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SIMULATION-BASED ANALYSIS OF INVENTORY LEVELS FOR LOW DEMAND SPARE PARTS IN A COOPERATIVE INVENTORY POOLING-SYSTEM

Yannic Hafner[a], Christian Looschen[b], Johannes Fottner[c]

[(a),(b),(c)]Technical University of Munich, Chair of Materials Handling, Material Flow, Logistics, Boltzmannstr. 15, 85748 Garching, Germany

[(a)]yannic.hafner@tum.de, [(b)]christian.looschen@tum.de, [(c)]j.fottner@tum.de

ABSTRACT

Due to their systemic relevance, a high availability of intralogistics systems is crucial. This requires the stockpiling of capital-intensive spare parts. Strategies are therefore needed to reduce the severe capital commitment for spare parts management. No practical recommendations and solutions for this problem are available however. This contribution describes strategies and procedures for a cooperative inventory pooling-system and our model of a simulation-based analysis of inventory levels for low demand spare parts in these systems. We determine that companies can gain benefits and greatly lower their inventory level and associated costs when cooperating in spare parts management. Furthermore, we investigated effects of changing network compositions while cooperating over time.

Keywords: spare parts management, cooperative inventory-pooling, discrete event simulation, inventory optimization

1. INTRODUCTION

Intralogistics systems are the basis for internal material flows and value creation of producing or distributing companies. Therefore, a high availability of these systems is crucial. This requires the stockpiling of capital-intensive spare parts. The majority of the necessary spare parts are expensive and characterized by sporadic demand, which leads to an increased and often obsolete stock of spare parts (Huiskonen 2001). The annual material costs for the spare parts are up to approx. 2.5 % of the purchase price of an installation (Gallagher et al. 2005). Hence strategies are needed to reduce the severe capital commitment for warehousing of these necessary spare parts.

A cooperative inventory pooling-system is one promising solution to increase the efficiency of spare parts management. This contribution deals with a simulation-based analysis of inventory levels for low demand spare parts in a cooperative inventory pooling-system.

2. STATE OF SCIENCE AND TECHNOLOGY

An optimal inventory level can be calculated using analytical and simulation-based models and is the subject of numerous scientific studies. In this contribution, we focus on literature that deals with the inventory management for cooperating inventory pooling-systems. Paterson et al. (2009) summarize and review several publications on inventory models with lateral transshipments, a synonym for inventory pooling. These use different key characteristics to differentiate between the models introduced in the different papers and articles. These are, among others, the characteristics of the depicted system (number of echelons, number of warehouses, number of items), the ordering timing and policy, the transshipments and pooling types. Considering only models in which characteristics are most similar to ours, we can limit the relevant publication reviewed by Paterson et al. to models with reactive lateral transshipments in a single echelon logistics system with complete pooling. The review of the inventory in these systems is continuous and a (S-1, S) reordering policy is used. Full pooling of the models inventory is assumed.

Kukreja et al. (2001) define an analytical model for the required network stocking level that minimizes inventory costs while respecting the desired Service Level of the cooperation. A Poisson distribution is used to derive a lower bound for the stocking level. All companies in the network have identical spare part demands.

Wong et al. (2006) also use an analytical model to measure the performance of their single-echelon pooling system with *n* different companies sharing repairable items. The performance is measured by the system's Service Level, the expected total downtime for a company and the expected number of lateral transshipments.

While many other authors consider a zero lateral transshipment time, Wong et al. consider a non-zero lateral transshipment time that is distributed exponentially. The repair time of items, which includes the shipment time to the repair facility, is also modelled as exponentially distributed. The authors show, that delayed lateral transshipment have a big impact on the expected number of backorders and that this has to be considered when deciding how many and where items are to be stocked.

