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Disruption risk management

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de Vlugt, Luuk L.

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Technische Universiteit Eindhoven
University of Technology

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What are good strategies for a firm against disruptions in a supply chain and what is the value of a back up supplier in different situations?

Author:

L.L. de Vlugt (0862864)

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1 The problems in a supply chain

When you order a product online or buy it in a store, you expect that the product is in stock and delivered in time. However in the process of getting the product to the customer there are many different factors that can cause problems. The transportation must be on time. The firm must have enough capacity to make the product. The raw materials to make the product must be available and delivered on time. And more kind of processes that must go well to make sure that the product is delivered. To make sure that there are as little problems as possible it is important to optimize every step in this process. An important step in this process is the supply part.

There are many companies who had major issues when their suppliers were down. In 2016 Tesla had big problems with the delivery of the batteries that where needed for the car. The supplier of the batteries, Gigafactory, had difficulties with the high demand of Tesla. Nevertheless Tesla continued to sell cars that it could not deliver to their customers. The big problems that the Gigafactory had with the delivery where not known by the Tesla company. These delivery problems developed up to the point that there are still people waiting for their Tesla at the moment (2018). Another case is the delivery problem of Volkswagen. Volkswagen had some issues with two factories that where part of the Prevent Group. These two factories should deliver products to make the gear box and the seats in the car. Volkswagen did withdrawn a big order at these factories. Due to this action of Volkswagen the two factories refused to deliver their products at Volkswagen. The negotiations with the Prevent Group to solve the problem where really inert. The two companies even took their problems to the courtroom because Volkswagen wanted their products that they had asked for delivered. On the other hand the Prevent Group had big problems because of the withdrawn of such a big order of Volkswagen. They had to fire employees and shut down parts of the factory because there was no money to keep them up and running. In this case the customers who bought a car were not immediately the victim however it cost Volkswagen a lot of money. When there are no products delivered there can be no products made. Some factories where shut down for a short time. The costs for a shut down of one week of the factory in Wolfsburg where these parts are made, could already lead to a cost of 100 million euro's.

To prevent this kind of issues it can be convenient to have good ordering strategies or a backup supplier who can deliver the products when the primary suppliers, the supplier where the firm normally orders their products from, can not deliver the needed products. When the primary supplier is down a good ordering strategy can prevent delivery problems to the client. Or when a backup supplier can be used, the backup supplier can simply take over the production. In the meantime the problems with the primary supplier can be solved. Of course the use of a backup supplier brings some new issue's along. What are the conditions to make use of such a backup supplier and does it bring extra cost when a backup supplier is used? When is it convenient to use a backup supplier and when not? This will raise the question; "what is the best way to make use of a backup supplier". The answer of this question will strongly depend on the situation of the supply chain; how often is a primary supplier down and when the supplier is down how long is this supplier down? What kind of cost are there attached to a backup supplier and how can we optimize the use of this backup supplier? In this paper we will discuss these different situations and what the best options and solutions are.

2 Research direction

First we will establish what the research direction is and what the exact questions are we want to answer. Thereafter the model will be explained and some concepts will be introduced. Then the model will be simplified to the model we want to use to answer the research questions which eventually will lead to solving the problem and give the answers to the research questions.

The problem we want to tackle is to minimize the problems at a firm when the products that are needed to manufacture the end product are not delivered. There are many possible solutions that can help to minimize these problems. For instance having a good understanding, terms and conditions with the primary suppliers can already prevent a lot of problems. We assume that this is all in order and therefore we will look at the following two solutions; the first solution is having smart ordering strategies that can tackle the problems when the primary supplier is down. The main concepts behind it is to order enough products during the uptime of the primary supplier to have no problems when the primary supplier is down. The way of ordering these extra products during the up time can be done in a lot of different ways. The second solution to tackle this problem is to make use of a backup supplier that can take over the productions when the primary suppliers are down. That is why the problem is split into two parts with the following research questions:

- How do different ordering strategies perform in different situations? And how do these performance compare to each other?

- How do different ordering strategies perform in different situations for a firm that uses the flexible backup supplier? And how do these performance compare to each other?

The first question is about the possible strategies a firm can use to cover for the lost supplies during a disruption of a supplier. With these strategies the firm will make sure that it can compensate for the down time of the supplier during the uptime of a supplier. The way of ordering these products can be done in a lot of different ways and strategies will have advantages and disadvantages. To establish how a strategy performs, the strategies will be compared to each other in different situations. It might be possible that one strategy works perfect in a certain situation and another strategy works not so well in this situation. However if we change these circumstances, this might be the other way around. We will look at the stability of the firm's inventory of a product and at different cost situations to see how a strategy performs.
With the second question we want to find an answer to the questions on how to make use of a backup supplier. There will be a few strategies to make use of the backup supplier. To check how these strategies perform, we will look at the influence of a few important parameters. This way we want to establish what the sensitivity of a strategy is to a parameter. If a small change in a parameter already causes a big difference in the total cost of a strategy we may say that this parameter has a bigger influence on the system then the other parameters . Maybe it works well when all the parameters are really constant however when there is a small change in a parameter and the costs of this strategy become much higher, this strategy is maybe not a good choice. If we have a good answer to this question we can make a lot of different statements about the importance of the strategy for different situations.
First all possible scenario's, solving techniques and solution strategies will be discussed. This will lead to some assumptions and choices that will be made on how to tackle this problem.

3 The model of a supply chain

For this discussion there will be one firm that needs n different types of products. These products can be delivered by n different primary suppliers where one supplier can deliver product 1, the second supplier can deliver product 2 and the n^{th} supplier can deliver product n. The order quantities of the firm will be named q^j, where q is the quantity and j stands for the supplier where the product is coming from. All these suppliers can be backed up by the flexible supplier who can deliver all the n different products. The order quantities from the flexible supplier will be named q_j^f, where q is again the order quantity, f stands for the fact that it is ordered from the flexible supplier and j denotes the product. The flexible supplier only has the restriction of a maximum capacity. So all the different products that can be ordered at the flexible supplier cannot be greater than some maximum capacity say Q^f. Thus $\sum_{j=1}^{n} q_j^f \leq \overline{Q}^f$. When the firm makes use of the flexible backup supplier it needs to pay upfront cost. This upfront cost will be the function $g(u^f, \overline{Q}^f)$ which depends on the reservation cost, u^f, and the maximum capacity, $\overline{Q}^f$, of the backup supplier. The other details of this function will be specified in Section 5.2. Each product will have a stochastic demand F_n and every supplier has a Markov stochastic disruption process W^n. The whole model is visualized in figure 1. Furthermore there are holding costs and penalty costs specified in the following itemization where subscript is used for products and superscripts for suppliers:

- h_j: Holding cost per unit of product j per period
- p_j: Penalty cost per unit of unmet demand of product j
- r_j: Revenue per unit of product j
- c^j: Per unit purchasing cost of product j form primary supplier j
- c_j^f: Per unit purchasing cost of product j from the flexible backup supplier
- u^f: Per unit capacity reservation cost of the flexible backup supplier
- $\overline{Q}^f$: Reserved capacity from the flexible backup supplier
- $g(u^f, \overline{Q}^f)$: Investment cost function at the flexible backup capacity
- q^j: Order quantity from primary supplier j
- q_j^f: Order quantity from the flexible backup supplier for product j

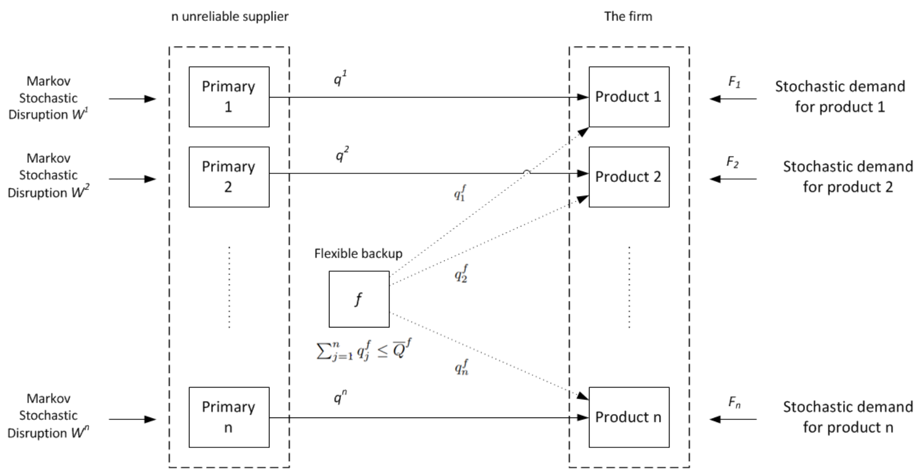


Figure 1: The supply chain

We will say that the system is fully flexible if all the suppliers and thus all the products can be backed up by the flexible backup supplier. When the system is partially flexible this means that only a part of the suppliers and products can be backed up by the flexible backup supplier. If the n different products have the same values for all the properties and have equal demands, we will say that the products are fully symmetric. If one or more values of the properties of the products are different, we will say that the products are asymmetric.

The disruption risk processes will be modeled with a discrete time Markov process where s_j denotes the threat level of supplier j. When $s_j = 0$ this means that the supplier is down, when $s_j = k$ it means that its threat level is k. Now the disruptions can be modeled as a Discrete Time Markov Chain (DTMC) with state space $\mathcal{S}^j = 0, 1, \ldots, k$ for dedicated supplier j. In the model $W^j = [w^j_{lm}]$ will be the transition matrix of supplier j, where w^j_{lm} is the probability that it will be in threat level m in the next period given that the current threat level is l. So every situation will start at $t = 0$ and from there every step will follow an order of events. At $t = 0$ the firm starts with an inventory level of zero and needs to decide how many products it wants to have from the primary suppliers. The firm also needs to decide how many products it wants from the flexible supplier. How many products the firm wants and from which supplier depends a lot on the order of events because the order of events determines what information is available for the suppliers and the firm. For both suppliers and the firm information is very important. For the firm it could be convenient to know if the supplier is up or down, or even to know what the chances are of a supplier to change state. If the firm could anticipate on the changes of the suppliers this could be of huge help to the firm.

One way to do this is to use the machine learning technique. With this technique the firm observes the state of the supplier and keeps hold of this information. After some time the firm has enough data to make a good guess of what the possible average down time of a supplier could be. Or what the chance is that the supplier changes state. This could be a good technique when the firm knows what the state of the supplier is only after the firm placed its order. Because it is useful to have a good guess on what the state of the supplier could be before you place the orders. Especially when there are more health states then two. When the firm has a good guess of what the health state could be and their guess is that the suppliers capacity is down by 20 % it could anticipate by ordering 20 % more then normally. In our discussion the firm will always know the state of the supplier before it places the orders and there will only be two states. Therefore we will not make use of machine learning, although it is a very interesting technique.

The next itimization gives the order of events that is used every step. In this order of events the firm does know the states of the suppliers before ordering. However it does not know the chances of the suppliers to change state.

1. The firm observes the state of the system (inventory levels and disruption threat levels).
2. The firm decides the order sizes and orders from all suppliers subject to the contracts.
3. The ordered products will be added to the inventory of the firm.
4. Product demands are realized.
5. The inventory levels are updated.

