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Assessing the price of robustness for dynamic production processes

Bernd Scholz-Reiter
BIBA - Bremer Institut für Produktion und Logistik GmbH, University of Bremen
Hochschulring 20, 28359 Bremen, Germany
bsr@biba.uni-bremen.de
+49 (0) 421 – 2185576

Thomas Makuschewitz
BIBA - Bremer Institut für Produktion und Logistik GmbH, University of Bremen
Hochschulring 20, 28359 Bremen, Germany
28359 Bremen, Germany
mak@biba.uni-bremen.de
+49 (0) 421 – 2185579

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Abstract

Expected and unexpected events, like scheduled maintenance or a temporary machine-breakdown, reduce the available production capacity and can put the timely satisfaction of customers at risk. In addition the aging of production equipment or new technological requirements lead to reduced on average available capacities. A robust capacity allocation to the production processes enables a supply chain to cope with a certain magnitude of reduced production capacities. This paper presents a new approach to robust capacity allocation with respect to such reductions and the price of capacity. To this end dynamic supply chains are modeled by multiclass queueing networks that can be approximated by fluid models. The stability radius reflects the smallest perturbation that destabilizes the supply chain and is used as a measure for the robustness. Based on findings concerning this measure a mathematical optimization problem for the price-oriented capacity allocation is formulated. This approach allows assessing the price of robustness that is related to a certain stability radius.

Keywords: Supply Chains; Network Engineering; Capacity Management; Robustness

Track: Inventory and Capacity Management

I. INTRODUCTION

Assessing the price for a robust capacity allocation in dynamic supply chain is in general a challenging task. In particular, required levels of production capacity are also subject to a changing availability of these capacities. On the operational planning level perturbations of the available production capacities occur either in an expected or unexpected way. For instance production capacities may change due to a scheduled maintenance or a machine breakdown. On the strategic planning level long-term shifts of the on average available production capacity are in general unknown and have to be appropriately anticipated while allocating the required production capacity to each production process in the network. Such shifts are triggered by an aging production equipment or new technological requirements enforced by the customers.
Robustness characterizes the capability of a supply chain to handle such fluctuations or shifts of available production capacities at the different production locations, by remaining in a stable state [1]. This means that given such dynamics the customer demand can still be fulfilled. In this sense robustness can also be interpreted as a kind of capacity that is not required to handle ordinary daily operations. From a managerial point of view the costs for unused production capacity should be minimized. Nevertheless a certain level of robustness is desirable, since it allows a supply chain to handle changes of the customer demand up to a certain magnitude. In the following mainly strategic aspects related to a robust capacity allocation are addressed.

Nowadays strategic management decisions related to network design and the allocation of production capacities are usually based on future scenarios. These scenarios project the evolution of key parameters, e.g. on average available production capacity, and allow to find a reasonable network configuration. Since the evolution of the production capacity is not known prior, the creation of reasonable future scenarios is a challenging task. Another way to choose an appropriate capacity allocation is given by simulation and related sensitivity analysis. Simulation models allow to capture the dynamics of a supply chain by properly combining stochastic production processes and customer demand. Mathematical modeling approaches are also able to describe such dynamics and can be analyzed in an analytic way. Multi-class queueing networks are a typical representative of such modeling approaches. However, these approaches lack a reasonable and precise measure for the magnitude of robustness of a supply chain subject to a changing on average available production capacity. Such a measure is required in order to assess the price of a robust capacity allocation.

In this article the stability radius [2] is used as a measure for the robustness of a supply chain [3]. The stability radius is given by the smallest shift/decrease of on average available production capacity that destabilizes the supply chain. In particular the presented price-oriented approach for a robust capacity allocation aims to prepare a network precisely for a
reduced on average available production capacity of a certain magnitude on the long-term. To this end the approach comprises the following steps:

1) Set-up of a multiclass queueing network that models the stochastic processes of the original supply chain.

2) Approximate the queueing network by a fluid model.

3) Measure the robustness with the stability radius and minimize the price of the allocated capacity.

4) Transfer of results to the original supply chain

This analytic approach incorporates knowledge about the dynamic behavior of a supply chain as well as a consideration of uncertainty. In addition it allows to identify indicators for the point in time when it becomes necessary to adjust the available production capacities.