Karsten and Basten (2014) investigate a joint inventory pooling and the influence on the cost for spare parts management. Multiple companies, each having a Poisson demand process for expensive, low demand items, are storing every spare part at a single mutual location. The authors calculate the necessary on-hand stock, if *n* companies are pooling their spare parts. Using cooperative game theory, they derive a function for the expected storage costs and a function for allocating the costs throughout the cooperation of companies so that each company benefits economically.
A stochastic cost model for joint spare part inventories is described by Wang (2012). The model optimizes the inventory control of the required spare parts and the machine inspection interval. Wang uses an algorithm with stochastic dynamic programming to find optimal joint solutions.
Fritzsche (2012) considers further cost estimations in a cooperative inventory pooling-system. Assuming a dynamic failure rate and using the MFOP (maintenance free operating period) process, the author shows that using dynamic failure rates instead of constant ones to describe the failure of spare parts results in the reduction of costs and improvement of operational stock planning. This is achieved by MFOP, which guarantees multiple maintenance free periods and the use of memory learning systems to optimize the calculation of the failure.
State of science and technology show a wide range of analytical and simulation-based models to find an optimal joint inventory level. Karsten and Basten (2014) extend their model using cooperative game theory, in consideration of the behavior of the different members. All models have in common that the inventory pooling describes a situation in which the companies are cooperating before buying necessary spare parts and without already acquired spare part inventories. The situation of companies starting a new cooperation with existing inventories is not considered. An optimal solution will be reached in the future, but interested companies have no way to investigate their benefits and evaluate the effect of the cooperation beforehand. New companies might want to join the cooperation, whereas other companies leave. New spare parts can be pooled and necessary costs reduced or other spare parts can't be stockpiled economically in the network anymore. This research gap is addressed in our contribution.

3. CONSIDERED SYSTEM AND STRATEGIES

The simulation depicts a network with *n* different companies, one central internal supplier, one external supplier and one central network platform as a control unit.
We consider two different representative spare parts (*SP1*, *SP2*) with varying demands, with not every company having a need for each spare part. The demand of a company is characterized by the failure of the parts inside the companies' machines. The demands of the companies are independent from each other.
Every spare part is stored centrally at one location, since delivery times between companies are negligible in our network. It is assumed that the time between ordering a spare part and receiving it from a cooperation partner is equal to the time for disassembling the machine to access the faulty part. To reduce necessary deliveries, the spare parts are stored at the company with the highest demand, which acts as a central internal supplier. A one-for-one replenishment policy (S-1, S) is implemented. Failed parts are removed from the system and not repaired.
The procedure for ordering a spare part is shown in Figure 1. If a spare part demand arises, the company that needs the spare part places the order in the central network platform. The platform then processes the order and checks which spare part is needed and whether the order can be fulfilled from the cooperative inventory. Orders are hereby processed on a first-come, first-served basis. If a spare part is available, the storage location will be checked. Spare parts stored at the ordering company can be taken directly from the stock. A new part will immediately be reordered by the platform from the supplier to ensure a desired Service Level. This part is sent to the company that acts as the central internal supplier. The delivery time for this reorder is t_s. If the spare part is available at a network partner, it will be handled as an internal order and delivered from this location before a new spare part is reordered.
If an order cannot be filled from the system inventory, the platform inquires if an already ordered spare part of the same kind is close to delivery to the central internal supplier. If the remaining delivery time of the needed spare part is smaller than an accepted downtime t_{dt}, the part is rerouted to the company which placed the order and is finally delivered to this company in need, before a new spare part will be reordered. The accepted downtime is hereby shorter than the total delivery time for reordering a spare part from the central supplier ($t_{dt} << t_s$). If no part is available in the network inventory and there is no sufficient open order, an emergency order with penalty charges is placed with an external supplier that can supply the spare part within the accepted downtime t_{dt} of the manufacturing process. Ordering costs are accounted once the spare part arrives at the company.

