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# An analytic approach to production capacity allocation and supply chain design

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## Abstract

The aim of this paper is to propose a framework by which the risks related to a customer–supplier relationship, the service requirements by the customers and the strategies of the supplier company can be included in production capacity allocation and supply chain design. Essentially, the target is to prepare a sales plan where the limited production capacity is allocated to the customers based on their strategic importance and the risk involved. Furthermore, the supply chain is designed on the basis of the customers' strategic importance and service requirements. The framework is demonstrated with a numerical example and it is based on integrating the analytic hierarchy process (AHP) and mixed integer programming (MIP). © 2002 Elsevier Science B.V. All rights reserved.

*Keywords:* Production capacity allocation; Supply chain; Analytic hierarchy process

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## 1. Introduction

Historically, the three stages of the supply chain, procurement, production and distribution have been managed independently and buffered by large inventories [1]. This policy has changed, especially manufacturers have increasingly given their attention to the management of the total logistics chain. This means also that the focus of companies has been expanded from improving one logistics operation towards improving the total chain and crossing the borders of companies acting in the same supply chain. It is a well-known fact that it is

possible to gain even more advantage by improving the logistics chain instead of improving the performance of one player in the chain. The area of logistics chain is not solely restricted to the production process itself but has spread into a wide range of subjects relating to the entire material flow into, within and out of the organization [2]. Therefore, the traditional and the most widely used cost and profit based optimizations for production capacity allocation and supply chain design are not sufficient in the present competitive business environment.

## 2. The proposed framework

The aim of this paper is to propose a framework by which the risks related to a supplier–customer

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relationship, the customers' preferences concerning logistics and the strategies of the supplier can be included in production capacity allocation and supply chain design. The main utilization area of this approach is the preparing of an annual sales plan where the limited production capacity is allocated to the customers on the basis of their strategic importance and the risk related to the relationships with the customers. Furthermore, the supply chain is planned by taking into account the customers' preferences.

The proposed approach is based on integrating the analytic hierarchy process (AHP) and mixed integer programming (MIP). The AHP and linear programming have earlier been used together e.g. by Liberatore for selecting R&D projects [3], by Korhonen and Wallenius [4] for formulating a marketing strategy, by Gass [5] for large-scale personnel planning models, and by Olson et al. [6] for an export planning model for a developing country.

The AHP and linear programming have previously been used together for logistics network design by e.g. Korpela and Tuominen [7], Korpela and Lehmusvaara [8], Korpela et al. [9,10], and Lehmusvaara et al. [11]. In these papers, the basic principle has been that both the qualitative and quantitative characteristics of the alternative supply chains (either as a whole or in parts) have been analyzed with the AHP, resulting in a priority for each alternative. In some of the papers, the importance of the customers has also been analysed by using the AHP and the importance has also been included as a decision variable in the MIP-model which has been used for optimizing the supply chain. Thus, the design of the supply chain is not only based on quantitative factors like costs but on qualitative factors as well.

The approach presented in this paper builds on the results presented in the papers mentioned above. The analysis of the strategic importance of the customers and the analysis of the alternative supply chain structures are components that are based on the earlier papers. However, the proposed approach extends the earlier research in two main ways: (1) the risks related to supplier–customer relationships are included in the decision process and (2) not only the supply chain capacity but also

the production capacity is divided between the customers by using the MIP-model.

The proposed approach consists of five basic steps:

1. *Defining the problem.* The first step involves defining the decision problem by e.g. stating the objectives, and determining the scope of the problem in terms of e.g. alternative transportation modes and routes.
2. *Analyzing the strategic importance of the customers.* The second step involves analyzing the strategic importance of the customers affected by the supply chain planning process. The AHP is used for this analysis, resulting in an importance priority for each customer. This priority reflects how well a certain customer fits the strategic objectives of the supplier company.
3. *Analyzing the risk involved in the supplier–customer relationship.* The AHP is used for analyzing the risk level related to a certain customer relationship. This risk level basically reflects the potential deviations from the agreed sales quantities per customer during the planning period. Ultimately, the risk level is a factor measuring the certainty level of the relationship with a certain customer. The risk level might be affected by e.g. economical factors or competitors' actions. Taking the risk level into account in the production capacity allocation enables the supplier company to anticipate the possible deviations.
4. *Analyzing the customers' preferences for supply chain structures.* The fourth step consists of an analysis of the alternative supply chain structures from the customer point of view. Each customer defines the criteria for analyzing the alternative structures from their point of view and then defines the importance of the criteria on the basis of their requirements. Customers then set preferences for the alternative supply chain structures, based on these criteria. The AHP-method is used for supporting this step.
5. *MIP-based optimization.* The final phase in the proposed approach involves optimizing the utilization of the production capacity and the supply chain structure alternatives, based on the priorities defined in the previous phases. Thus,