The remainder of this paper is structured as follows. Section II presents a brief review of relevant literature. In Section III an introduction to the stability and robustness of fluid models is given. Section IV presents a mathematical optimization model for a price-oriented allocation of capacity to the production locations. On the sequence a real world test case is presented together with a computational analysis. Some conclusions and an outlook are given in Section VI.

II. LITERATURE REVIEW

A main objective of the network design process is to ensure the capability of a supply chain to cope with a prior unknown development of key parameters by staying profitable. In this context not only locations of production locations have to be chosen but also appropriate production capacities for each location and processed product type. Advanced Planning Systems (APS) support the planning processes within supply chains. The underlying structure of APSs is illustrated by the Supply Chain Planning Matrix [4], shown in Fig. 1. The matrix comprises modules for the planning tasks that are characterized by time horizon and involved business functions. The degree of detail increases and the planning horizon decreases by shifting from the long-term to the short-term. These consecutive modules allow to handle the
complexity of an overall planning process [5]. The modules are often based on mathematical programming formulations or heuristics that assume deterministic planning information [6, 7]. However, it can be shown that such approaches fail to cope with a dynamic environment and the considerable uncertainty of the underlying planning information [1].

Figure 1. Supply Chain Planning Matrix.

Operations in supply chains are subject to time-varying internal and external fluctuations of key parameters. Such fluctuations occur either in an expected or unexpected way [8]. A typical example is given by scheduled maintenance or an unexpected breakdown of a resource. In particular such fluctuations determine the statistical dispersion of the probability distributions that describe each production process as well as the customer demand for certain products. Together, these distributions shape the dynamics of the whole supply chain. In this context it is a challenging task to determine whether a supply chain is able to fulfill customer demand or not [9]. Simulation models are a common tool to answer this question of stability or instability for a given network [10, 11]. A shift of the expected value of the underlying distributions captures mid- and long-term trends. For instance such a trend can be given by decreased production capacities. Companies collaborating in complex and dynamic supply chains have to adapt frequently their allocated production capacity in order to handle the given customer requirements [8].

Robustness characterizes the capability of a supply chain to handle shifts/trends of one or more relevant parameters, e.g. on average available production capacity, by remaining in a stable state [1]. Comprehensive sensitivity analyses based on simulation are used to understand
the impact of changing expected values. In this context results depend on the quality of the simulation model, the simulation software and the complexity of the analysis. Robust supply chain design is given by the capability of the network to cope with several possible future developments in an efficient manner [6, 12]. To this end planning approaches have to cope with a dynamic environment and the considerable uncertainty of the underlying planning information [6]. Stochastic programming and robust optimization are two methods to set up a robust plan that addresses uncertainty of relevant parameters [13]. These approaches are applied to network engineering problems [12, 14]. Nevertheless, the obtained planning results depend on the arbitrarily chosen scenarios.

Multiclass queueing models are a well established approach to capture the dynamics and uncertainty of manufacturing systems [15, 16, 17]. In addition they can be used to model coupled processes within supply chains. A queueing network and hence a supply chain is said to be stable if the total number of products in the network remains bounded over all time. This means that the long-run input rate of the network equals the long-run output rate. In particular the customer demand can be fulfilled and no products accumulate within the network. For a precise definition of stability for multiclass queueing networks see [18]. References [19] and [18] present an approach to investigate the stability of queueing networks by using a fluid limit model. The fluid approximation model is a continuous deterministic analogue of the discrete stochastic model. The stability of a corresponding fluid limit model implies the stability of the original queueing network [19]. In comparison to a queueing model the stability of a fluid model can be determined more easily.

Since the evolution of relevant external and internal parameters is not known prior a measure for the robustness of a supply chain is required. The stability radius of a network quantifies the size of perturbations that are guaranteed not to destroy stability [9]. This measure can be used to determine the smallest decrease of on average available production capacity that destabilizes a given supply chain.
III. STABILITY AND ROBUSTNESS OF FLUID MODELS

Multiclass queueing models that describe the dynamics of supply chains are the starting point for the price-oriented approach to capacity allocation. Since stability and robustness analyses of such networks are a difficult task, especially when the networks become large-scale, the fluid approximation of a queueing network is used on the sequence. The concept of the stability radius for dynamical systems can be adapted to the case of fluid network models and allows to measure their robustness [2]. The theoretical foundation for this paper is given in [9, 20] and especially in reference [21]. In this section the notation of fluid models as well as relevant results are summarized.