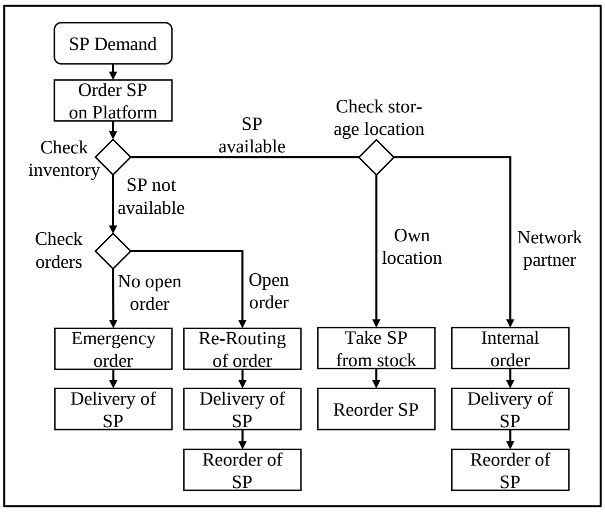

Figure 1: Procedure when ordering a spare part

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4. SIMULATION MODEL

We followed the typical proceeding of building and evaluating a simulation, generalized by the VDI-3633 (VDI 2014) guideline of the Association of German Engineers, to transfer the considered system into a simulation model in the simulation environment *Tecnomatix Plant Simulation*.

The simulation model consists of different modules and elements, the main ones being the *company*, the *central network platform*, the *external supplier*, the *central internal supplier* and the considered *spare parts*.

A company module consists of a component representing the inventory, the machines used by the company, a receiving area and a distribution area. Methods control the flow of goods in and out of the inventory, the distribution of incoming goods inside the company and the distribution of goods out of the company. Another method in the module manages the company's order procedure, while it is presumed that the company has a limitless storage capacity. The machines of a company are depicted as a working station, which can hold multiple (spare) part elements. A method inside the machine module calculates the time until the failure of the part. A formula for the Weibull distribution with the form parameter β and the scale parameter η is used to calculate this time.

A method controlling the machine output destroys the spare part element after its time in the machine has run out and then initiates a spare part order.

Imbedded inside the module for the network platform are the methods controlling the spare parts order process. These can be classified into methods controlling the replacement of the stocked part, the network internal delivery, the order process from the central internal supplier, the order process from the external supplier and the rerouting of a nearly completed order from one company to another. Included in the network platform is also a method calculating and updating the Service Level of the cooperative inventory pooling-system every twelve hours. For evaluation, we take track of the current demand of the companies and record the inventory level in the pooling-system. The Service Level is calculated by dividing the number of total deliveries minus the number of emergency deliveries from the external supplier by the total number of deliveries.

The modules for the central supplier and for the external supplier are similarly built. Both have methods for creating a spare part element when ordered and for distributing these spare parts to the ordering companies. The production or acquisition of a spare part is represented by the creation of a spare part element inside a buffer module. The element stays in the module for the whole delivery time. As the delivery time for reordered spare parts to the central internal supplier (t_s) is longer than the ones coming from the external supplier (t_{ex}), the central internal supplier module documents the information of current reorder procedures at the supplier. In terms of real and simulation, the time for delivering the spare parts is of no consequence.

The input variables are:

- the experiment number e_n
- the spare part type *SPn*
- the number of companies in the cooperation nr_c
- the number of warehouses nr_w
- the desired Service Level SL_d
- the inventory level of the whole cooperation to be investigated I
- the Weibull form-parameter β
- the Weibull scale-parameter η in days
- the delivery time of an internal delivery from the central internal supplier to another company t_{id} in days
- the delivery time of a reordered spare part from the supplier t_s in days
- the delivery time for an emergency order from the external supplier t_{ex}
- the tolerated machine downtime t_{dt}
- the number of parts needed by a company for their machines nr_p equivalent to the average demand per characteristic lifetime d_{cl}

Additional variables are the internal delivery costs for orders from the central internal supplier C_{id}, the spare part costs for a spare part ordered from the central internal supplier C_s, the spare part costs for ordering the spare part from the external supplier for emergency orders C_e and the inventory holding costs C_h. In addition, the input control allows the user to choose if the number of companies changes over time. This means that an additional company module is included into the simulation model, having the attributes set in the specific tables inside the simulation control, or a company is removed from the model.