the production capacity can be allocated first to the customers with a high strategic importance and a low risk level. Furthermore, the utilization of the alternative supply chain structures can be planned so that the requirements and preferences of the customers with a high strategic importance and a low risk level are satisfied first.

The utilization of the proposed approach is demonstrated with a numerical, illustrative example.

### 3. An illustrative example

#### 3.1. Defining the problem

The first step of the proposed approach is to define the problem. In this illustrative example, the supplying company (corporation A) is preparing the sales plan for the next year. This planning process includes allocating the production capacity to the customers and defining the supply channels that will be used for supplying the products to the customers. The basic elements of the decision problem are the following: (1) one production plant, (2) 10 customers located in the same market area, and (3) four alternative supply chain structures, each of which can be used to transport the goods to all customers. The constraints of the decision process include the production capacity of the production plant and the throughput capacities of the supply channels. The anticipated demand for the products is defined by estimating the upper and lower limits for the amount of products sold to each customer.

#### 3.2. Analyzing the strategic importance of the customers

The second step in the proposed approach involves determining the strategic importance of the customers for corporation A. The AHP is used for this step as the analysis involves multiple criteria, many of which are qualitative. The analysis shown here is based on the analyses presented in Lehmusvaara et al. [11] and Korpela et al. [9].

The AHP is a systematic procedure for representing the elements of any problem in the form of a hierarchy [12]. AHP can be described as a theory

of measurement for dealing with quantifiable and intangible criteria [13]. AHP is based on three principles: decomposition, comparative judgements and the synthesis of priorities [14]. First, a complex, multicriteria problem is decomposed into a hierarchy where each level consists of a few manageable elements [15]. These elements are then divided into another set of elements. Second, a measurement methodology based on pairwise comparisons is used for deriving priorities for the elements. Third, the priorities of the elements are synthesized to calculate the overall priorities for the decision alternatives. A detailed description of the AHP method can be found e.g. in [16].

According to the principles of the AHP method, the first step in analyzing the strategic importance of the customers involves defining the criteria on which the analysis will be based. In this example, the strategic importance of the customers is analyzed on the basis of the following criteria: (1) the long-term profitability potential for the company resulting from serving a certain customer, (2) the possibilities of establishing a partnership-type relationship with a customer, and (3) the anticipated development of the volumes purchased by a certain customer.

As shown in Fig. 1, the overall goal for the analysis is located on the highest level of the hierarchy, and the criteria can be found on the second level. In a typical AHP-hierarchy, the actual decision alternatives are located on the lowest level of the hierarchy. In this example, however, the ratings-feature (see [17]) of the AHP-method and the corresponding Expert Choice-software is utilized, i.e. a set of ratings is located on the lowest level of the hierarchy. The ratings are qualitative descriptions about the characteristics of a customer with regard to a certain criterion. The customers are then analyzed by using the ratings scales with respect to each criterion. The use of the ratings feature enables the analysis of several customers and makes it easy to add new customers to the evaluation process at any time. Naturally, the ratings can be different for each criterion but in this illustrative example the same ratings scale is used for all criteria.

The second step in using AHP is to derive priorities for each element in the hierarchy. The priorities

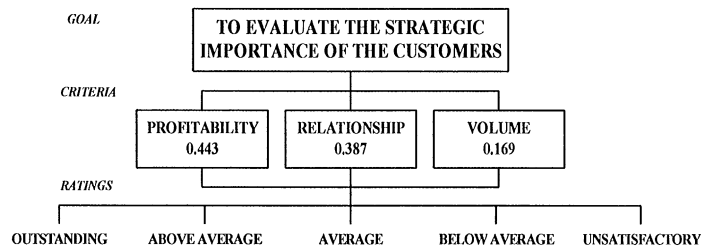


Fig. 1. The AHP-hierarchy for analyzing the strategic importance of the customers.

are set by comparing each set of elements pairwise with respect to each of the elements in a higher level [15]. A verbal or a corresponding 9-point numerical scale can be used for the comparisons, which can be based on objective, quantitative data or subjective, qualitative judgements. In a group setting, there are several ways of including the views and judgements of each person in the priority setting process including e.g. (1) consensus, (2) vote or compromise, (3) geometric mean of the individuals' judgements, and (4) separate models or players [18].