A fluid model allows to captures the essence of a multiclass queueing network on the long-term. To this end the expectation values of the underlying stochastic processes are considered instead of the stochastic distributions. The following model description is taken from [18]. The considered network consists of $j$ production locations and different product classes $k$. Every product class is processed exclusively at one location. The mapping $s : K \rightarrow J$ determines which product class is processed at which location and generates the so called constituency matrix $C$. Every product class $k$ has the exogenous arrival rate $\alpha_k$ and the process rate $\mu_k$. The external arrival rate models the customer demand of the real world network. The process rate $\mu_k$ is interpreted as the allocated production capacity that is available for the manufacturing of products of type $k$. After a product of class $l$ has been processed at a location it either leaves the network or becomes a product of another class $k$. This proportion $p_{lk}$ is modeled by the corresponding $K \times K$ transition matrix $P$. $P$ is chosen such that ultimately all products leave the network. A policy determines the order in which the arriving products are processed at each location. In this paper the head-of-the-line proportional processor sharing discipline (HLPPS) is used. Under this discipline all nonempty product classes present at a location are produced simultaneously proportional to their queue length.
A fluid network $Q$ is said to be stable, if there exists a finite time $\tau \geq 0$ such that all waiting queues of products become zero. Since fluid networks can contain re-entrant flows, the effective arrival rate for product class $k$ may be higher than the purely external arrival rate. The nominal workload $\rho_j$ of a production location $j$ is determined by the locally processed product classes, the internal routing of the network and the external arrival rate of relevant product classes. A necessary condition for the stability of a fluid network is that the nominal workload of every location $j$ is strictly less than one. However, a sufficient condition depends on the service discipline, i.e., fluid networks may be stable under one discipline but not under another, see [22]. For HLPPS a nominal workload less than one for all locations is a sufficient condition for stability [19].

In this paper the robustness of a given fluid network $Q$ is measured with respect to a shift of the on average available production capacity $\Delta \in \mathbb{R}_+^k$ that influences the effective process rates $\mu$, $Q(\Delta) = (\alpha, \mu - \Delta, P, C)$. The stability radius is given by the smallest shift of on average available production capacity $\Delta \in \mathbb{R}_+^k$ such that $\rho(\Delta) \geq 1$ holds for at least one production location $j$. This approach allows to quantify for a given network, determined by $\alpha$, $\mu$, $P$ and $C$, the robustness with respect to shifts of the process rates. Furthermore, the stability radius is a property of a given system. Consequently different values of $\alpha$, $\mu$, $P$ or $C$ lead to different stability radii [21]. In particular the stability radius can be calculated in the following way: Consider every location separately. Then shift the on average available production capacity, changing the process rate of exactly one product class, and find the $\Delta$ that destabilizes the network. Finally take the minimum of all $\Delta$. This procedure is as well sufficient to ensure stability of combined decreases of process rates, as long as their aggregated magnitude remains below the stability radius. In particular this means that the production capacity of several product classes can decrease at the same time and the supply chain remains stable. Fig. 2 shows an illustration of the stability region for decreased process rates. In this
case a production location manufactures 2 different product types and has to allocate its capacity between them.

Figure 2. Illustration of the stability radius for one production location processing two product classes.

The light gray area presents the region of stable combinations of production capacities / process rates that are able to fulfill a given customer demand. The dark gray area within the rhombus illustrates the region of the stability radius. In particular the smallest decrease of production capacity that leads to instability is given by a decrease of process rate $\mu_2$. A decrease of the same magnitude of process rate $\mu_1$ would not lead to instability. In addition, a combined decrease of $\mu_1$ and $\mu_2$ would not lead to instability as long as the combined magnitude does not exceed the region of the stability radius. It can be argued by the convex shape of the stable region, depicted by the light gray color in Fig. 2, that any point within the region of the stability radius does not leave the stable region.