6. Holding costs or shortage costs accrue.

7. The state of the system is updated, including the disruption threat levels. The firm has to pay the purchasing cost c^j and c_j^f per order of product $j \in \mathrm{N}$ delivered by dedicated supplier j and the flexible backup supplier, respectively. The flexible backup supplier has a shared and limited capacity $\overline{Q}^f$. It can deliver any combination and quantity of products as long as it does not exceed $\overline{Q}^f$.

8. We assume none of the products in set N can be procured for free: $c_j^f + u^j > 0$ and $c^j > 0$ for $j \in \mathrm{N}$.

With this order of events the firm always knows the state of the system. So it knows its owns inventory level and the state of the suppliers. The only thing the firm does not know is the demand of the current step. Therefore the firm will make use of a certain ordering strategy to make sure they can meet the demand of the current step.

This model is mostly retrieved from [1] and [2].

4 Possible scenarios

To get a better insight in how we want to tackle this problem in this section the possible scenarios and solution methods will be discussed. There are a lot of possibilities and it is important to get an inside in which choices we make and why we make these choices.

4.1 The number of products

First it is important to specify how many products we want to model. For instance are the supplier specialists or can they deliver different products to the firm. An other option is a combination of suppliers who can deliver multiple products and some suppliers who can deliver only one product. How many products there are is also related to how many suppliers there are in the model. For our research questions it is better to simplify the model to come to better conclusions. If there are more products there are more parameters that can influence the answer. To make good observations we will look at a simplified model. Then we want to test the different parameters and their influence on the model, strategy or outcome of the problem. We can already do a lot of experiments if we only look at two suppliers with two products because there are a lot of different parameters that can be tested for their influence. Evenly important is how flexible the system is. Can the flexible backup supplier deliver all the products or only a set of products? When all the products can be backed up we will say that the system is fully flexible. When only a part of the products can be backed up we will say that the system is partly flexible. Because we only look at two supplier who can only make one product we can look at two scenario's: one supplier backed up or two suppliers backed up. However when there are more suppliers there will be more flexibility combinations. Furthermore the two products will have a stochastic demand. There are a lot of different possibilities for distributions that can be used as long as a distribution is discrete. We will test a few distribution with a different variability to see what the effect is on the ordering strategies.

4.2 The state of the suppliers

Secondly we will discuss the state space of the suppliers. The disruptions of the supplier are modeled with a discrete Markov process. This means that there are different states and that depending on the current state of the supplier the state of the supplier can change with a certain chance to an other state. The state when a supplier is up and can manufacture on 100 % capacity will be named the healthy state. The state when a supplier is down and can manufacture on 0 % of its capacity will be named the unhealthy state. In between these states there is a wide variation of possibilities. It is possible that only a certain part of the supplier is down or only a certain location of the supplier is down. So there can be different health states with different chance of becoming this state. For instance when the supplier is at 100 % capacity, the chance that it will immediately drop to 0 % capacity is not that big. This will only happen on rare occasions. However the chance that the capacity of a supplier will drop to 90 % could be much higher. Because there could be a small fire or there are some delivery problems at the supplier. Or a certain machine does not work properly. The chance that these events will happen are much bigger then that the supplier is not available at all. So a Markov chain with different health states could give a realistic view of the disruption processes of a supplier. However in our problem we will only look at a Markov chain with only two states, a healthy state and an unhealthy state. In this paper we want to make statements about the importance of ordering strategies with one supplier backed up or two suppliers backed up. When the supplier can have different health state there will be two many situations and factors that can have influence on the strategies and this will make it difficult to make good statements about the usefulness of these strategies. Therefore we will only look at suppliers with an uptime and a down time. This way we can make concrete statements about the results we will find. Also the values of the transitions matrix are important. The choice of these values will determine the reliability, disruption frequencies and the disruption lengths of the supplier. The values of the transition matrix will be different for a few situations to test the strategies with different disruption frequencies and disruption lengths. It is interesting to look at a supplier with a lot of disruptions for short moments in comparison to a supplier with long disruptions that have a way lower frequency of happing. The exact values of the transitions matrix will be discussed later on when the experiments will be specified in section 5.3.

4.3 The ordering strategy

The last important thing is the ordering strategy. The ordering strategy can be based on a lot of things. It can be based on the product demand. The firm can order a constant amount that is based on the demand. Or it could use the last known demand as indication of the next demand. However if the product demand is unpredictable or is not known to the firm when it needs to order this can be a bad strategy. An other way to make an order strategy is to make use of the inventory. There are a lot of inventory control strategies. The purpose of these strategies is to keep the inventory stable. A third way to make an ordering strategy is one based on the cost. For instance always order from the cheapest supplier. If the flexible supplier is cheaper then the primary supplier then why not use this flexible supplier all the time? How we will use all these options will be further explained when we choose the strategies in Section 5.1.

In the upcomming sections the model will be used to give meaningfull answers to the research questions. First the two suppliers with one supplier backed up model will be discussed. Thereafter the ordering strategies will be explained and the choices that are made for calculating the cost. The last thing that needs to be done before the start of the simulation is to create different situations to test the different parameters in the model. How do these parameters behave when the circumstance change? To create these different situations, different Markov chains will be made. Also different demand distributions will be introduced.
After the simulation of the two suppliers one supplier backed up problem, the results will be presented and conclusions will be drawn. When this is done the next model that will be simulated is the two suppliers with two suppliers backed up problem. Again the goal is to find meaningfull answers to the research questions that are proposed in section 2. Now the flexible backup supplier plays an important role. Therefore different ordering strategies will be made to see what the best way is to make use of such a flexible backup supplier. In this part the influence of the parameters on the system will be tested. So how much does the whole cost of the system change in comparison to the change that is made in a parameter. When this is all explained the results will be presented and conclusions will be drawn. Eventually in the last two sections the overall conslusion will be drawn and discussed.

5 Two suppliers problem with one supplier backed up

The questions that we want to answer is: "How do four different ordering strategies perform in different situations? And how do these performance compare to each other?". To give a meaningfull answer to this questions we will say that only one supplier can be backed up. So we will make a simulation of the following situation: we will have two suppliers and only one supplier will be backed up (so the system is partly flexible). The firm will need two different products, product 1 will be delivered by supplier 1 and product 2 will be delivered by supplier 2. The flexible backup supplier can only deliver one product to the firm, depending on the situation this can be product 1 or product 2. In this model the suppliers can only be in two different states. Or the supplier is "up" and therefore in a healthy state. Or the supplier is "down" and therefore in a unhealthy state. The situation is visualized in figure 2.

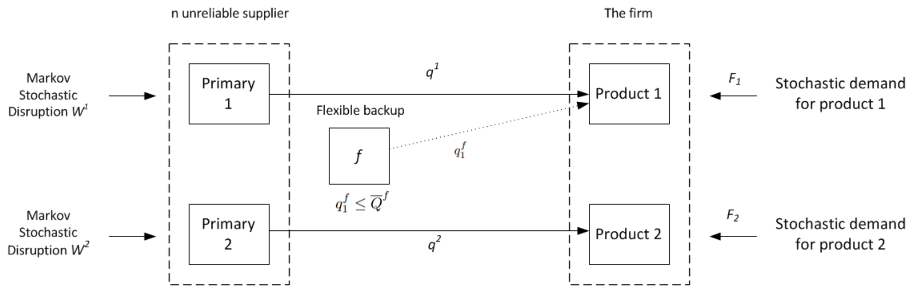


Figure 2: The supply chain for two suppliers

So if supplier 1 is down the firm can simply make use of the backup supplier. However when supplier 2 is down it can not make use of the flexible backup supplier and thus it needs a good ordering strategy to compensate for the downtimes of supplier 2. The importance of this strategy will be shown in this section. To see how the different strategies perform, we will compare two different objects of every strategy with each other:

- The stability of the inventory for the product that is not backed up.
- The average cost per step for both products and the whole system.

Stability of the inventory

The stability of the inventory is important because the firm needs enough products in the inventory to meet the demand, however an overload of inventory is inconvenient when holding costs need to be payed. So we want the inventory to stay more or less between a minimum and a maximum. What these values are will strongly depend on the demand of the product. What the values are for a stable inventory will therefore be discussed at the and of the section.

The average cost per step for both products and the whole system

The second point that will be discussed is the average cost per step for both products and the whole system. If the average cost per step of the system for strategy A is lower then the average cost per step of the system for strategy B, strategy A will be a better strategy to choose then strategy B based on the cost. Important is the difference between the average cost per step for the different strategies. Is the difference between the average cost per step big or small?

When there is a difference between the average cost per step that is smaller than 1 % this is a very small difference when the simulation is long. Is there a difference more then 5 % we can say there is a significant difference between the strategies. An other interesting thing to look at when the average cost per step of the systems are compared is the way the average cost per step develop. For instance is the cost of the system increasing very fast in the beginning of the simulation or at the end of the simulation? Do the average cost per step of the system develop in a constant way or are there points in the simulation where the average cost per step increase so fast that you should question if the firm is able to pay this and possibly could go bankrupt. This way we can establish what could be possible difficult times for a firm when a certain strategy is used. We will look multiple times at the average cost per step by changing a few parameters and important conditions and see how the average cost per step develop. For instance we will make the holding cost for one product much higher then the holding cost for the other product. Then first supplier one will be backed up and to order from supplier two a certain strategy will be used. Then these rolls will be switches and supplier two will be backed up and to order from supplier one this chosen strategy will be used. Then the results can be compared to see which strategies works the best in combination with a certain holding cost. This experiment can be repeated for a lot of different parameters and conditions.

The way of modeling
With a simulation we can get a good inside in the possibilities of the strategies. The model that is explained above is programmed in Java. By making use a simulation a lot of different experiments can be tested. Parameters can easily be changed and a lot of different conclusions can be drawn of the different experiments. At this moment a lot of parameters and formula's are explained in a general way. Therefore the model will be further specified in the next subsection. The ordering strategies need to made and the way of calculating the cost need to be explained. After this the different experiments will be made and then the results will be presented.

5.1 Ordering strategies

For supplier 1 the firm will always order the demand of product 1 from step $t-1$ at step t. When supplier 1 is down it will simply order the demand of product 1 from step $t-1$ from the backup supplier. This way the average ordering size will converge to the average demand for a long simulation. This way the firm will always have more or less enough units of product 1 to meet the demand. However for the firm to have enough units of product 2 it will need a good ordering strategy because if supplier 2 is down it can not make use of the backup supplier. Important is that these strategies have the same expected ordering size to make sure that every strategies orders the same amount in the long run. When this is not the case the strategies can not be compared to each other. Because when one strategy orders more then an other strategy the cost for the strategy that orders more has a higher probability of being high then the strategy that orders less. Now the four different ordering stategies will be presented.

