Hindawi
Mathematical Problems in Engineering
Volume 2017, Article ID 7430248, 9 pages
https://doi.org/10.1155/2017/7430248

Research Article

Supplier Selection by Coupling-Attribute Combinatorial Analysis

Xinyu Sun

School of Management, The State Key Laboratory for Manufacturing System Engineering, Xi'an Jiaotong University, Xi'an, China

Correspondence should be addressed to Xinyu Sun; xinyu.sun@xjtu.edu.cn

Received 14 May 2017; Revised 5 September 2017; Accepted 14 September 2017; Published 25 October 2017

Academic Editor: Danielle Morais

Increasing reliance on outsourcing has made supplier selection a critical success factor for a supply chain/network. In addition to cost, the synergy among product components and supplier selection criteria should be considered holistically during the supplier selection process. This paper shows this synergy using coupled-attribute analysis. The key coupling attributes, including total cost, quality, delivery reliability, and delivery lead time of the final product, are identified and formulated. A max-max model is designed to assist the selection of the optional combination of suppliers. The results are compared with the individual supplier selection. Management insights are also discussed.

1. Introduction

Managing the outsourcing process productively is the key to enhancing competitiveness because for every dollar an industrial company generates, 50 to 90 cents are spent on purchasing [1]. Selecting the right outsourcing suppliers becomes essential in shaping company performance. Supplier selection is the process by which suppliers are reviewed, evaluated, and chosen to become a part of a company's supply chain [2]. Several reviews have been published recently to summarize research development in this area [3–7].

A company's primary supply chain goal is to efficiently and effectively provide the required products for its customers. To meet the customer-specified criteria to achieve this aim, a company must choose the best suppliers in order to produce the best finished products. A number of publications have focused on the development of various methodologies to select individual suppliers [3, 7]. Most of these publications have assumed that the best supplier combination is composed of the best suppliers of different parts/components, which are evaluated and selected individually. However, this assumption may not apply to all situations. This paper explains the reasons for this and focuses on the following two issues to be considered when evaluating suppliers.

First, the interdependencies between different products and components can affect the choice of suppliers. Synergies may apply when the suppliers that are selected aggregately for a group of products or components outperform the suppliers that are selected separately for individual products or components. With synergy, both buyers and suppliers can be more profitable. One research direction of this synergy is the combinatorial auction, which considers economies of scale and scope. The basic motivation of utilizing a combinatorial auction is the presence of complementarities among items supplied by different suppliers [8]. The most relevant research to our study is the Giacon et al. [9] study, which proposed a combinatorial optimization model that combines multicriteria value analysis for evaluating the trade-offs among the defined criteria. Nobar and Setak [2] presented two layers of suppliers and studied the correlations between price and quality on supply chain performance. Rothkopf et al. [10] studied simultaneous auctions in which the value of assets to a bidder depended on other assets that the bidder won, and they pointed out that the bid for combinations of assets might be beneficial to total revenue. However, so far, there has not been an attempt to quantify the degree to which the synergies are present among the components and attributes. We fill this gap by offering a max-max model that is designed to facilitate the selection of the optional combination of suppliers. The synergies are identified using coupled-attribute analysis. As the coupling attributes of the parts/components affect the attributes of the finished product, the best supplier combination should be considered as a whole rather than individually. Otherwise, the trade-offs and synergies are overlooked.

Second, the literature pointed out that a different production mode (i.e., made to order (MTO) or made to stock (MTS)) has different supplier selection criteria [11]. The more complicated supply network is the combination of MTO and MTS [11]. The production mode has an impact on the supplier selection, and the existing suppliers can affect the selection of the production mode reciprocally. The supplier with a long delivery time may change the production mode from MTO to MTS since the supplier cannot quickly respond to the market. Thus far, there has been no attempt to investigate the synergies of the suppliers with different lead times on the production mode. This paper calculates the production time under the defined supply structure, the lead time of suppliers, and the production mode. We investigate the effect on the production mode when selecting a supplier using the different experimental scenarios.