The output of the simulation is as follows:

- the Service Level of the cooperative inventory pooling-system over time
- the cumulated total costs for each company in the cooperation
- the costs per company for each year
- the number of total deliveries divided into the separate delivery types for the whole network and for each company
- the time every part is installed in the machine module (depicting the time between demands)

At the beginning of the simulation, after the matching of the input variables, the number of companies nr_c specified in the input are created and the spare part elements are distributed over the number of warehouses nr_w with the companies with the highest demand assigned the central internal supplier. Subsequently, elements are created according to the number of parts nr_p in the machines of the companies. Failure times are calculated using the Weibull distribution function and assigned to the parts.

Once the set-up is complete, the simulation follows the previously described procedures (Section 3).
The simulation model needs to be validated and verified before experiments can be conducted. In a first step we used a structured walkthrough to verify that the implementation does not have any mistakes and that the model and the running processes matched the considered system description (Section 3 and Section 4). A second step included the carrying out of experiments to verify, that the distribution of the times between demands in the simulation model concur with the Weibull distribution chosen for the depiction of demand in the network. The results of the experiments showed a consistency of the analytical and simulated distributions. The simulation model is therefore regarded to be valid.

5. EXPERIMENTS

The conducted experiments aimed to answer the following questions

1. What is the needed inventory level to reach a desired Service Level of 95 % in different representative cooperative inventory pooling-systems warehousing low demand spare parts?
2. What is the effect during an increase of spare parts demand d_{cl} for certain inventory levels?
3. What are the costs and the amount of necessary spare parts per company for companies that are part of the cooperative inventory pooling-system compared to a stand-alone solution?
4. What is the effect over time when a new company with existing inventories joins or leaves the cooperative inventory pooling-system?

Due to the randomly distributed spare part demand of each company in our cooperative inventory pooling-system we need to determine the number of simulation runs for each experiment. We aim to receive a confidence interval for the average Service Level of 1 % with a confidence level of 95 %. By testing a number of simulation runs we achieved this confidence interval with 500 runs for every experiment.
The first experiments were used to analyze the needed inventory levels for two different spare part types (*SP1*, *SP2*) to reach a desired Service Level of at least 95 % with different network sizes. *SP1* represents a typical gear motor and *SP2* a conveyor belt that is subject to high wear and tear. Effects and costs are analyzed during an increase of the spare part demand d_{cl}. The parameters for the simulation are given in Table 1. The Design of Experiments was used to create an experimental design with an experiment number of 270 for each spare part type.

Table 1: Parameters for experiments analyzing the needed inventory level for a desired Service Level of 95 %

Parameter	*SP1*	*SP2*
nr_c	2-10	2-10
nr_w	1	1
SL_d	95 %	95 %
I	1-10	1-10
β	1.2	1.2
η	3 years, 5 years, 10 years	0.5 years, 1 year, 1.5 years
t_{id}	0	0
t_s	35	28
t_{ex}	1	1
t_{dt}	1	1
d_{cl}	1	1

The cost function takes inventory holding costs C_h in percent per day, costs for an internal delivery C_{id}, costs for the spare part served from the cooperation C_s and costs for the spare part from an external supplier C_e, which is three times C_s, into account. The values for these costs are based on analyzed industry data sets and are shown in Table 2.
Inventory costs are distributed among the companies of the network; all other costs are accounted when a spare part is ordered.

Table 2: Parameters for the spare parts related costs for experiments analyzing the occurred costs for companies that are part of the cooperative inventory pooling-system

C_{id}	C_s	C_e	C_h
80 €	2105 €	6315 €	15 %

The second excerpt of experiments was used to analyze the reaction of the networks' Service Levels over time if a company joins or leaves the cooperative inventory pooling-system. Therefore, a network of four companies with one central internal supplier was set up. After roughly three years, a company joins or leaves the network with its own inventory and a machine part already in use. In this scenario, all companies have the same demand for each spare part of the type *SP1* with a characteristic lifetime of three years.
The simulation time for all conducted experiments was 15 years.