Strategy 1: Ordering the average demand during the uptime of a supplier
This is a constant ordering strategy that is based on the average demand. The order size of the firm for every step that the supplier is up will be the average demand divided by the mean up time of the supplier (π_0):

$$Ordersize = \mathbf{E}[Demand]/\pi_0$$

This way in the long run the firm will exactly order the average demand. The percentage uptime of the supplier times the ordering size during the up time, plus the percentage downtime of the supplier times the ordering size during the downtime is the overall ordering size of the firm from the supplier:

$$\mathbf{E}[Ordersize] = \pi_0 * (\mathbf{E}[Demand]/\pi_0) + \pi_1 * 0 = \mathbf{E}[Demand]$$

Thus by compensating during the uptime of the supplier for the down time of the supplier the firm can maintain its inventory on a level such that the demands are met. An other advantage of this strategy is that it can be implemented for the different Markov chains that will be used. The only thing that will be changed in the Markov chains are the disruption lengths and frequencies. The uptime of the Markov chains much remain the same because otherwise the situations can not be compared. If the uptime of the suppliers is not the same the firm has less time to order from one supplier in comparison to the other supplier. Then the overall ordersize will differ which will give problems when the strategies will be compared.

Strategy 2: repair the unmet demand after downtime

This strategy repairs the damage of the down time of the supplier afterwards and works with a backlog. When the supplier is up the order size of the firm is equal to the demand of the last step just like the ordering strategy of supplier 1. However when supplier 2 is down the firm remembers the orders of each step the supplier was down. When supplier 2 is up again it orders the amount of unmet demand. This way the firm compensates after the disruption the amount of units it could not order from the supplier. Again the overall order size of the firm will be equal to the average demand. Because the firm orders every step the demand of the last step the firm will order actually the average demand in the long run. During the uptime of the supplier the firm orders the demand of the last step plus the unmet demand of the supplier during the downtime. Over a long time, ordering the demand of the last step is the same as ordering the expected demand:

$$\mathbf{E}[Ordersize] = \pi_0 * DemandLastStep + \pi_1 * DemandLastStep = (\pi_0 + \pi_1) * DemandLastStep$$

$$= DemandLastStep => \mathbf{E}[Demand]$$

If every step the demand of the last step is ordered it will converge to the average demand because of the law of large numbers. Which means that the expected order size of this strategy is also equal to the expected demand.

Strategy 3: (s,S) model

This strategy is based on the inventory and makes use of a minimum and maximum. When the inventory is less or equal to the minimum s it orders an amount such that the inventory is equal to the maximum S again. In this strategy the minimum will be s = -$\mathbf{E}[demand]$ and the maximum will be S = $\mathbf{E}[demand]$. With this strategy the inventory is set back to the average demand. In the long run the average inventory must be around zero. If the average inventory is around zero this means that the amount of ordered products is equal to the amount of demanded products. So again: $\mathbf{E}[Ordersize] = \mathbf{E}[Demand]$. The interesting thing about this strategy is that it is more independent of the disruptions of the supplier because the order sizes are only based on the level of inventory and not on the down or up time of the supplier. Of course the level of the inventory could go beneath the minimum level during a disruption of the supplier. This will cause a problem because it can not set the inventory back to the maximum level. However it will continue this process until the supplier is up again and then orders everything what is needed to set the inventory back to the average demand. When different demand distributions will be tested this ordering strategy will still be the same. The different demand distributions will only differ in variability. The average demand of the distributions will be the same for all distributions.

Strategy 4: high level of inventory
With strategy 4 the firm, just like with strategy one, orders a little too much during the up time of the supplier. It now orders a bit more then when strategy 1 is used. In strategy 1 the $Ordersize = \mathbf{E}[Demand]/\pi_0$. With strategy 4 the firm will order on average 0.5 units more, of course it will always order an entire amount but on average the $Ordersize = \mathbf{E}[Demand]/\pi_0 + 0.5$ for strategy 4. This way the inventory will most certainly rise and it will overcompensate for the down times of the supplier and thus the inventory will increase quickly. However every time the firm is about to order it checks whether the inventory is on level x. If the inventory is on level x or above it does not order products until the inventory is back to level y. In this model the maximum level for the inventory x will be equal to three times the average demand. Thus x $= 3 \cdot \mathbf{E}[demand]$ and the minimum y is equal to one time the average demand thus y $= \mathbf{E}[demand]$. For this strategy the same holds as with strategy three that the total ordered will be equal to the total demand in the long run because the inventory is stable. Thus again $\mathbf{E}[Ordersize] = \mathbf{E}[Demand]$.

The way the strategies will be compared is mostly based on the cost of the strategies. Every step of the simulation the cost of that step will be calculated. A good explanation of how the cost for each step is calculated is important. After that the different situations in which the strategies will be tested are specified.

5.2 Calculation of the cost

Purchasing costs
The upfront reservation cost, purchasing cost, penalty cost and holding cost for every step will all be calculated linear. For the purchasing cost this means that the numbers ordered from the primary supplier j times the purchasing cost of a product j form supplier j are the total purchasing costs of supplier j: $q^j \cdot c^j$. This can be done for all the suppliers. The purchasing cost of the flexible supplier is the number of ordered units of product j, times the purchasing cost of product j from the flexible supplier: $q_j^f \cdot c_j^f$.

Upfront reservation costs
The upfront reservation cost function will be linear: $g(u^f, \overline{Q}^f) = u^f \cdot \overline{Q}^f$. How much capacity will be reserved will be discussed later on.

Penalty costs
If the inventory is negative there is an unmet demand and therefore the firm has penalty cost. So the number of unmet demand times the penalty cost per unit is the total penalty cost of one step. Because unmet demand is backlogged this means that the penalty costs are always the inventory times the penalty cost per unit if the inventory is negative. Because all the products needs to be delivered although the firm had not enough inventory it again needs to pay penalty cost for products that also can not be delivered the second step after they are demanded. Therefore the inventory is an exact indication of the products that are not delivered for that step. The penalty cost for one step is the negative inventory times the penalty cost per product.

Holding costs
Holding cost are paid when the inventory is positive. This also will be done linear, so if the inventory is positive the holding cost for one step is the positive inventory level times the holding cost per product.

5.3 Designing the experiments

Now that is explained how the costs per step are calculated the experiments need to be designed. To evaluate the four strategies it is necessary to create some different situations because the performance of the four different strategies need to be compared. Therefore there are 3 different Markov chains created. Important for these Markov chains is that the average up time of the supplier is the same. This way in every situation the actual time the firm can order products is the same for every situation. The only thing that is different for every situation are the disruption lengths and the frequency of disruptions. In order to achieve this the expected disruption lengths are changed. Then the expected disruption lengths are used to calculate the chance of staying healthy (α) and staying unhealthy (β). The chance of becoming unhealthy is then 1-β and the chance of becoming healthy is 1-α. The expected uptime will always be 0.96 because the average uptime of the suppliers must be the same. α and β will be an indication of the disruption frequencies so by only changing the expected disruption length the whole Markov chain will changes. The formulas to calculate α and β follow from some calculations to the Markov chain where $\mathbf{E}[X]$ is the expected disruption length and π_0 is the average up time. Also is used that the expected disruption length is Geometric distributed. The expectation of the Geometric distribution is used to give a representation for β and solving the Markov chain equation for two states is used to give a representation for α:

$$\beta = \frac{1}{\mathbf{E}[X] + 1}$$

$$\alpha = \frac{2 * \pi_0 - \beta + \beta * \pi_0}{\pi_0}$$

Three different expected disruption lengths will be used to create three different Markov chains. The expected disruption lengths $\mathbf{E}[X]$ that will be used are: 11/10, 3/10, 11/5. For Markov chain 1 this means that $\alpha = 0.978$ and $\beta = 0.476$. For Markov chain 2 this means that $\alpha = 0.99$ and $\beta = 0.769$. For Markov chain 3 this means that $\alpha = 0.971$ and $\beta = 0.313$. The α's do not differ that much. This is because the reliability of the supplier must be equal to 0.96 and α strongly dependent on the reliability of the supplier. β only depends on the expected disruptions length and therefore has bigger differences. The chance of becoming unhealthy is the biggest for Markov chain 3, however the chance of staying unhealthy is the lowest for Markov chain 3. For Markov chain 2 this is the opposite, it has the smallest chance of becoming unhealthy of all the three Markov chains. However the chance of staying unhealthy is pretty big. The chances for Markov chain 1 are a bit in the middle of Markov chain 2 and 3.

Different demand distributions
For the different demand distributions it is important that they have the same expectation but a different variability. The variability of a distribution can be tested with the coefficient of variation. The coefficient of variation is determined by the expectation and the standard deviation of the distribution and is calculated the following way: $c_v = \frac{\sigma}{\mu}$. Different demand distributions can cause for different results. When the demands are very predictable every step, it is easier to make a strategy then for a demand that is very unpredictable. With predictable we mean that

the variation of the distribution is very small in comparison to the expectation, and thus the coefficient of variation is then very small. When a distribution is very unpredictable we mean the the variation of the distribution is very high. Which means that the coefficient of variation is very high. The three different distributions that will be used are the uniform distribution, Poisson distribution and the Bernoulli distribution. The average of all these demands will be equal to 3. For the uniform distribution this means that an interval from 1 to 5 is used ([1,5]). The coefficient of variation is: $c_v = \frac{\sigma}{\mu} = \frac{\frac{4}{\sqrt{12}}}{3} = 0.385$.

The second distribution that will be used is the Poisson distribution. This can be seen as the number of possible orders that arrive at the firm in one step. Again the expectation of this distribution must be equal to 3. For a poisson distribution holds that the expectation is equal to the variation of the distribution. So the variation of this distribution is equal to 3. Then the coefficient of variation is $c_v = \frac{\sigma}{\mu} = \frac{\sqrt{3}}{3} = 0.577$. This is a higher c_v then the c_v of the uniform distribution that is used. This means that this distribution is less predictable then the uniform distribution.

The last distribution that will be used is the Bernoulli distribution. The Bernoulli distribution gives with a certain probability p the number 1 and with probability $1 - p$ the number 0. This distribution can be implemented by saying that with probability p the demand is 1·demand and with probability $1 - p$ the demand is 0. Thus the demand is really high or the demand is 0. The expectation for a Bernoulli distribution is: $\mathbf{E}[X] = p$. However we want the expected demand $\mathbf{E}[X]$ to be equal to 3 again. So when the Bernoulli distribution gives 1, this will be multiplied by $\frac{3}{p}$. Then the expected demand is equal to 3 again. Now p can be chosen freely and how p will be chosen will depend on the c_v. The other two c_v where 0.385 and 0.577 so it would be interesting to have a c_v more close to 1. Thus p needs to be chosen a bit small, say 0.2. Then the $c_v = 0.8$. Now for the Bernoulli distributions holds that with chance 0.2 the demand will be $\frac{3}{p} = \frac{3}{0.2} = 15$ and with chance 0.8 the demand will be 0. This will make the Bernoulli distribution the most unpredictable of the three distributions that will be used.