With the hierarchy illustrated in Fig. 1, the priority setting procedure is started by comparing the criteria pairwise with respect to the goal. The second step is to derive priorities to the ratings with respect to each evaluation criterion. In a classical weights and scores approach, the ratings would be given ordinal numbers, such as 1 for unsatisfactory and 5 for outstanding [17]. Forman et al. state that the classical approach violates the proper use of "scales of measurement" with the implicit and incorrect assumption that, for example, outstanding is five times better than unsatisfactory. The problem is avoided in the AHP-method by deriving the priorities to the ratings with regard to each criterion using pairwise comparisons. The overall priorities for the elements in the hierarchy are calculated by adding all the contributions of the elements in a level with respect to all the elements in the level above.

The priorities of the evaluation criteria are shown in Fig. 1. The profitability potential is the most important aspect of a customer's strategic importance with a priority of 0.443. The possibility of establishing a long-term partnership is also a major factor with an importance priority of 0.387.

Table 1  
The strategic importance of the customers

Customer	Total	Profitability	Relationship	Volume
Customer 4	0.690	Abv.aver	Outstand	Abv.aver
Customer 1	0.621	Outstand	Blw aver	Abv.aver
Customer 3	0.581	Outstand	Blw aver	Average
Customer 2	0.517	Average	Abv.aver	Outstand
Customer 8	0.483	Abv.aver	Abv.aver	Average
Customer 7	0.401	Blw aver	Abv.aver	Abv.aver
Customer 10	0.351	Abv.aver	Average	Unsatidf
Customer 6	0.324	Average	Average	Average
Customer 5	0.318	Abv.aver	Blw aver	Blw aver
Customer 9	0.243	Average	Blw aver	Blw aver

The development of the volumes sold to a customer has a priority of 0.169.

The strategic importance of customers is analyzed by relating a rating and the corresponding priority to a customer with regard to each evaluation criterion. The ratings are assigned to the customers by using the software program Expert Choice. The ratings module of the program makes it easy to enter and modify the evaluations. The results of the evaluation of the strategic importance of the customers are shown in Table 1. The column labeled Total shows the overall strategic importance of the customers. The analysis reveals that, the Customer 4 is the most important with the priority 0.690 whereas the priority of the Customer 1 is 0.621 and the priority of Customer 3 is 0.581.

### 3.3. Analyzing the risk related to a supplier–customer relationship

The aim of the third phase in the proposed approach is to analyze the risk related to the

supplier–customer relationships. Corporation A is involved in an industry with many competing companies. As there are no huge differences between the products offered by these companies, it is easy for the customers of this industry to switch suppliers. Therefore, it is important for corporation A to be able to develop business relationships with those customers that are ready to commit themselves to the agreed volumes to be bought and to joint development both in the short and long term. Risk analysis is the tool for measuring the level of uncertainty related to the customer relationships. Risk analysis is important especially for supporting production allocation: e.g. allocating a lot of production capacity for a high-risk customer (i.e. the probability of not achieving the expected annual sales is high) might result in ineffective utilization of production capacity during the course of the year.

The AHP is applied to risk analysis as the analysis involves multiple criteria and subjective judgments. The risk factors to be included in the first level of the AHP-hierarchy are the following: (1) the history of the relationship with a customer – i.e. how the relationship has worked in the past concerning e.g. loyalty, (2) the position of corporation A in the purchasing policy of a customer, meaning e.g. the share of corporation A of the total purchases of the customer and the level of satisfaction that the customer has concerning the products and service provided by corporation A, (3) competitor’s expected actions – i.e. how interested the competitors are to gain more sales with a customer and what actions they might take in order to reach their objectives, and (4) development of a customer’s business – i.e. what the prospects of the future de-

velopment of the customer are in terms of turnover, profitability and other key factors.