6. RESULTS

In this section, we present and discuss the results obtained by the experiments described in section 5.

6.1 Inventory levels for a Service Level of 95 % in different representative cooperation networks

A cooperative inventory pooling-system is highly interesting for companies that aim to reduce their required inventory levels and therefore, the necessary capital commitment costs to serve a specific Service

Level. As a basis for comparison, Table 3 shows the required inventory levels of a single company not cooperating at different demands d_{cl} to reach a 95 % Service Level for spare part *SP1* and *SP2*.

Table 3: Results for analyzing the required inventory levels for achieving a desired Service Level of 95 % at different demands d_{cl} of a single company for spare part *SP1* (η = 3 years) and *SP2* (η = 1 year)

Demand d_{cl}	*SP1*		*SP2*	
	Inventory Level	Service Level in %	Inventory Level	Service Level in %
1	1	98.77	1	95.6
2	1	95.77	2	99.58
3	2	99.76	2	98.46
4	2	99.55	2	97.43
5	2	99.13	2	95.57
6	2	98.81	3	99.21
7	2	98.32	3	98.81
8	2	97.91	3	98.35
9	2	97.28	3	97.77
10	2	96.65	3	97.03

For *SP1*, an inventory level of one is sufficient to satisfy a demand d_{cl} of up to two parts. A higher demand of ten parts requires the stockpiling of one more part. *SP2* has a significant shorter characteristic lifetime which leads to an inventory level of up to three parts.
The results presented in Table 4 and Table 5 show the maximum number of companies with a demand d_{cl} of one each that can cooperate to guarantee a 95 % Service Level with an identified inventory level. As expected, the number of companies able to be supplied, and the achieved Service Level rise with the number of spare parts on stock.

Table 4: Results for analyzing the required inventory levels for achieving a desired Service Level of 95 % in different sized cooperation networks for spare part *SP1*

Characteristic Lifetime in years	Inventory Level	Max. number of companies	Service Level in %
3	1	2	95.59
3	2	10	96.72
3	3	10	99.69
5	1	3	95.43
5	2	10	98.61
5	3	10	99.91
10	1	5	95.64
10	2	10	99.79
10	3	10	99.96

The jump between the maximum number of companies for an inventory level of one and two for *SP1* with a characteristic lifetime of three years is prominent in Table 4. A maximum of two companies can be supplied with an inventory level of one spare part and a Service Level of 95.59 % will be reached. Warehousing just one more spare part allows the cooperative inventory pooling-system to supply up to ten companies, which results in an even higher Service Level of 96.72 %.
Table 5 shows comparable results: An inventory level of a maximum of four spare parts is sufficient to supply a cooperative inventory pooling-system of ten companies.

Table 5: Results for analyzing the required inventory levels for achieving a desired Service Level of 95 % in different sized cooperation networks for spare part *SP2*

Characteristic Lifetime in years	Inventory Level	Max. number of companies	Service Level in %
0.5	2	2	97.78
0.5	3	5	97.31
0.5	4	10	97.09
1	2	5	95.77
1	3	10	97.2
1	4	10	99.45
1.5	2	5	98.1
1.5	3	10	98.91
1.5	4	10	99.89

Comparing the results of Table 4 and Table 5 show that an increasing inventory level is necessary for spare part *SP2* to satisfy the demand of the same number of companies. Seeing that the form-parameter β is the same for *SP1* and *SP2* the increase can be explained with a reduction of the average characteristic lifetime of *SP2*, as is to be expected.
With an increasing inventory level, the average amount of spare parts per company needed to guarantee a desired 95 % Service Level is reduced (Figure 2). Supplying ten companies with two spare parts *SP1* results in 0.2 spare parts per company that have to be financed and stored at a time compared to an inventory level of one for a single company. Similar results can be determined for spare part *SP2*, where 0.3 spare parts per company are required.