6 Implementation and execution of the experiments

6.1 Confidence intervals

Before we can compare any results it is important that the comparison we make is based on significance. To make a good comparison between the average costs per step it is important to make confidence intervals. Al the average costs that will be found will differ from each other because simulation is used. Therefore we need to know if the difference between the average costs of two experiments is a difference because two different situations are used, or that there is a difference due to the fact that simulation is used. When confidence intervals are made, the difference between the average costs can be explained as a difference because of the parameters that are changed or that simulation is used. When the confidence intervals of two average costs overlap it means that these values are more or less the same. If the confidence intervals of two average cost do not overlap these values actualy differ from each other. The confidence intervals are based on the cost of the whole system. All the confidence are constructed with a 95 % certainty and constructed the following way: $P(\bar{X} - 1.96 \cdot \frac{\sigma}{\sqrt{n}} < \mu < \bar{X} + 1.96 \cdot \frac{\sigma}{\sqrt{n}})$. For all the upcoming experiments confidence intervals are made and can be found in appendix

B. If we look at all these comparisons we see that there are no overlapping confidence intervals for any of the experiments. This means that there are no differences in the results that fall in between the error of the simulation and that all the differences between the experiments are caused by the changed in the parameters.

6.2 Test the inventories

Besides looking at the average cost per step of the system it is also important to look at the development of the inventory. Interesting here to see is how the different strategies work for the different Markov chains and different demand distributions. These are the only two concepts that have an influence on the inventory and thus only these different situations are simulated. In these experiments we will keep track of the development of the inventory and that will be plotted in a graph. The total steps for all the runs are 10 000, but when the inventory is plotted for every step this would give a really ugly graph which is not readable. Therefore only the first 500 steps are plotted. For every Markov chain in combination with one of the demand distribution the inventory is plotted of the product that can not be backed up. The inventory for the product that is backed up is not plotted because this will give the result of a very predictable and stable inventory. All these experiments will result in 9 graphs. These graphs can be found in Appendix A.

If we look at the graphs it strikes that the high average demand strategy (the green line) is very unstable in all the graphs. Sometimes the inventory level becomes really high or sometimes really low. There is no clear pattern on what the inventory is going to do. Another thing that catches the eye is that when Markov chain 2 is used (when Markov chain 2 is used the disruption frequencies are low but the disruption lengths are long) that the repair after down time and (s,S) model quickly recover after a long disruption. However for the high average demand strategy and high level of inventory strategy this takes more steps. Moreover the high level of inventory strategy has quite some time a negative level of inventory. When we look at Figure 4a the level of inventory of the high level of inventory is pretty stable when there are short or no disruptions and the level of inventory is positive and relative high in comparison to the other strategies. But when there are long disruptions this strategy is not able to hold this position and drops to a negative level of inventory. For a strategy that is based on the fact that the inventory should be high this is not a nice outcome. Now this strategy has worst of both sides: when the penalty cost are high it will be an expensive strategy because there are long periods with a negative level of inventory. And when the holding costs are high it will again be an expensive strategy because there are long periods where the level of inventory is high. So there is no situation where this strategy could have an advantage. When we look at the Figures 5a, 5b and 5c where Markov chain 3 is used (when Markov chain 3 is used there are more disruptions with shorter disruption lengths) the high level of inventory level holds better. But again when the demands are pretty high, for instance when a demand distribution with high variability is used (see Figure 5c), again the strategy does not work very well. There are long periods of a negative level of inventory.

Overall we can conclude that the inventories when the repair after down time and the (s,S) model are used are pretty stable. Also when the variability of the demand distribution is changed these strategies seem to work fine. These strategies seem to work well when the firm makes use of inventory control. Also strategy 4 looks like a nice strategy, however in certain situations it looks like the inventory can still be deeply negative although it is a strategy based on high inventory. It could be that when costs are added to the simulation that strategy 4 will be expensive. Strategy 1 seems to be very unstable however it could be that in the long run it does not have so much influence on the cost. So to draw better conclusions about the strategies, costs will now be added and for different situations simulations will be made. To begin with testing the strategies when different Markov chains are used.

6.3 Test strategies for the different Markov chains

The first thing we want to check is how the different strategies perform with different disruption lengths and disruption frequencies. To achieve this, all the different parameters will be equal to each other. The only difference will be that supplier 1 will have the disruption process simulated by Markov chain 1 and supplier 2 will have the disruption process simulated by Markov chain 2. Now first supplier 1 will be backed up and to order from supplier 2 one of the strategies will be used. The cost will be calculated for this situation which will result in the average cost per step of the system. Then the rolls will be switched, to order from supplier 1 the chosen strategy will be used and supplier 2 will be backed up. Again the cost will be calculated which will result in the average cost per step. When these results are found, these results can be used to compare the two different situations and the conclusions can be drawn for which situation the strategy works best. This experiment will make use of the following values for the variables: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100. This experiment will be repeated for all the strategies and three Markov chains. In the first series of experiments, for supplier 1 Markov chain 1 is used and for supplier 2 Markov chain 2 is used. Then all the four different strategies will be tested. For the second series of experiments, for supplier 1 Markov chain 2 will be used and for supplier 2 Markov chain 3 will be used. The logical thing to do for the last experiment is to give supplier 1 Markov chain 3 and supplier 2 Markov chain 1. However this gives no extra results about the strategies. It will only give a result about the Markov chains that are already used. Because the suppliers, demand distributions and ordering strategies do not influence each other and are independent this gives no extra inside. In the first experiment the average cost per step is calculated for a supplier with Markov chain 1 and a supplier with Markov chain 2, in the next experiment the cost are calculated for when Markov chain 2 and 3 are used. It is to be expected that the cost for the supplier with Markov chain 2 are the some for both experiments and thus the difference in the average cost per step will be completely determined by the supplier with Markov chain 1 or 3. Therefore it is not use full to do the experiment where there is a supplier with Markov chain 1 and a supplier with Markov chain 3 because these results are already generated in the other experiments. So this will result in 8 experiments and 16 simulations. In the following tables in the first column the strategy is stated that is used for the supplier that is not backed up. In the first row the supplier that is backed up is stated. In the boxes of the table the average cost per step of products or the system is stated.

	Supplier 1 backed up			Supplier 2 backed up		
Strategy	product 1	product 2	System	product 1	product 2	System
Backed up	€10.21	-	-	-	€10.59	-
High average demand	-	€281.52	€291.73	€209.77	-	€220.36
Repair after down time	-	€11.40	€21.61	€10.39	-	€20.98
(s,S) model	-	€17.25	€27.46	€16.18	-	€26.77
High level inventory	-	€22.77	€32.98	€16.06	-	€26.65

Table 1: The average cost per step for product 1, 2 and the whole system where for supplier 1 Markov chain 1 is used and for supplier 2 Markov chain 2 is used. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up			Supplier 2 backed up		
Strategy	product 1	product 2	System	product 1	product 2	System
Backed up	€10.43	-	-	-	€10.53	-
High average demand	-	€236.34	€246.77	€299.20	-	€309.73
Repair after down time	-	€9.95	€20.38	€11.01	-	€21.54
(s,S) model	-	€15.96	€26.39	€17.25	-	€27.78
High level inventory	-	€14.90	€25.33	€23.32	-	€33.85

Table 2: The average cost per step for product 1, 2 and the whole system where for supplier 1 Markov chain 2 is used and for supplier 2 Markov chain 3 is used. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

6.3.1 Explanation of the results

If we compare the results of Table 1 we see that all the strategies work better when Markov chain 2 is used instead of Markov chain 1. This means that the strategies work better with a supplier that has a very low disruption frequency but long disruption lengths. Apparently all the strategies are capable to withstand a long disruption however a lot of disruptions of shorter lengths gives more problems. In particular the high level of inventory strategy performs much better when the supplier has disruption process like Markov chain 2.

In table 2 Markov chain 2 and 3 are used, again we see that the strategies work better when the disruptions are long but with a low frequency of happening. When the results of the experiment where supplier 2 is backed up and has a disruption process of Markov chain 3 are compared to the experiments where supplier 1 is backed up and has disruptions process of Markov chain 1 the results of the second experiment are better then the results of the first experiment. Again this confirms the conclusion that strategies handle long disruptions with a lower frequency of happening better then short disruptions with a high frequency of happening. Because Markov chain 3 has shorter disruptions with a higher frequency of happening then Markov chain 1.

In general the repair after down time strategy seems to work the best. When for supplier 2

Markov chain 3 is used the repair after down time strategy is even cheaper (€9,95) then backing up the supplier with Markov chain 3 (€10,53). This is probably because the purchasing cost of a product from the flexible backup supplier is higher then the purchasing cost per product from the primary supplier. When Markov chain 3 is used there are short disruptions with a high frequency of happening. Apparently the repair after down time is good withstand against such disruptions. What is striking is that the high average demand strategy has a very poor performance. It is way out of proportion in comparison to the other strategies. It is possible that in other situations the high average demand strategy performs better in comparison to the other strategies. For instance when the disruption process is more predictable.

6.4 Testing strategies for different holding cost

Now that is established which strategies work the best for which Markov chains, it is interesting to look how the strategies hold for different cost. Again for both suppliers everything is kept the same only this time the holding cost for the products will differ. Again we will backup supplier 1 and the firm will use a strategy to order product 2. Then this will be switched and the results will be compared. Now a conclusion can be drawn if a strategy works better when the holding cost are high or when the holding cost are low. All the strategies will be tested for only two Markov chains. In the first series of experiments, we will use Markov chain 2 for both suppliers. For the second series of experiments, we will use Markov chain 3 for both supplier. We had to choose between 3 Markov chains and the two most "extreme" Markov chains are chosen. The difference between the 3 Markov chains are the disruption frequencies and the disruption lengths. We have chosen a Markov chain with relative long disruptions with a low frequency of happening and the Markov chain with relative short disruptions with a high frequency of happening. This way we have tested the two most "extreme" situations. Furthermore the following parameters are used: $c^j = 2$, $h_1 = 1.5$, $h_2 = 3.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up			Supplier 2 backed up		
Strategy	product 1	product 2	System	product 1	product 2	System
Backed up	€10.50	-	-	-	€11.98	-
High average demand	-	€393.22	€403.76	€284.86	-	€296.83
Repair after down time	-	€12.49	€23.03	€10.81	-	€22.79
(s,S) model	-	€17.54	€28.08	€17.22	-	€29.20
High level inventory	-	€28.59	€39.13	€22.61	-	€34.59

Table 3: The average cost per step for product 1, 2 and the whole system where for product 1 $h_1 = 1.5$ and for product 2 $h_2 = 3.5$ is used and Markov chain 2 is used for both suppliers. Furthermore the following parameters are used: $c^j = 2$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up			Supplier 2 backedup		
Strategy	product 1	product 2	System	product 1	product 2	System
Backed up	€10.80	-	-	-	€12.00	-
High average demand	-	€332.81	€343.60	€206.18	-	€218.18
Repair after down time	-	€11.01	€21.81	€10.01	-	€22.01
(s,S) model	-	€16.35	€27.15	€15.97	-	€27.97
High level inventory	-	€21.48	€32.28	€14.87	-	€26.87

Table 4: The average cost per step for product 1, 2 and the whole system where for product 1 $h_1 = 1.5$ and for product 2 $h_2 = 3.5$ is used and Markov chain 3 is used for both suppliers. Furthermore the following parameters are used: $c^j = 2$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c^f_j}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

6.4.1 Explanation of the results

If we look at Table 3 all the costs went up in comparison to the first two tables which makes sense because the holding cost for product two went up. If we compare the results in the table with each other the high average demand strategy is much influenced by a change in the holding cost. The average cost per step for product 2 when supplier 1 is backed up are €393.22. When supplier 2 is backed up the average cost per step for product 1 is only €284.86. This means that when the holding cost go up with 57 % ($\frac{1.5}{3.5}$) the average cost per step goes down with 28 %. If we compare this with the other results this is a big improvement. The repair after down time only goes down with 14 %. The (s,S) model stays more or less the same and even the high level of inventory shows not as much improvement as the high average demand strategy. (21 %) On forehand you expect that the high level of inventory strategy has the most benefit from a lower holding price because in general the inventory with this strategy will be high. An explanation can be that the high average demand strategy is really unpredictable. When we looked at the graphs we saw that this strategy can have very low levels of inventory but also very high levels of inventory. This is due to the fact that the high average demand strategy exactly orders the demand that is expected in the long run. So over a whole simulation this strategy ordered exactly what was needed. But in large periods of time the strategy does not match the demand because for instance the demand was very low a few times in a row. However this strategy keeps ordering the same amount every time. In such a period the inventory level goes up really quickly. This can also work the other way around. It seems logical that this strategy works perfect if the variability of the demand is really small. We will come back to this when the different demand distributions will be compared.