We believe that this work contributes to several areas. First, we aim to develop an analytical model considering the synergies among product components and supplier selection criteria under the production mode framework, thus enhancing the effectiveness of supplier selection. This paper integrates combinatorial optimization with coupling attributes of the final product, which is the real objective of the end user. It also investigates the balance between component attributes and its effect on the production mode when selecting a supplier. Second, we apply the model to a real case and show it to be an appropriate methodology for evaluating suppliers. The results let practitioners know the importance of balance between suppliers. We structure the rest of this paper as follows: Section 2 cites the relevant literature. Section 3 gives the supplier combinatorial selection methodology. We apply this methodology to a real case in Section 4; we also provide a scenario analysis and some managerial insights. Finally, we offer some concluding remarks in Section 5.

2. Literature Review

The supplier selection literature contains much research studying selection criteria. Dickson [12] pointed out that cost, quality, and delivery performance are the three most important criteria that should be considered for supplier selection. Weber et al. [13] and Sun et al. [14] confirmed these criteria based on empirical data collected from purchasing managers and Chinese companies, respectively. Lin and Kuo [15] stated the supplier's product quality is one of the three most frequently used criteria for selection, the others being delivery time and cost [7, 16, 17]. In this paper, we also focus on cost, quality, and delivery performance. In terms of cost, quantity, and business volume, discounts are common topics when a range of products is to be purchased, and linear programming is a common method to deal with the related problems.

Several approaches and techniques have been developed to determine an effective supplier selection process. According to Chai et al. [18] and Ho et al. [7], the most common approaches for this type of supplier selection are analytic hierarchy process [19] and data envelopment analysis [20], which are followed by mathematical programming, linear programming [21], case-based reasoning (CBR), ideal solution [22], analytic network process [23], fuzzy set theory [24], simple multiattribute rating technique (SMART), and genetic algorithm (GA). All these methods consider only suppliers, so some limitation exists in reflecting the harmony of the supplier, demand, and operational policies. Moreover, these methods require additional information or assumptions, such as a joint probability density function, accurate transformation function, and normality assumption.

Much attention has been given to the coordination between procurement and production planning or intervention of suppliers to develop supply chain management systems. Cook et al. [25] have developed a DEA method for supply chains with intervened inputs and outputs. Chen and Yan [26] have proposed DEA approaches with centralized, decentralized, and mixed decision makers. Park et al. [27] have proposed a stochastic simulation-based DEA approach to the vendor selection problem, in which a DMU is assigned as a supply chain instead of an individual vendor. This proposed approach, adopting a stochastic simulation scheme, helped the purchaser choose a proper set of vendors with a holistic perspective. Although these DEA methods are advantageous for assessing structural efficiency, the approaches can handle only simple structures such as a two-echelon model with a buyer and two suppliers and product flows in an assembly perspective. Hlioui et al. [24] have proposed to integrate replenishment, production, quality control, and supplier selection decisions for a manufacturing-oriented supply chain under a combination of mathematical formulation, simulation, and optimization techniques. Asadabadi [28] proposed a method that takes into account customer needs as a determinant factor in finding the best supplier and considers possible changes in the priorities of customer needs as time passes. Chen and Zhang [29] proposed a stochastic framework to determine the optimal production control policy and supplier selection procedure for a three-echelon supply chain. All these studies have shown that supplier selection must not be studied separately from the sole supplier and production system. However, only a few of them include holistic effects of ordered items among the supplier selection criteria. Moreover, they do not consider any production mode strategy for the supply chain management.

3. Coupling Attributes Combinational Analysis

3.1. Formulation of the Problem. We evaluate the impacts of different supplier combinations on the finished product performance and identify the optimal combination with the highest performance level. To facilitate the presentation, we summarize Notation and Symbols Used in Section 3.1.