In order to estimate the risk level related to a customer relationship, the following risk classes are added to the second level of the AHP-hierarchy: (1) low risk (0–20%), (2) moderate risk (20–40%), (3) high risk (40–60%), (4) very high risk (60–80%), and (5) extremely high risk (80–100%). These alternatives are used for measuring the probabilities of having problems with a customer relationship, referring especially to the probability of not achieving the expected and agreed sales levels with a customer.

The described AHP-hierarchy can be considered to be an application of the AHP to forecasting, and the structure of the hierarchy is a simplified version of the one presented by Dyer and Forman [19] for forecasting enrollment growth of certain educational programs. Applications of the AHP for forecasting and prediction can be found in e.g. [20–24].

The risk level is analyzed separately for each customer by using the described AHP-hierarchy. The priorities for the elements in the hierarchy are derived by following the standard AHP-procedures. The first step is to derive the priorities for the risk factors in the first level of the hierarchy by using pairwise comparisons. The second step involves deriving probabilities for the risk classes separately for each of the risk factors. An example of the hierarchy and the priorities of the elements at the first level of the hierarchy is presented in Fig. 2. The overall probabilities of the risk classes are presented in Fig. 3.

The results presented in Fig. 3 show the probabilities of the risk classes concerning the relationship with Customer 1. As shown in the figure, the

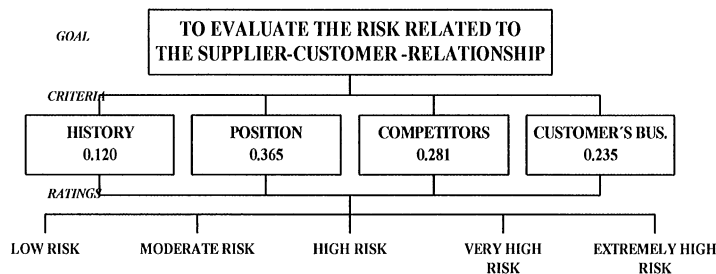


Fig. 2. Risk analysis concerning Customer 1.

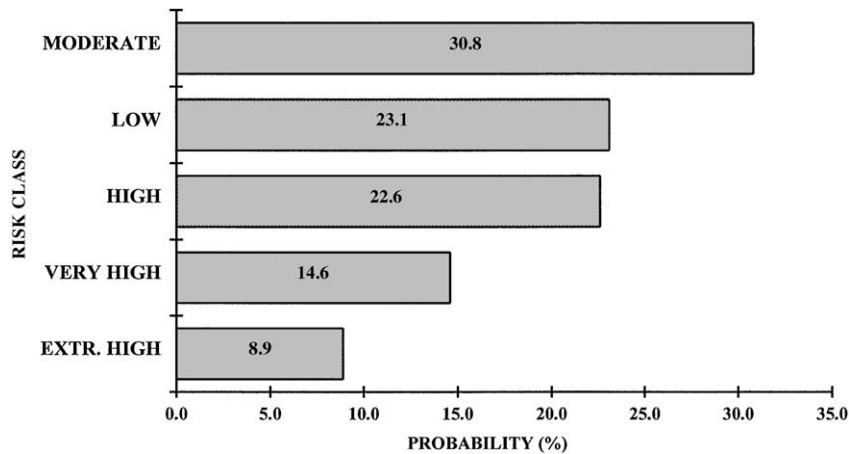


Fig. 3. The probabilities of risk classes concerning Customer 1.

Table 2  
Calculation of the composite risk rate

Risk class	Range (%)	Range average (RA) (%)	Overall probability (OP)	RA*OP (%)
Low risk	0–20	10	0.231	2.31
Moderate risk	20–40	30	0.308	9.24
High risk	40–60	50	0.226	11.30
Very high risk	60–80	70	0.146	10.22
Extremely high risk	80–100	90	0.089	8.01
Total			1.000	41.08

risk class “moderate risk” has the highest probability. In order to calculate the composite risk related to a customer relationship, the probabilities of the different risk classes are combined by multiplying the average of each risk class by its overall probability. The composite risk is then defined by calculating the sum of the multiplication results (see e.g. [22]). The calculation of the composite forecast is presented in Table 2.

As shown in Table 2, the composite risk related to the relationship with Customer 1 is 41.8%. The composite risk rates concerning the other customers are calculated in the same way.