The last interesting thing about this table is that the (s,S) model has almost the same cost for both situations. Apparently the inventory of this model is not that high. The inventory is always set back to the average demand, so you would expect that the (s,S) model would have some profit of a lower holding price but this is not the case. Table 4 shows a bit of the same results. In this table every parameter that is used is the same as in table 3 the only difference is that Markov chain 3 is used. Only in general the average cost per step seems to be a bit lower. This can be due to the fact that with Markov chain 3 the supplier has more disruptions altough of shorter length. Now that the holding cost for product 2 are a bit higher it is better for a firm to have more disruptions of shorter lengths because this means that in general the inventory is a bit lower so there are less inventory costs. However the disruptions are not to long so the inventory will not become deeply negative like with Markov chain 2 where the disruptions are much longer of length and thus can cause higher penalty cost. An other thing is that with Markov chain 2 the inventory will be constant on a high level for a long time because there are not a lot of disruptions. This will causes a lot of inventory costs every step. Then all of the sudden there is a disruption for a long time, the inventory becomes negative and there are penalty cost. Why was this not the case in the first two tables? Because then the holding cost for product 2 where pretty low. Then it is less important that there is a high level of inventory because the holding costs have not so much influence.

6.5 Testing strategies for different penalty costs

For the penalty cost we will do exactly the same as with the holding cost experiment only now for the two different products the penalty cost will be different and the holding cost will be the same. For this experiment we will again test all the strategies because we want to make a statement about the performance of the strategies. Just like with the holding cost we will only test the two most "extreme" Markov chains.

	Supplier 1 backed up			Supplier 2 backed up		
Strategy	product 1	product 2	System	product 1	product 2	System
Backed up	€9.07	-	-	-	€10.20	-
High average demand	-	€273.15	€282.22	€192.63	-	€202.84
Repair after down time	-	€10.94	€20.01	€8.83	-	€19.04
(s,S) model	-	€17.25	€26.32	€10.99	-	€21.19
High level inventory	-	€22.80	€31.87	€15.83	-	€26.03

Table 5: The average cost per step for product 1, 2 and the whole system where for product 1 $p_1 = 1.5$ and for product 2 $p_2 = 3.5$ is used and Markov chain 2 is used for both suppliers. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up			Supplier 2 backed up		
Strategy	product 1	product 2	System	product 1	product 2	System
Backed up	€8.99	-	-	-	€10.20	-
High average demand	-	€205.18	€214.17	€148.20	-	€158.41
Repair after down time	-	€9.95	€18.94	€8.30	-	€18.50
(s,S) model	-	€15.97	€24.96	€10.43	-	€20.64
High level inventory	-	€14.84	€23.83	€12.64	-	€22.84

Table 6: The average cost per step for product 1, 2 and the whole system where for product 1 $p_1 = 1.5$ and for product 2 $p_2 = 3.5$ is used and Markov chain 3 is used for both suppliers. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

6.5.1 Explanation of the results

In Table 5 and 6 the influence of the penalty cost is tested. The penalty cost seems to have less influence on the strategies then the holding cost. Especially if we look at table 6 the differences in the average cost per step for the whole system are really small. If Markov chain 2 is used there are some differences. For instance the (s,S) model seems the be performing better when the penalty cost are low. This was also concluded when the influence of the holding cost where tested. Then was the conclusion that there was not really a change in the average cost per step for the (s,S) model when the holding cost where lower or higher. This is because the inventory is in general pretty low for this strategy, actually the inventory is a lot of the time negative. When we look at the cost the same conclusion can be drawn, because the (s,S) model has a lot of benefit when the penalty cost are low. Then the average cost per step for the (s,S) model are relative low in comparison to the other strategies. Again the performance of the repair after down time is really well. The average cost per step for this strategy is really low and also the influence of changes in a parameter seems to be of almost no influence on the average cost per step. However it was to expect that this strategy would perform worse if the penalty cost went up, because it keeps the inventory on a constant low level. For instance when the supplier goes down this strategy just accepts the penalty cost because it repairs the lost demand after the down time of the supplier, the inventory goes negative and you would expect high penalty cost. However if we look at table 5 there is a difference in the average cost per step but the average cost per step of the whole system has only a difference of 5% although the penalty cost differ by 57% for both products. If we only look at the cost difference between the average cost per step of the supplier that uses the strategy the difference is a bit higher: the situation where supplier 2 is backed up the average cost per step is 19% lower. This is still not so much for a change in the penalty cost of 57 %

So the repair after down time strategy seem to work fine when the penalty cost are high. Also the average cost per step of the high level of inventory strategy do not differ to much for both situations. The high average demand and the (s,S) model are becoming much more expensive when the penalty cost go up.

6.6 Testing for different demand distributions

The last thing that will be tested for the two suppliers one supplier backed up problem are the three different demand distributions. The three different demand distributions will be tested the same way as the three different Markov chains. First product 1 will have a uniform demand distribution and product 2 will have a Poisson demand distribution. Then product 1 will get the Poisson demand distribution and product 2 will get the Bernoulli distribution. Again the last option does not give extra inside in the problem and thus only these two combinations will be simulated. Again first supplier 1 will be backed up and to order from supplier 2 a strategy will be used. Then for the second simulation it will be switched around and the results can be compared.

	Supplier 1 backed up			Supplier 2 backed up		
Strategy	product 1	product 2	System	product 1	product 2	System
Backed up	€12.88	-	-	-	€13.24	-
High average demand	-	€276.87	€289.74	€221.86	-	€235.04
Repair after down time	-	€11.46	€24.34	€9.97	-	€23.21
(s,S) model	-	€16.34	€29.22	€16.16	-	€29.40
High level inventory	-	€18.92	€31.80	€15.88	-	€29.12

Table 7: The average cost per step for product 1, 2 and the whole system where product 1 has a uniform demand distribution between [1,5] and product 2 has a Poisson demand distribution with $\lambda = 3$. For both suppliers Markov chain 1 is used. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 9$, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up			Supplier 2 backed up		
Strategy	product 1	product 2	System	product 1	product 2	System
Backed up	€13,88	-	-	-	€19,71	-
High average demand	-	€762,68	€776,56	€295,50	-	€315,21
Repair after down time	-	€17,38	€31,25	€11,30	-	€31,01
(s,S) model	-	€18,64	€32,52	€16,36	-	€36,07
High level inventory	-	€122,88	€136,76	€18,81	-	€38,52

Table 8: The average cost per step for product 1, 2 and the whole system where product 1 has a Poisson demand distribution with $\lambda = 3$ and product 2 will have a Bernoulli demand distribution with a 0.2 percent chance of ordering 15 units. For both suppliers Markov chain 1 is used. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 15$, Total steps = 10 000, Total runs = 100.

6.6.1 Explanation of the results

The last comparison is between the demand distributions. When a poisson distribution is used the difference with a uniform demand distribution is not that big. The only strategy that shows a big difference in the average cost per step is the high average demand. Apparently this strategy is really sensitive for random demands. When the Bernoulli distribution is used, the most unpredictable distribution, the average cost per step is really high. Especially when we compare this to the average cost per step of the other strategies. These strategies seems to have less problems with the unpredictability of the demand distributions. Also the result of the (s,S) model seems the be pretty stable.

In general the repair after down time strategy seems the perform really stable. It has some problems when the demand distribution is unpredictable, the average cost per step when a product has a Bernoulli distribution is €17,38. This is almost 1,5 times as much as when the demand of a product has a uniform distribution of a Poisson distribution. (€9.97 and €11,46 respectively). But is still very consistent if we compare this to the high average demand distribution where the cost almost become three times as much when a product has a Bernoulli demand distribution. Also the high level of inventory strategy has some problems when the demand distribution becomes unpredictable.

6.7 Most important findings

The results of the repair after down time and the (s,S) model are the most stable. However when the holding cost are low, the high level of inventory is a very good strategy to use. Important is that this strategy works the best when the demand is predictable. When the demand is a bit unpredictable the inventory is not so stable any more which causes an increase in the average cost per step.

Secondly the high average demand is a very unpredictable strategy. It is not a bad strategy because products are delivered and when the demand is predictable and the holding cost are not to high it is a good and simple strategy to use. However when the circumstance change a bit this strategy is not stable and the average cost per step is higher.

7 Two suppliers problem with two suppliers backed up

For this problem we will look at the same model, only now also the second supplier is backed up. In this part of the paper the second research question will be answered: How do three different ordering strategies perform in different situations for a firm that uses the flexible backup supplier? And how do these performance compare to each other? Now that both suppliers can be backed up by the flexible backup supplier, there is an allocation problem when both suppliers are down. How many units of product 1 does the firm order and how many units of product 2 does the firm order from the flexible backup supplier? What is an efficient way and what are good allocation strategies in certain situations. To give a meaning full answer to this question we will again create different strategies and situations to make a good comparison between the different strategies. In this discussion four different parameters will be compared. The purchasing cost, penalty cost, holding cost and the maximum capacity of the backup supplier. To show the influence of these parameters we will calculate the average cost per step for one situation. Subsequently one parameter will be changed, for instance the holding cost for both products will be ten percent higher. Again the average cost per step will be calculated. Then the two results will be compared to see how much the change is in the average cost per step. If the average cost per step also went up with 10 percent, like the parameter that was changed, we say that the input of this parameter is consistent with the output of the system. But maybe the average cost per step only went up with five percent then this parameter does not have that much influence on the average cost per step. Or it could be that a ten percent change in this parameter causes a change in the average cost per step that is more then 10 percent. Then the parameter has more influence on the whole system. We will call this the sensitivity of a parameter. This will of course strongly depend on the allocation strategy. Therefore we will make different strategies to make use of the flexible backup supplier. Then different experiments will be made and at the end statements will be made about these results.