IV. MATHEMATICAL OPTIMIZATION MODEL

The theoretical findings for the stability radius, briefly presented in Section III, enable the quantification of the magnitude of robustness of a supply chain. In addition the allocation of the production capacity can be chosen in a way that the robustness of a given supply chain is maximized. In the real world different prices/costs are related to the allocation of production capacity. Depending on the real world situation theses costs can be described by certain cost
functions, e.g. linear, non-linear continuous or cost functions with jump discontinuities. For simplicity in the following a linear correlation between allocated production capacity and total capacity price is assumed. On the sequence a mathematical program is formulated that allocates the production capacity $\mu$ to the different product types with respect to a pre-given required robustness $\Delta$ of the network. The objective of the program is to minimize the required total capacity price. Hence, the program seeks for a sustainable capacity allocation that enables the supply chain network to handle a reduced production capacity with a minimum of additional costs. The resulting mathematical formulation is a mixed integer non-linear optimization program.

A. Nomenclature

**Sets**

$K$ Product classes $(k,l,n \in K)$

$J$ Locations $(j \in J)$

$C(j,k)$ Assignment of product class $k$ to location $j$

**Parameters**

$\alpha_k$ External arrival rate of product class $k$

$C_{j,k}$ Constituency matrix; production of $k$ at $j$

$\Delta$ Desired robustness

$P_{l,k}$ Routing matrix; share of $l$ that becomes $k$

$I_{l,k}$ Identity matrix of product classes

$R$ Inverse matrix of $\left(I - P^T\right)$

$L$ Large scalar (bigM)

$\psi_k$ Cost per allocated capacity unit to product class $k$

**Variables**

$\mu_k$ Process rate of product class $k$
\( \rho_{j,n} \) Nominal workload of location \( j \) in the case that product class \( k \) is disturbed \((k = n)\)

\( CM_{j,k,n} \) Auxiliary matrix \( CM^{-1} \)

\( A_{j,k,n} \) Auxiliary matrix \( CM^{-1}(I - P^T)^{-1} \)

\( X_{j,k} \) Binary variable denoting that location \( j \) has a nominal workload \( \rho_{j,n} = 1 \) if \( k \) is perturbed

**B. Mathematical model**

The considered external arrival and production rates are measured by the strength of their flow (in parts) per time unit. In (1) the required processing time per product unit is calculated. These times depend on the allocated production capacity \( \mu_k \). Furthermore, \( N \) scenarios are created where each time exactly one process rate \( \mu_k \) is reduced by \( \Delta \). Each scenario comprises all production locations.

\[
CM_{j,k,n} = C_{j,k,n}\left(\mu_k^{-1} - \Delta \cdot \delta_{n,k}\right) \quad (j \in J; k, n \in K) \tag{1}
\]

Here the notation of the Kronecker delta is used:

\[
\delta_{n,k} = \begin{cases} 
1, & n = k \\
0, & n \neq k 
\end{cases}
\]

Constraint (2) connects the matrix \( CM_{j,k,n} \) with information about the routing of products within the network. Given the assumption that one unit of a certain product class needs to be manufactured the effectively required processing times for the affected product classes are determined in \( A_{j,k,n} \).

\[
A_{j,k,n} = \sum_l CM_{j,l,n} R_{l,k} \quad (j \in J; k, n \in K) \tag{2}
\]

These effective required processing times for the individual product classes are weighted with the external arrival rate \( \alpha_k \) in (3). This yields the effective workload of the production locations for each scenario.
\[ \rho_{j,n} = \sum_k A_{j,k,n}(\alpha_k) \quad (j \in J; n \in N) \]  

(3)

The supply chain has to be stable for all scenarios. In particular the effective workload of the locations has to remain equal or below one (4). This objective is ensured by adjusting the allocated production capacity \( \mu_k \) in (1).

\[ \rho_{j,n} \leq 1 \quad (j \in J; n \in N) \]  

(4)

Given the desired robustness \( \Delta \) the capacity allocation should be chosen in such a way that the effective workload of at least one production location in one scenario equals one. This complies with the definition of the stability radius, since all other effective workloads have to satisfy (4) and the network is able to handle precisely a reduction of production capacity by \( \Delta \).

Constraints (5) and (6) enforce this for exactly one production location and one scenario.

\[ \rho_{j,n} \geq 1 - (1 - X_{j,n})L \quad (j \in J; n \in N) \]  

(5)

\[ \sum_j \sum_n X_{j,n} = 1 \]  

(6)

The objective function (7) minimizes the required cost for the allocated production capacity to the different product classes at the production locations.

\[ \text{Min.} \sum_k \mu_k \psi_k \]  

(7)

V. COMPUTATIONAL ANALYSIS

The proposed approach for a price-oriented capacity allocation was applied to a real world test case. In this section some excerpts of the computational results are shown.