### 3.4. Analyzing the alternative supply chain structures

The aim of this step is to derive customer preferences for the alternative supply chain structures by

using the AHP. Each customer defines the criteria to be used for evaluating the structural alternatives, derives priorities for the criteria and evaluates the alternatives. As the customers may not always have the needed experience and knowledge concerning the alternative supply chain structures, the representatives of the supplying company will give supporting information. The hierarchy used in this analysis is based on the approach presented in [11], where the supply channels were evaluated as a whole. However, each node and link (e.g. warehouses, transportation companies) of the supply channel alternatives could also be analyzed separately as shown in [9].

As mentioned in the problem definition section, there are four alternative supply channels to be used for each customer. These supply channels consist mainly of the following parts: (1) production, (2) transportation from the production plant to the port of loading, (3) sea transport, (4) warehousing at the port of destination, and (5) final delivery to the customer either by road or rail.

In this example, the analysis is shown as performed by Customer 1. The criteria used for analyzing the alternatives are the following: (1) order lead time, (2) delivery time reliability, (3) absence of damage, (4) flexibility (e.g. urgent deliveries), and (5) total cost. As with the analysis of the strategic importance of the customers, the ratings feature of the AHP-method is utilized. The following ratings scales are defined for the criteria: (1) order lead

time: 1, 2, 3 weeks, or more, (2) delivery time reliability: products are normally delivered within 2 hours, 4 hours, 6 hours or 8 hours the target delivery time, (3) absence of damage: over 99%, 95–99%, 90–95%, or below 90% of the products are delivered without damage, (4) flexibility: outstanding, above average, average, below average or unsatisfactory, and (5) total cost level: outstanding, above average, average, below average or unsatisfactory. The AHP-hierarchy is shown in Fig. 4.

The priorities for the elements in the hierarchy are derived by using the standard AHP-procedure. Thus, the first step is to derive the priorities for the evaluation criteria through pairwise comparisons. Then, priorities are derived for the ratings with regard to each evaluation criterion. For example, concerning the order lead time, the representatives of Customer 1 define the preferences for the alternative lead times. The actual structural alternatives are then evaluated with regard to each criterion by selecting the rating that most accurately describes

the performance level of a certain alternative. The evaluation of the alternatives is shown in Table 3. The column Total shows the overall preference of the alternatives for the customer.

The other customers derive the priorities for the supply chain alternatives correspondingly. One of the main advantages of the approach is the flexibility it provides. Each customer can define the specific criteria they want to include in the analysis, as well as the desired performance levels with regard to these criteria, and the priorities for the elements in the hierarchy.

### 3.5. MIP-based optimization

In this example, there is one production plant that distributes its products to 10 customers either via three warehouses or by direct shipments from the plant to the customers. This means totally four alternative supply chains to each customer. In addition, the minimum and maximum levels of the

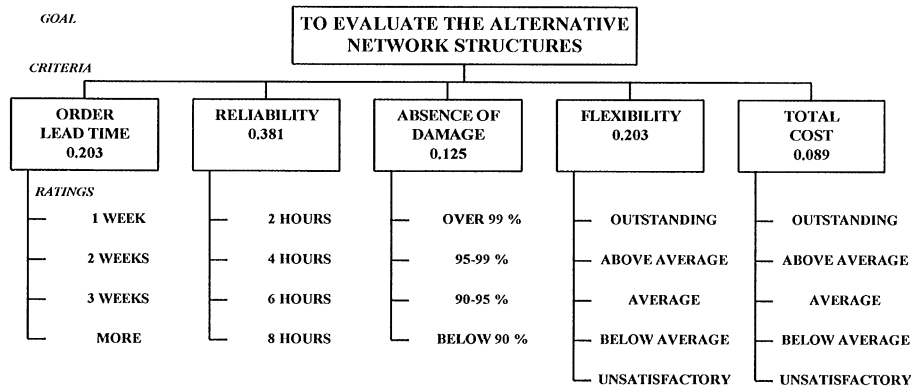


Fig. 4. The AHP-hierarchy for analyzing the alternative structures.

