking approach. After defining a base level of stock flexibility the supply chain has to be analysed to identify critical processes. At these processes, additional flexibility potential should be created. This can be capacity and/or stock flexibility. These steps have to be integrated not only in the management process of the individual institutions within the supply chain but also in the process of coordination and collaboration between institutions. By integrating considerations about flexibility into cross-institutional supply chain management the full benefit of flexibility potential can only be utilised.

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