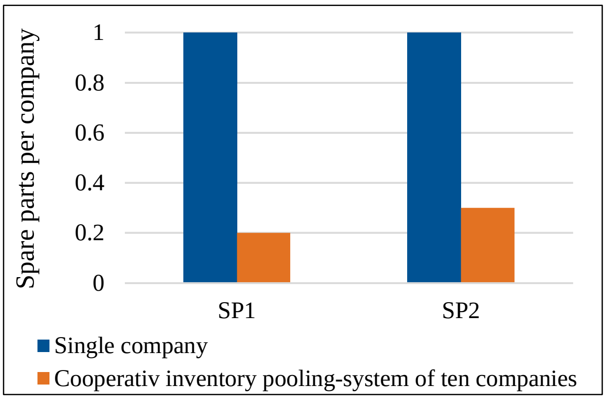

Figure 2: Spare parts per company for a single company and a cooperative inventory pooling-system of ten companies

6.2 Effects when increasing the spare part demand for certain inventory levels

Figure 3 shows the effect when increasing the spare part demand for *SP1* (η = 3 years) and *SP2* (η = 1 year) for certain inventory levels and completes the previous investigations. Each company faces the same demand of one spare part.

In the following, we note that the Service Level for *SP2* is more dependent on the inventory level as the characteristic life time is much shorter.

Furthermore, a demand for *SP1* and an inventory level of one lead to a Service Level of 98.5 %. A comparable Service Level can be achieved having two spare parts on stock for six companies. An inventory level of three leads to a Service Level of nearly 100 % in a cooperation of ten companies.

For *SP2*, we achieve a comparable Service Level of 95 % for one company warehousing one spare part or ten companies warehousing three spare parts.

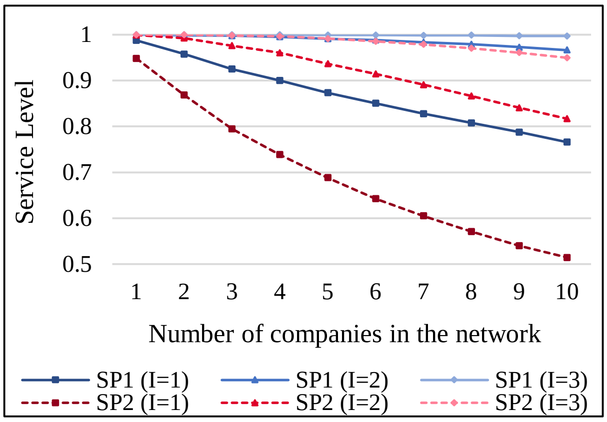

Figure 3: Service Level over networks' spare part demand for *SP1* and *SP2* for an inventory level of one to three

6.3 Costs evaluation of the cooperative inventory pooling-system

Joining a cooperative inventory pooling-system leads to a reduced amount of spare parts per company. However, the decision of joining such a system is cost-dependent. Necessary costs need to be examined. An initial cost function was therefore derived.

Using this simple cost function provides a first overview of the incurred cumulated costs for each company over a time of fifteen years (Figure 4). The referred representative network consists of five companies (C1 to C5) warehousing two spare parts *SP1* that result in a Service Level of 99.13 %. All companies face a spare part demand of one *SP1* with a characteristic lifetime of three years. The spare parts are stored centrally at Company 1 to fulfill occurring demands.

For the described scenario, savings of about 30 % to 40 % compared to a single company (SC) without a cooperative inventory pooling-system can be realized while the Service Level stays at this high level. The cost-saving effect increases with the number of cooperating members. However, a positive effect can already be seen when two companies are cooperating.