A. Real World Test Case

The considered test case scenario is based on real data of a European pump set manufacturer. In particular, the manufacturer concentrates on pump sets and its components as pump, motor, coupling, coupling guard, separator and base plate. These pump sets are assembled according to customer specification. Three basic pump types exist (type 1, type 2 and type 3). The organization of the company is segmented in business units. This means that one production facility concentrates on one pump type. While the pump production is
predefined, the pump set assembly can be carried out in every distribution or service-centre. Additionally, the situation for the manufacturer is characterized by diverse stock and assembly places for pump set components, different suppliers in different countries and different conditions in specific countries in Europe in terms of, e.g. customer behavior, delivery times and logistic providers.

For the sake of simplicity only two main production and assembly locations of the real world supply chain are considered in the following. In particular Location 1 (Germany) produces pump type 1 that is either sold directly to local customers or shipped to Location 2 (France), where it is adapted to the local requirements. In France pump type 1 is considered as pump type 3 and needs additional operations. The production location in France produces exclusively pump type 2. This type is sold as well to local customers and shipped to Germany (pump type 4) for adaptations before it can be distributed. Both locations have to allocate their production capacity to the locally manufactured/assembled pump types. A sketch of the considered network is given in Fig. 3.

The material flow within the pump set manufacturer network and customer demand was analyzed for the given observation period. As a result the distributions characterizing the customer demand for the different pump types in various countries were derived. Furthermore the routing of products within the supply chain could be obtained.

![Figure 3. Material flow of the pump set manufacturer supply chain.](image-url)
The parameters for the fluid model were chosen as follows:

\[
\alpha = \begin{pmatrix} 2.69 \\ 4.73 \end{pmatrix}, \quad P = \begin{pmatrix} 0.05 & 0 & 0.48 & 0 \\ 0 & 0.05 & 0 & 0.57 \end{pmatrix}, \quad C = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}.
\]

B. Computational Results

The mathematical model of Section IV was implemented in GAMS 23.6 with the solver BARON. For the computational analysis the given values of \( \alpha \), \( C \) and \( P \) were applied; \( L \) was chosen as 100. The aim of the analysis was to gain an insight into the required capacity allocation and total price for managing different levels of robustness. To this end different costs per capacity unit for the different product classes have been assumed.

In the first part of the analysis the price for one unit of capacity was chosen as 20 monetary units [MU] for all pump types. In addition 11 scenarios of reduced production capacity were created. Between two consecutive scenarios the desired reduction of the production capacity was increased by 1% that is multiplied with the total production capacity of the current scenario. The first scenario, \( \Delta = 0 \), ensures a stable capacity allocation, while the demand has to be met. A capacity allocation that minimizes the associated price of 457.59 MU is given by:

\[
\mu_{\text{stable}} = \begin{pmatrix} 5.666 \\ 7.582 \\ 3.959 \\ 5.674 \end{pmatrix}.
\]

Table 1 shows the corresponding effective workload of location 1 and 2 for the individual reduced production capacities. The first two lines belong to the capacity scenario with \( \Delta = 0 \) and the two lines marked with an * result from \( \Delta = 10\% \cdot \sum \mu_k \). In this context it is remarkable that the chosen capacity allocation leads to an effective workload of one for almost all production locations. Hence a further reduced capacity would lead to instability and the allocated capacity is highly utilized in the first scenario. In scenario* approximately 25% of the possible workload idles at those locations that do not host the production process with a reduced production capacity.
**TABLE I. EFFECTIVE WORKLOADS OF PRODUCTION LOCATIONS FOR INCREASED CUSTOMER DEMANDS**

<table>
<thead>
<tr>
<th>Location</th>
<th>$k_1$</th>
<th>$k_2$</th>
<th>$k_3$</th>
<th>$k_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Location 2</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Location 1*</td>
<td>1.000</td>
<td>0.747</td>
<td>0.747</td>
<td>1.000</td>
</tr>
<tr>
<td>Location 2*</td>
<td>0.753</td>
<td>1.000</td>
<td>1.000</td>
<td>0.753</td>
</tr>
</tbody>
</table>

Fig. 4 shows the relative increase of additional production capacity that is required in order to handle the stepwise reduced production capacities between subsequent scenarios. The overall trajectory is non-linear and indicates a larger requirement for additional capacity for higher robustness requirements.