Table 3  
Analysis of the supply chain alternatives

Supply chain alternative	Total	Order lead time (weeks)	Reliability (hours)	Absence of damage (%)	Flexibility	Total cost
Supply channel 1	0.315	3	6	90–95	Blw aver	Abv aver
Supply channel 2	0.721	2	2	95–99	Abv aver	Blw aver
Supply channel 3	0.391	2	6	90–95	Average	Abv aver
Supply channel 4	0.650	1	4	95–99	Abv aver	Average

annual demand have been defined for all customers. The production capacity of the plant is higher than the sum of the minimum level customer demands, and on the other hand it is lower than the maximum level customer demands. The ultimate idea of the proposed approach is to determine how much production capacity is given to each customer. This problem is solved with an MIP-model where the objective function takes into account the strategic importance of the customers, the risk related to the customers and the preferences that the customers have defined for the alternative supply channels. To summarize, the MIP-model tries to allocate the production capacity to the most important customers with the lowest risk levels, and to allocate the supply channels according to the preferences of the most important customers. The results of the AHP based evaluations are utilized as input figures in the MIP-model. The objective function of the preference maximization MIP model is defined as follows:

$$\text{MAXZ} = \sum_{t=1}^T \sum_{d=1}^D (I_d P_{td}(1 - R_d)) V_{td}$$

subject to

$$\sum_{d=1}^D \text{DEM}_d = \sum_{t=1}^T \sum_{d=1}^D V_{td} \quad \text{and}$$

$$\text{PVOL} = \sum_{t=1}^T \sum_{d=1}^D V_{td},$$

where  $I_d$  is the strategic importance of customer  $d$ ;  $P_{td}$  the preference of supply chain  $t$  from plant to customer  $d$ ;  $R_d$  the risk related to customer relationship  $d$ ;  $V_{td}$  the delivery from plant via supply chain  $t$  to customer  $d$ ;  $\text{DEM}_d$  the market demand of customer  $d$ ;  $\text{PVOL}$  the production of plant;  $t$  the supply chains,  $t = 1, \dots, T$ ; and  $d$  the customers,  $d = 1, \dots, D$ .

Basically, it is possible to build the MIP model in a way that it can solve several distribution structure related problems, e.g. it can be utilized in determining the number of warehouses by introducing 0/1 variables and needed constraints to the problem. Therefore, it is possible to introduce risk related factors more widely to the distribution network evaluation problems than in the given illustrative example. In addition, it is possible to give different

Table 4  
The results of MIP optimization

Cus- tomers	Lower demand	Upper demand	Risks	Supply channels			
				1	2	3	4
2	8000	13000	0.33		10000		8000
3	6000	8000	0.20		8000		
4	3500	3500	0.44				3500
5	4000	6000	0.25				4000
6	5500	6000	0.55	5500			
7	3000	7000	0.18		7000		
8	12000	15000	0.29		2000	10000	
9	7000	8000	0.48		7000		
10	15000	20000	0.22	10000			5000
Total				15500	34000	30500	

weights to customers' strategic importance, supply chain preferences and risk factors.

In this example, the throughput capacities of the supply channels are limited to be under 10 000 tons and the production capacity of the plant is 80 000 tons. The minimum and maximum levels of the annual demand, customer related risks, and the results of the MIP-model calculations are given in Table 4.

The table shows that the production has been 80 000 tons and supply channel 4 has not been used, and in addition transport volumes to Customers 8 and 10 come through two channels. In all cases the given upper throughput limit of 10 000 tons per channel has been followed. The customer related risks are relatively high to Customers 1, 6 and 9, and therefore, the model has selected lower market demands for those customers. On the other hand, the highest market demands have been selected to customers 3, 5 and 7, where the risk related factors are on the lowest level.

#### 4. Implementation and follow-up

After implementing the results of the analysis, the proposed approach forms a flexible procedure for solving the production allocation problem. The present customers can be evaluated periodically, e.g. two times a year, in order to recalculate the

problem. However, the AHP-models can be updated whenever needed and the results can be entered to the MIP-model in order to validate the present solution, which allows the model to be used also in the monthly level. In addition, the proposed approach forces to evaluate the strategic and risk factors related to customers, which also gives more information and understanding to solve other distribution related problems.

## 5. Conclusions

The proposed approach provides a systematic and flexible framework for solving production allocation problems that maximizes the strategic importance of customers, minimizes customer related risks, and in addition, maximizes the preferences of customers. Compared to the traditional cost and profit based approaches for production allocation, this approach makes it possible to take into account both qualitative and quantitative factors for solving the problem. Traditionally, the focus has been on the company's own quantitative viewpoints, but this approach enables focusing on the customers viewpoints. Finally, the proposed approach forms a basis for evaluating the production allocation problem on the tactical decision making level.

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