7.1 Strategies to use the flexible back up supplier

A lot of things that are already discussed in the first part will be used again. The three different Markov chains and the three different demand distributions will be used again. Furthermore three different ordering strategies will be made. Then the experiments will be made. The aim of these experiments is to test the sensitivity of the holding cost, penalty cost, purchasing cost and the maximum capacity of the flexible backup supplier on the strategy. But first the allocation strategies will be chosen.

50-50 model
In this model the firm will use the flexible backup suppliers always 50-50. So when one of the suppliers is down the firm will use the flexible backup supplier to compensate for the supplier that is down. When both suppliers are down the firm will use half of the capacity of the flexible backup supplier to order product one and the other half of the capacity to order product two.

Cost ratio model
An other way to order from the flexible backup supplier is a strategy based on the cost. It could be a good strategy to order more of the product that has a high penalty cost to make sure the firm has enough of this product. Or to order more of the product that has low holding cost because there are less costs to have more of this product in stock then the other product. This strategy can also be implemented for the purchasing cost. For now only a penalty based

strategy will be made. For three reason this is an interesting parameter. First it gives a good inside in the cost of the product. Secondly the holding cost works a bit the same only then reversed. The last reason is the satisfaction of the customer. When the firm pays less penalty cost this means that more customers reachieved their products on time. The way this strategy is made is that a certain ratio times the maximum capacity is ordered of product 1 and 1- this ratio times the maximum capacity will be ordered of the other product. This results in the following: $\frac{p_1}{p_1+p_2} \cdot Q^f$ is the amount that will be ordered of product 1 from the flexible supplier. $(1-(\frac{p_1}{p_1+p_2})) \cdot Q^f$ units will be ordered from the flexible backup supplier of product 2. When a product has a high penalty cost the ordering ratio will also be high and therefore there will be ordered more of this product from the flexible backup supplier.

Inventory control model
With the inventory control model the firm will only order from the flexible backup supplier if the inventory is lower then a certain amount. When both supplier are down the firm will only order from the flexible backup supplier if the inventory of a product is lower then zero. When the inventory is lower then zero the inventory is set back to the level that it has exactly the average demand back store. When the inventory is higher then zero the firm does nothing. This way the firm will only use the flexible backup supplier when it is necessary. If both inventories of the products are lower then zero the product that has the lowest inventory will first set back to the average demand. Thereafter the left over capacity of the flexible backup supplier will be used the get the inventory of the other product as close as possible to the average demand.

7.2 Influence of the different parameters

The maximum capacity of the flexible backup supplier
The flexible backup supplier has a maximum capacity. This maximum capacity has a lot of influence on the strategies that the firm will use to order from the flexible backup supplier. Because now that there is an allocation problem where choices need to be made it could be interesting to look at different maximum capacities and what the influence of this parameter is on the whole system. It could be that certain strategies work perfectly if the maximum capacity of the flexible backup supplier is pretty high but have major problems when the maximum capacity of the flexible supplier is low. For all the different strategies and cost situations different maximum capacities will be tested to see how the strategies perform. Three different maximum capacities will be used. The high maximum capacity will be the maximum demand of product 1 plus the maximum demand of product 2. This way the firm can always order enough products to meet the demand. The average maximum capacity will be the average demand of product 1 plus the average demand of product 2. The last maximum capacity that will be tested is the critical maximum capacity. This maximum capacity will be equal to the average demand of product 1. Because the average demand of product 2 will be the same for every situation this will give the same results.

Influence of the holding cost, penalty cost and purchasing cost
In this situation both suppliers will be backed up and the three different strategies will be used to order from the flexible backup supplier. First the fifty-fifty strategy will be used. All the parameters will be the same for the first experiment and we will use Markov chain 1 for both suppliers. In the second experiment the holding cost will be ten percent higher for both products. In both experiments the average cost per step will be calculated. When the average cost per step also went up with ten percent in the second experiment, the influence of the holding cost is consistent with the output of the system. When the average cost per step goes up with

less then eight percent we will say that the influence of the holding cost is not that big. When the average cost per step goes up with more then twelve percent we will say that the influence of the holding cost on the system is bigger then expected. These experiments will be repeated for the different maximum capacities to see if a parameter has more influence on the whole system when the maximum capacity is different.

For the influence of the penalty cost and the purchasing cost we will do exactly the same as with the holding cost. When all these experiments are finished the conclusion can be drawn which parameters have a big influence on which strategy. Also a conclusion about the performance of a strategy for different maximum capacities can be drawn. This is use full to know when firms find them selves in fast developing areas. If for instance the penalty cost on products change a lot, it would be wise to choose a strategy and a flexible backup supplier with a maximum capacity that is almost immune for a change in penalty cost. The same holds of course for the holding cost and purchasing cost. Also the indication of what strategies perform well for certain maximum capacities can be usefull. When the market offers different flexible backup supplier with all different maximum capacities, these experiments will give a meaningfull answer to the question which backup supplier the firm should choose.

7.3 Testing the different allocation strategies for different situations

For every experiment a certain maximum capacity and parameter y is chosen. Then the influence of this parameter y will be tested with all the strategies by first simulating all the average costs per step of the system with the value x for parameter y. Then the simulations will be repeated only now the value x of parameter y will be ten percent higher: 1.1·x. So the first column with results is called "default settings". The default settings are as follows: for both suppliers Markov chain 1 is used. The following values for the parameters are used: $c^j = 2$, $h_j = 2$, $r_j = 4.5$, $p_1 = 1.5$, $p_2 = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100. In the next collum everything is the same except the holding cost. The holding cost went up with ten percent, hence the name of the collum: "h_j = 2.2. In the next collum the holding cost are set back to the default setting and the penalty cost for both products went up with ten percent. In the last collum the penalty cost are set back to the default settings and the purchasing cost went up with ten percent. There are three tables because we wanted to test three different maximum capacities. In the first table Q^f = 10, in the second table $Q^f = 6$ and in the last table $Q^f = 3$. All the results are specified in the tables beneath.

Average cost per step for product 1				
Strategy	Default settings	$h_j = 2.2$	$p_1 = 1.65$, $p_2 = 3.85$	$c_j = 2.2$
50-50 model	€39.48	€43.76	€39.25	€42.83
Cost ratio model	€13.10	€13.46	€12.96	€14.22
Inventory control model	€11.71	€11.85	€11.81	€12.06
Average cost per step for product 2				
Strategy	Default settings	$h_j = 2.2$	$p_1 = 1.65$, $p_2 = 3.85$	$c_j = 2.2$
50-50 model	€39.33	€44.54	€40.06	€43.27
Cost ratio model	€70.29	€80.28	€71.40	€77.20
Inventory control model	€13.89	€13.92	€14.20	€14.33
Average cost per step for the whole system				
Strategy	Default settings	$h_j = 2.2$	$p_1 = 1.65$, $p_2 = 3.85$	$c_j = 2.2$
50-50 model	€78.81	€88.30	€79.31	€86.10
Cost ratio model	€83.39	€93.74	€84.36	€91.42
Inventory control model	€25.60	€25.77	€26.00	€26.39

Table 9: The average cost per step for supplier 1 and 2. For both suppliers Markov chain 1 is used and $Q^f = 10$. Every column indicates a change in a parameter. Furthermore the following values for the parameters are used as default settings: $c^j = 2$, $h_j = 2$, $r_j = 4.5$, $p_1 = 1.5$, $p_2 = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100

Average cost per step for product 1				
Strategy	Default settings	$h_j = 2.2$	$p_1 = 1.65$, $p_2 = 3.85$	$c_j = 2.2$
50-50 model	€12.26	€12.47	€12.59	€13.39
Cost ratio model	€32.61	€32.65	€33.53	€31.52
Inventory control model	€12.73	€11.98	€12.39	€12.54
Average cost per step for product 2				
Strategy	Default settings	$h_j = 2.2$	$p_1 = 1.65$, $p_2 = 3.85$	$c_j = 2.2$
50-50 model	€15.98	€15.15	€16.01	€15.77
Cost ratio model	€24.21	€26.66	€24.03	€25.01
Inventory control model	€18.70	€17.33	€17.84	€17.71
Average cost per step for the whole system				
Strategy	Default settings	$h_j = 2.2$	$p_1 = 1.65$, $p_2 = 3.85$	$c_j = 2.2$
50-50 model	€28.24	€27.62	€28.59	€29.17
Cost ratio model	€56.82	€59.30	€57.57	€56.54
Inventory control model	€31.42	€29.32	€30.23	€30.23

Table 10: The average cost per step for supplier 1 and 2. For both suppliers Markov chain 1 is used and $Q^f = 6$. Every column indicates a change in a parameter. Furthermore the following values for the parameters are used as default settings: $c^j = 2$, $h_j = 2$, $r_j = 4.5$, $p_1 = 1.5$, $p_2 = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100

Average cost per step for product 1				
Strategy	Default settings	$h_j = 2.2$	$p_1 = 1.65$, $p_2 = 3.85$	$c_j = 2.2$
50-50 model	€176.08	€175.77	€191.44	€177.06
Cost ratio model	€188.39	€188.02	€204.52	€189.83
Inventory control model	€170.12	€170.55	€184.92	€171.62
Average cost per step for product 2				
Strategy	Default settings	$h_j = 2.2$	$p_1 = 1.65$, $p_2 = 3.85$	$c_j = 2.2$
50-50 model	€400.93	€403.30	€428.82	€399.93
Cost ratio model	€372.20	€374.71	€398.30	€370.11
Inventory control model	€387.39	€389.03	€415.47	€385.03
Average cost per step for the whole system				
Strategy	Default settings	$h_j = 2.2$	$p_1 = 1.65$, $p_2 = 3.85$	$c_j = 2.2$
50-50 model	€577.01	€579.06	€620.26	€576.99
Cost ratio model	€560.58	€562.72	€602.81	€559.95
Inventory control model	€557.52	€559.57	€600.40	€556.65

Table 11: The average cost per step for supplier 1 and 2. For both suppliers Markov chain 1 is used and $Q^f = 3$. Every column indicates a change in a parameter. Furthermore the following values for the parameters are used as default settings: $c^j = 2$, $h_j = 2$, $r_j = 4.5$, $p_1 = 1.5$, $p_2 = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100

8 Results and discussion of the two suppliers problem with two suppliers backed up

8.1 Comparison of the results

There are three tables. The only difference between the three tables is that for every table a different maximum capacity for the flexible backup supplier is used. For the first table a maximum capacity of 10 is used. This is the maximum of the demand distribution of product 1 plus the maximum of the demand distribution of product 2. When we look at the 50-50 model the holding cost have the biggest influence on the system. This makes sense because when both suppliers are down the whole capacity of the backup supplier is used every time. However it could be possible that in a lot of cases this is not necessary at all. When the cost ratio model is used the cost for product 1 seems not to be influenced by the fact that the holding cost went up. This is probably because the inventory of product 1 is better because there are bought more units of product 2 because this penalty cost is higher. The results of product 2 confirm this. There the cost for product 2 went up with 12%. That is more then the 10% that the holding cost went up. The inventory control model seems not to be influenced by any change of the parameters. Only when the purchasing cost go up, the average cost per step of the whole system goes up with 2.5%. When these results are compared to the experiments where the maximum capacity was equal to 6 the results of Table 10 are much better. This is probably because with the 50-50 model and the cost ratio model the whole capacity of the backup supplier is used but in a lot of cases this is not necessary. So when the maximum capacity of the backup supplier is 6 the average cost per step is much lower. Also because you have to pay less upfront reservation cost. However when the maximum capacity of the backup supplier is to low like in Table 11 where the maximum capacity of the backup supplier is 3, there are problems with the deliveries. When the penalty cost go up with 10% in Table 11 the cost for all the models goes up with around 7%. If we compare this with the holding cost this is a huge difference. The average cost per step of the system when the holding cost go up with 10% seems not to be affected at all. So a lot of penalty cost need to be paid when the maximum capacity of the flexible supplier is only 3.