![Figure 4](image_url)

**Figure 4.** Additional required production capacity for the capacity scenarios.

Fig. 5 depicts the relative cost increase in relation to the different levels of robustness. In addition the trajectory of the gap between relative cost and relative robustness is shown. The evolution of this trajectory is in line with Fig. 4, since it shows that in the beginning smaller expenses are required for the associated levels of robustness. At higher levels of robustness, e.g. 8%, 9% and 10%, an additional production capacity of approximately 3%-4% is required for every 1% increase of robustness. In summary Fig. 4 and Fig. 5 show that for a 10% increase of robustness the total allocated production capacity has to rise for more that 33%, which is reasonable given the internal material flow structure of the original supply chain.
In the second part of the analysis 20 MU were assumed as the price for the production capacity for pump types 1 and 2. The capacity price for pump types 3 and 4 was chosen as 10 MU. A stable capacity allocation, with $\Delta = 0$, is given by:

$$\mu_{\text{stable}} = \begin{pmatrix} 4.834 \\ 6.815 \\ 5.046 \\ 6.851 \end{pmatrix}^T.$$

Since capacity for pump types 3 and 4 is less expensive the solution allocates more production capacity for these types. This means that more units of type 3 and 4 could be processed per time unit. For the given customer demand $\alpha$ this leads to less time that each production location has to spend with type 3 and 4 pumps per time unit. Hence, the production locations can spend more time on processing pump types 1 and 2, by reducing total prices. In Fig. 6 the evolution of additional production capacity that is required in order to handle the stepwise decreased production capacity between subsequent scenarios is shown.

In comparison to the analysis with the even price distribution the trajectory of the additional price is rising less strong. Hence, the required total production capacity for a 10% decrease of
production capacity is lower in the mixed capacity price case. This can be also observed in Fig. 6. The growth of the gap between relative price and relative robustness is growing less strong compared to Fig. 5 of the even price case. As a result it can be observed that the robust capacity allocation depends strongly on the actual price of production capacity.

![Figure 7.](image.png)

Additional capacity prices for handling different robustness levels.

In summary these analyses allow to gain valuable managerial insights into the relation between robustness, required allocation of production capacity and associated prices. Given an uncertain evolution of production capacity the management of a supply chain can select and implement a desired robustness level. Another advantage of this approach is that as soon as production capacity should decrease towards the implemented level of robustness an indicator for further actions is given.

### VI. CONCLUSIONS

This paper introduced a new managerial approach to robust capacity allocation within dynamic supply chains that can be modeled as a multiclass queueing network. In particular, the article introduced a new way of measuring and maximizing the robustness of a supply chain, subject to a decreasing production capacity. To this end the price-oriented approach comprises four steps.

1) Set-up of a multiclass queueing network that models the stochastic processes of the original supply chain.

2) Approximate the queueing network by a fluid model.
3) Measure the robustness with the stability radius and minimize the price of the allocated capacity.

4) Transfer of results to the original supply chain

The computational analysis was based on a part of a real world supply chain and presented some of the obtained results. Since the stability of the fluid approximation is sufficient for the stability of the underlying queueing model the results can be directly transferred to the real world network. A major advantage of the approach is that the price for the robustness of a supply chain, subject to a dynamic evolution of production capacity, can be precisely analyzed. Hence, the management can select a certain level of robustness for a known price. This robustness can be also interpreted in the following way: Given a decrease of production capacity for any kind of product within the network, the impact on the network depends on its own magnitude and maybe other decreases of other production capacities present at the same time. The accumulated magnitude of decreases can be directly used as an indicator whether the network is able to fulfill customer demand or not.

In the future different specific cost functions for the allocated production capacity should be analyzed. Furthermore a changing customer demand should be taken into account at the same time. This is motivated by trends that determine the average customer demand or reasonable events leading to an increased demand. In addition the presented approach might provide further managerial insights when embedding it into other planning processes on the tactical or strategic planning level.

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