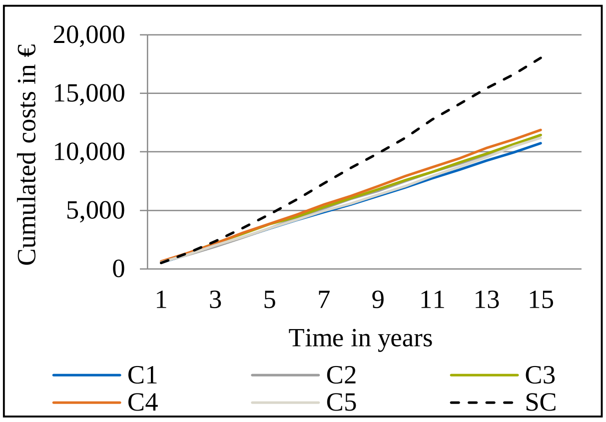

Figure 4: Cumulated costs for a cooperative inventory pooling-system of five companies warehousing *SP2*

6.4. Changing the network composition while cooperating

In another excerpt of experiments, we analyzed the effects of changing the network composition while cooperating. We analyzed the resulting Service Level over time. The results showing the Service Level for a System with

- no changes (NC),
- a joining company without its own inventory (J-0SP),
- a joining company with an own stock level of one spare part (J-1SP),
- a joining company with an own stock level of two spare parts (J-2SP) and
- a leaving company (LC)

are shown in Figure 5.

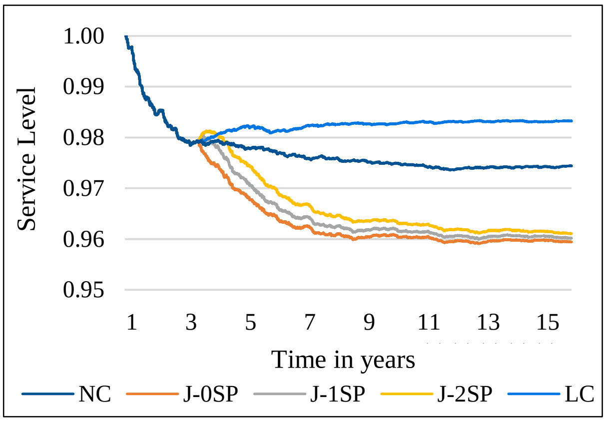

Figure 5: Service Level over time when changing the network composition while cooperating

A system with no changes as reference shows a Service Level of about 97.4 %. Companies joining the cooperation lead to an increased spare parts demand; in our experiments; this results in a growth of 25 %. The Service Level over time therefore drops to 96 %. The difference between companies joining with or without an own stock of spare parts is a delayed drop of the Service

Level. For a short period of time, the actual Service Level increases when joining due to the own stock. This effect is enhanced when the company joins with two spare parts.
When a company leaves the cooperation, the demand is reduced. This leads to an increase of the Service Level over time to about 98.4 %.

CONCLUSION AND OUTLOOK

In this contribution, we considered a cooperative inventory pooling-system for low demand spare parts. We conducted a series of simulation experiments to compare cooperation to the stand-alone solution based on required inventory levels and costs to achieve a desired Service Level.
We were able to show that companies can lower the amount of necessary spare parts per company greatly when cooperating. A cooperation size of ten companies leads to a reduction of required spare parts per company of 70 % to 80 %. A first cost function was derived and showed, that economic benefits of 30 % to 40 % can be gained in the long-term.
Furthermore, the effects of changing the network composition while cooperating were examined. It can be noted that a joining company has a low negative long-term effect on the cooperation. The effect is delayed when bringing an own inventory. Companies leaving the cooperation slightly raise the Service Level over time.
By way of next research, we suggest implementing a detailed cost function that considers date of payment and the resulting free cash flow individually for each company and for the cooperation.
In addition, recommendations for companies that are interested in a cooperative inventory pooling-system that faces different demands for specific spare parts need to be developed and derived.

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YANNIC HAFNER has been working as a research associate at the Chair of Materials Handling, Material Flow, Logistics at the Technical University of Munich, since 2017. His research deals with digital platforms for cooperative inventory pooling-systems.

CHRISTIAN LOOSCHEN graduated from the Technical University of Munich. His master's thesis deals with a simulation-based analysis of inventory levels for low demand spare parts in cooperative inventory pooling-systems.

JOHANNES FOTTNER is professor and head of the Chair of Materials Handling, Material Flow, Logistics at the Technical University of Munich. His research interests include investigating innovative technical solutions and system approaches for optimizing logistical processes.