So in these three cases the best maximum capacity for the flexible backup supplier is 6. When we look at table 10 there are some strange results. If we look at the 50-50 model the cost for the whole system seems to be lower when the holding cost went up with 10%. However the confidence interval for the average cost of the whole system for the 50-50 model is: (27,03 ; 29,45). The average cost per step when the holding cost are 10% higher lies in this interval. So the difference between these results is due to the error in the simulation. So we can say that the influence of the holding cost on the 50-50 model is pretty small. When the purchasing cost go up with 10% the difference is bigger but still the difference lies in between the confidence interval of the default settings. This is the case for all the results of table 10

So the influence on the strategies depends very much on the maximum capacity of the flexible supplier. Is there enough capacity or is the capacity to small? It seems that for a maximum capacity of 6 the amount of products that are ordered with all the three strategies seems to be in order. There are no big holding cost and there are no big penalty cost. Also the purchasing cost do not have so much influence. If we look at the results for when the capacity is only 3 the average cost per step of all the strategies seems to be really high. This is mostly due to the fact that the penalty cost for product 2 are much higher then the holding cost for product 1. So it is better to have a lot of inventory then have a negative inventory when this situation is used. In general the results for a backup supplier are not much better then the results of the strategies that are used when a supplier is not backed up. The problem with this conclusion is that we only look at the cost. With a strategy like repair after down time the products are not delivered for a long time when there is a long disruption. This could cause other problems in the production at the firm. Maybe the supply costs are in control but when there is no production it could be that there arise other problems that are not taken into account in this model. We will come back to this in the discussion.

8.2 Most important findings

The most important finding is that when a flexible backup supplier is used it is very important for the firm that it closely looks at the maximum capacity that the firm needs. Even when a strategy as the inventory control model is used it is important that the maximum capacity of the flexible supplier matches the needs of the firm. With the other two strategies this seems almost trivial because the orders are based on the maximum capacity of the firm. However like stated also for a strategy that bases the orders on the level of inventory this is important. Important to take into account is that a high maximum capacity works better for a firm then a maximum capacity that is to small.

9 Conclusion

9.1 Two suppliers one supplier backed up problem

The most important finding is that good strategies can perfectly cover for possible disruptions of a supplier. The repair after down time and the (s,S) model seem the be performing the most stable. Of course a good strategy depends a lot on the situation. For instance when the holding cost are relative low the high level of inventory is a good strategy.

The different Markov chains are more difficult the interpret. The best thing about the model is that a firm can make an estimation of what Markov chain is most fitting for their supplier. Based on this estimation we can look in the table what the best matching strategy is. If we use it the other way around there is no clear conclusion. The strategies seem to work better when the frequency of disruptions is very low and the disruption lengths are long like Markov chain 2. However when the penalty cost are relative high Markov chain 3 seems to be more preferable. That is why it is better to use this tool the other way around and try to look for suppliers that have a disruptions process that looks like one of the Markov chains and then look which strategy performs the best.

The high average demand seems to be a naive strategy. It orders exactly the same as what is demanded in the long run. But it does not make use of long periods of low demand or high demand and thus in some situations the holding cost get really high or the penalty cost get really high. So it is better to choose a strategy that keeps in mind more factors then only that it needs to meet the demand in the long run.

Of course the demand distribution has a lot of influence on the strategies. The more predictable the demand is the better the strategy works. Especially for the high average demand strategy is this the case. The repair after down time and the (s,S) model seem to be pretty stable when the demand is more unpredictable.

9.2 Two suppliers two suppliers backed up problem

The most important finding is that the maximum capacity of the flexible supplier is very important. It is so important that when the maximum capacity seems to fit the demand a 10 % change in the parameter holding cost, penalty cost and purchasing cost seems to have almost no influence on the average cost per step. When the demand for both products is uniform between 1 and 5 the a maximum capacity of 6 seems to work the best out of the three maximum capacities 3, 6 and 10.

In a lot of situation the inventory control model seems to work the best. This is because it keeps track of the inventory and thus the recent demand. The other models just order a percentage of both products of the whole capacity although it is not necessary in a lot of cases. Therefore an inventory control model seems to work the best.

At last the value of a flexible supplier is difficult to measure because when you order from a flexible backup supplier the supplies have no delay in delivery. Of course in the model the penalty cost should represent that late delivery punishment for the firm. However penalty cost can be covered by other optimized cost. But when deliveries are late they can cause much more problems then only a small penalty cost. The strategies of the flexible supplier are performing really well but there are some cases where the use of a strategy is more then a good alternative for the backup supplier. The importance of this missing factor in the model will be discussed in the next section.

10 Discussion

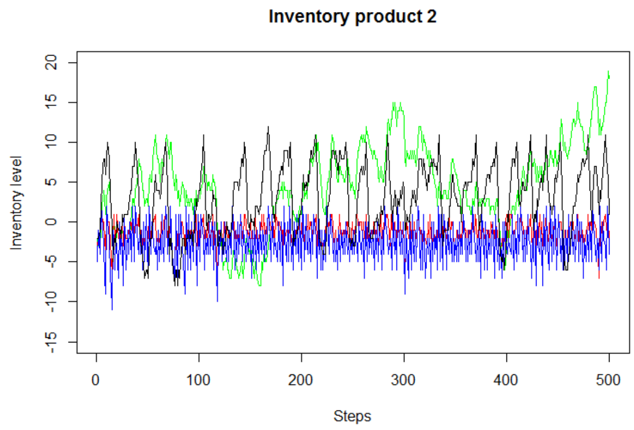
The value of a flexible backup supplier is visible in the results. The cost in a lot of different situations is pretty stable and not much higher then when certain strategies are used. However this model does not take into account that a late delivery can have much more influence then just a penalty cost. The value of a flexible backup supplier is that the supplies are delivered although the primary supplier is down. This is difficult to model but should taken into account. An other important factor are lead times. This is related to the first discussion point that is stated. Long lead times can cause for big problems in a supply chain. Now the supply chain is not that big. But if the firm needs to deliver to an other firm or store, the problems double. Lead times are not taken into account in this model and this is a disadvantage for the flexible backup supplier in this model. The flexible backup supplier can deliver immediately although the primary supplier is down. The strategies will perform much worse if lead times are taken into account. Take for instance the repair after down time. It just lets the inventory become negative, pays the relatively low penalty costs and orders the units that are needed after the down time, way to late for the firm that ordered the units a few steps back. This can be confirmed by the fact that this strategy was pretty stable until the penalty cost went up. Because the penalty cost are pretty low in this model this was not a big shock and every thing seemed okay. But if long lead times lead to extra penalty cost the repair after down time strategy would perform a lot worse.

In line with this is the fact that only costs are taken into account. However a firm wants to please their clients with good deliveries that are on time. So a strategy that has a lot of cost advantages could lead to unsatisfied clients.

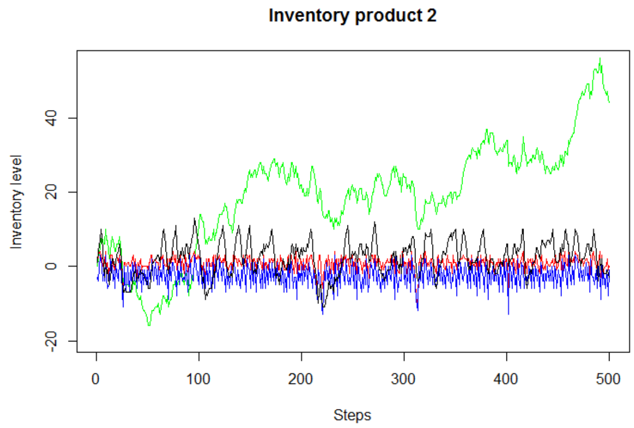
Of course the way of modeling can lead to a lot of problems. This model is simulated which also cause for results that has an error margin. This is taken into account by constructing the confidence intervals. But still the model is pretty static and has no big surprises. All the assumptions that are made also influence the results. The assumptions are explained in the first sections and are taken into account.

The last discussion point is the state of the supplier. We only looked at two states, up or down. However a supplier could be in a lot more states. In a lot of situations the supplier can be down for a percentage of its capacity. If this was taken into account this would lead to whole other results.

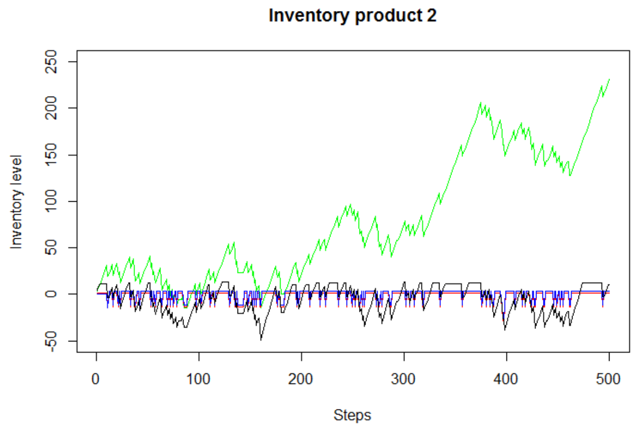
A Inventory tables of the two suppliers one supplier backed up problem



(a) The inventory of product 2 with uniform demand

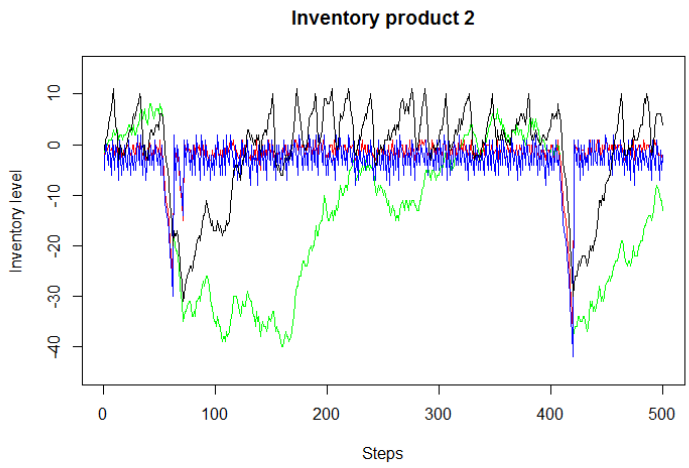


(b) The inventory of product 2 with Poisson demand

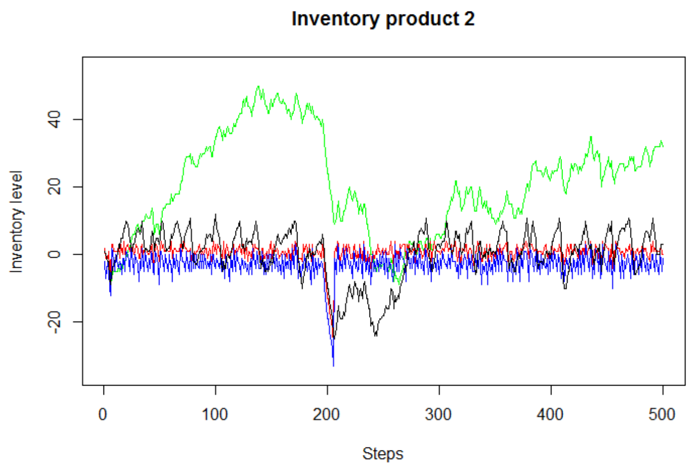


(c) The inventory of product 2 with Bernoulli demand

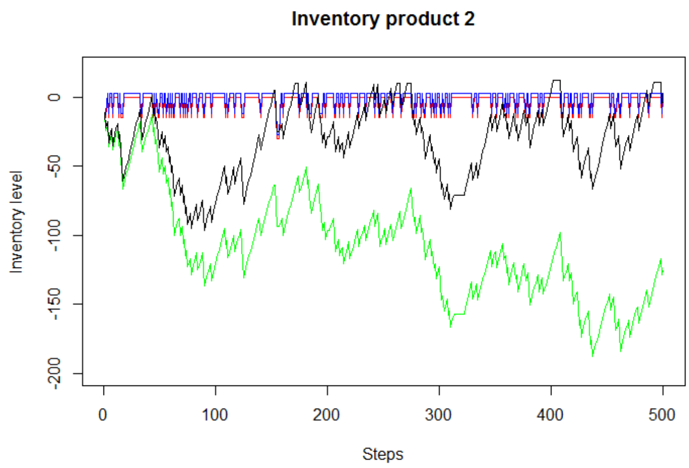
Figure 3: Graphs of the inventory of product 2 where for supplier 2 Markov chain 1 is used with different demand distributions



(a) The inventory of product 2 with uniform demand

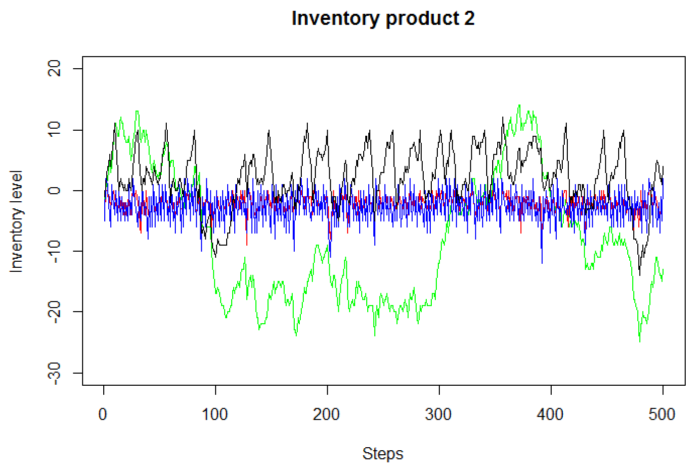


(b) The inventory of product 2 with Poisson demand

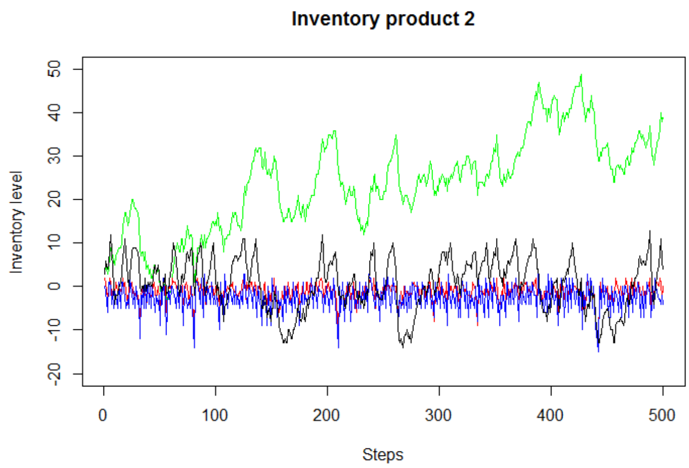


(c) The inventory of product 2 with Bernoulli demand

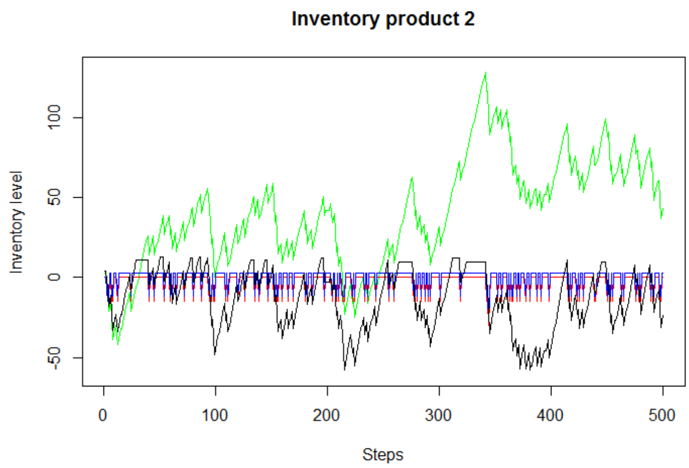
Figure 4: Graphs of the inventory of product 2 where for supplier 2 Markov chain 2 is used with different demand distributions



(a) The inventory of product 2 with uniform demand



(b) The inventory of product 2 with Poisson demand



(c) The inventory of product 2 with Bernoulli demand

Figure 5: Graphs of the inventory of product 2 where for supplier 2 Markov chain 3 is used for different demand distributions

B Tables for the confidence intervals of the two suppliers one supplier backed up problem

	Supplier 1 backed up	supplier 2 backed up
Strategy	product 1	product 2
High average demand	(287.14 ; 296.32)	(217.47 ; 223.25)
Repair after down time	(21.57 ; 21.65)	(20.93 ; 21.03)
(s,S) model	(27.43 ; 27.49)	(26.74 ; 26.80)
High level inventory	(32.91 ; 93.05)	(26.01 ; 26.69)

Table 12: The confidence intervals in Euro for the average cost per step for the whole system where for supplier 1 Markov chain 1 is used and for supplier 2 Markov chain 2 is used. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up	supplier 2 backed up
Strategy	product 1	product 2
High average demand	(243.73 ; 249.81)	(305.34 ; 314.12)
Repair after down time	(20.34 ; 20.42)	(21.50 ; 21.58)
(s,S) model	(26.36 ; 26.42)	(27.75 ; 27.81)
High level inventory	(25.30 ; 25.36)	(33.78 ; 33.92)

Table 13: The confidence intervals in Euro for the average cost per step for the whole system where for supplier 1 Markov chain 2 is used and for supplier 2 Markov chain 3 is used. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up	supplier 2 backed up
Strategy	product 1	product 2
High average demand	(339.94 ; 347.26)	(215.12 ; 221.24)
Repair after down time	(21.77 ; 21.85)	(21.97 ; 22.05)
(s,S) model	(27.12 ; 27.18)	(27.94 ; 28.00)
High level inventory	(32.24 ; 32.32)	(26.84 ; 26.90)

Table 14: The confidence intervals in Euro for the average cost per step for the whole system where for product 1 $h_1 = 1.5$ and for product 2 $h_2 = 3.5$ is used and Markov chain 2 is used for both suppliers. Furthermore the following parameters are used: $c^j = 2$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up	supplier 2 backed up
Strategy	product 1	product 2
High average demand	(399.19 ; 408.33)	(292.98 ; 300.68)
Repair after down time	(22.99 ; 23.07)	(22.75 ; 22.83)
(s,S) model	(28.05 ; 28.11)	(29.17 ; 29.23)
High level inventory	(39.06 ; 39.20)	(34.52 ; 34.66)

Table 15: The confidence intervals in Euro for the average cost per step for the whole system where for product 1 $h_1 = 1.5$ and for product 2 $h_2 = 3.5$ is used and Markov chain 3 is used for both suppliers. Furthermore the following parameters are used: $c^j = 2$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up	supplier 2 backed up
Strategy	product 1	product 2
High average demand	(278.93 ; 285.51)	(200.67 ; 205.01)
Repair after down time	(19.98 ; 20.04)	(19.01 ; 19.07)
(s,S) model	(26.31 ; 26.33)	(21.16 ; 21.22)
High level inventory	(31.80 ; 31.94)	(25.99 ; 26.07)

Table 16: The confidence intervals in Euro for the average cost per step for the whole system where for product 1 $p_1 = 1.5$ and for product 2 $p_2 = 3.5$ is used and Markov chain 2 is used for both suppliers. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up	supplier 2 backed up
Strategy	product 1	product 2
High average demand	(211.49 ; 216.85)	(156.85 ; 159.97)
Repair after down time	(18.91 ; 18.97)	(18.47 ; 18.53)
(s,S) model	(24.95 ; 24.97)	(20.62 ; 20.66)
High level inventory	(23.82 ; 23.84)	(22.82 ; 22.86)

Table 17: The confidence intervals in Euro for the average cost per step for the whole system where for product 1 $p_1 = 1.5$ and for product 2 $p_2 = 3.5$ is used and Markov chain 3 is used for both suppliers. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 5$, Uniform demand distributions between [1,5] are used, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up	supplier 2 backed up
Strategy	product 1	product 2
High average demand	(286.00 ; 293.48)	(232.09 ; 237.99)
Repair after down time	(24.29 ; 24.39)	(23.16 ; 23.26)
(s,S) model	(29.19 ; 29.25)	(29.35 ; 29.45)
High level inventory	(31.76 ; 31.84)	(29.07 ; 29.17)

Table 18: The confidence intervals in Euro for the average cost per step for the whole system where product 1 has a uniform demand distribution between [1,5] and product 2 has a Poisson demand distribution with $\lambda = 3$. For both suppliers Markov chain 1 is used. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 9$, Total steps = 10 000, Total runs = 100.

	Supplier 1 backed up	supplier 2 backed up
Strategy	product 1	product 2
High average demand	(764.77 ; 788.35)	(310.53 ; 319.89)
Repair after down time	(31.21 ; 31.29)	(30.97 ; 31.05)
(s,S) model	(32.48 ; 32.56)	(36.06 ; 36.08)
High level inventory	(136.22 ; 137.30)	(38.50 ; 38.54)

Table 19: The confidence intervals in Euro for the average cost per step for the whole system where product 1 has a Poisson demand distribution with $\lambda = 3$ and product 2 will have a Bernoulli demand distribution with a 0.2 percent chance of ordering 15 units. For both suppliers Markov chain 1 is used. Furthermore the following parameters are used: $c^j = 2$, $h_j = 1.5$, $r_j = 4.5$, $p_j = 3.5$, $u^f = 0.2$, $\frac{c_j^f}{c^j} = 1.1$, $Q^f = 15$, Total steps = 10 000, Total runs = 100.

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