Suppose that there are c types of components and each component has ns suppliers. $n = c^{\mathrm{ns}}$ possible supplier combinations can be obtained. Let S denote the set of all types of components, $S :: \{cs_1^k, cs_2^k, cs_i^k, \ldots, cs_c^k\}$. Any $V_p = \{s_1, s_2, \ldots\} \in S$ represents a vector of a supplier combination. The problem of finding the optimal combination can be formulated as $\max_{V_p \in S} f(V_p)$, where $f(V_p)$ represents the finished product performance of a supplier combination. The performance is related to the attributes of the suppliers in the combination.

$$\begin{aligned} V_p^* &= \operatorname{argmax} f\left(V_p\right) \\ V_p &= \left(s_1, s_2, \ldots, s_i, \ldots, s_c\right), \\ s_i &\in \left\{cs_i^1, cs_i^2, \ldots, cs_i^{\mathrm{ns}}\right\} \\ c^{\mathrm{ns}} &\geq p \geq 1. \end{aligned} \tag{1}$$

Considering the productivity of supplier combination, the attributes of the final product can be classified as two types: (a) higher values, defined as outputs, which indicate better levels of performance such as product quality, and (b) lower price, defined as inputs, which indicate better levels of performance such as component cost. $f(V_p)$, defined as the ratio of weighted outputs to weighted inputs, is maximized and minimized to obtain a set of dual productivity scores in each combination p [30], as follows:

For each p,

$$f\left(V_p\right) = \max_{a_r, b_t} \quad \frac{\sum_{r=1}^{v} a_r y_{rp}}{\sum_{t=1}^{u} b_t x_{tp}} \tag{2}$$

$$\text{subject to} \quad \frac{\sum_{r=1}^{v} a_r y_{rj}}{\sum_{t=1}^{u} b_t x_{tj}} \leq 1, \quad j = 1, \ldots, c^{\mathrm{ns}} \tag{3}$$

$$a_r, b_t \geq 0 \quad \forall r, t \tag{4}$$

$$y_{rp} \geq \overline{y_r} \tag{5}$$

$$x_{tp} \leq \overline{x_t}, \tag{6}$$

where p represents evaluation of the supplier combination, and each unit has u inputs and v outputs of supplier combination. y_{rj} represents the value of the rth output; x_{tj} stands for the tth input for combination; j, a_r signifies the weight given to the rth output; and b_t denotes the weight given to the tth input. The supplier combination consumes an x_{tp} amount of input t and produces an y_{rp} amount of output r, which can be incorporated into an efficiency measure, the weighted sum ratio. This definition requires a set of factor weights a_r and b_t, which are the decision variables.

Each supplier combination p is assigned the highest possible efficiency score by choosing the optimal weights for the outputs and inputs [31]. The term *combinatorial analysis* is used to describe the mechanism that simultaneously selects a supplier from the supplier list for each component. The supplier's determination is the problem of finding a maximum allocation V_p with respect to the objective $f(V_p)$, which is also a maximum function (2) conditional on p from 1 to c^{ns}. Therefore, the problem is defined as the *max-max* approach.

Constraints (5) and (6) reveal that at least the threshold of all the inputs and outputs should be satisfied. In retail, for example, the total delivery lead time should not be more than seven days if the retail shop promises that its products will reach its customers no later than seven days after the order confirmation. The problem definition is similar to Charnes et al. [32]. The number of possible solutions of V_p is c^{ns} and the computation scale to solve models (2)–(6) will increase very rapidly if there are many extreme components. However, our objective is to select the most efficient supplier combination p, not to rank the combinations. It is very practical to develop a model to find the most efficient combination directly without assessing the performance of the other combinations. Wang and Jiang [33] proposed a mixed integer linear programming model to identify the most efficient decision-making unit. The most efficient supplier combination in models (2)–(4) can be found based on the following model proposed by Wang and Jiang [33]:

$$\begin{aligned} \min \quad & \sum_{t=1}^{u} b_t \left(\sum_{j=1}^{c^{\mathrm{ns}}} x_{tj} \right) - \sum_{r=1}^{v} a_r \left(\sum_{j=1}^{c^{\mathrm{ns}}} y_{rj} \right) \\ \text{subject to} \quad & \sum_{r=1}^{v} a_r y_{rj} - \sum_{t=1}^{u} b_t x_{tj} \leq I_j, \quad j = 1, \ldots, c^{\mathrm{ns}} \\ & \sum_{j=1}^{c^{\mathrm{ns}}} I_j = 1 \\ & I_j \in \{0, 1\}, \quad j = 1, \ldots, c^{\mathrm{ns}} \\ a_r \geq{} & \frac{1}{(u+v) \max_j \left\{y_{rj}\right\}}, \quad r = 1, \ldots, v \\ b_t \geq{} & \frac{1}{(u+v) \max_j \left\{x_{tj}\right\}}, \quad t = 1, \ldots, u, \end{aligned} \tag{7}$$

where I_j ($j = 1, \ldots, c^{\mathrm{ns}}$) are binary variables, only one of which can take a nonzero value of one. The model contains ($c^{\mathrm{ns}}+1+u+v$) constraints and ($c^{\mathrm{ns}}+u+v$) decision variables. It aims at seeking a set of input and output weights to maximize the efficiencies of the whole supplier combinations. Based on model (7), only a mixed linear program needs to be solved.

In this paper, there are two inputs: final product cost and total delivery lead time. In addition, there are two outputs: final product quality and delivery reliability of final product. Cost and quality are key factors in evaluating the performance of finished products, whereas delivery lead time and delivery reliability are key supply chain management performance indicators. Their formulae are given in Section 3.2.

3.2. Computation Method of Coupling Attributes. In this section, we define the inputs and outputs in models (2)–(6) as the coupling criteria. The value of a coupling criterion is affected by all suppliers in a supplier combination. It is evident that the purchasing costs of all components in a supplier combination are added together and become the total cost of the finished product. However, in general, the value functions are nonlinear. We describe the formulae of coupling criteria as follows.

3.2.1. Total Cost. The purchasing cost of the finished product is $\mathrm{TC} = \sum_{i=1}^{n} \mathrm{BOM}(i) P_i$, where n and BOM(i) are the number of components and the number of components i needed for a finished product, respectively, and P_i is the unit purchasing price of component i.

3.2.2. Final Product Quality. The quality of the finished product is related to its components. We treat the finished product as a system, which may be composed of unreliable components. In order to analyze the system reliability and other related characteristics, we use reliability block diagrams (RBDs). RBDs are widely used in engineering and science for describing the interrelations among components [34]. A system can be classified as series, parallel, or mixed. In a series configuration, a failure in any component results is the failure of the entire system. Let us assume that the components of a computer, such as the motherboard, the hard drive, the power supply, and the processor, are arranged in a series. If the power supply does not work, the computer will not work. In other words, the system only works when all components work. System quality is calculated as $R = \prod_{i=1}^{n} Q_i$, where Q_i is the quality of component i, in terms of reliability rate.

In a parallel system, at least one of the units must succeed for the system to succeed. Units in parallel are also referred to as redundant units. Redundancy is a very important aspect of system design and reliability in that adding redundancy is one of several methods for improving system reliability. For example, in a computer with a redundant array of independent disks (RAID), there are many hard disks. To put it another way, if disk A, disk B, or any of the n disks succeed, then the system succeeds. The system quality is then given by $R = 1 - \prod_{i=1}^{n}(1 - Q_i)$.

While many smaller systems can be accurately represented by either a simple series or parallel configuration, there may be larger systems that involve both series and parallel configurations in the overall system. Such systems can be analyzed by calculating the reliabilities for the individual series and parallel sections, respectively. Then, we combine them in an appropriate manner. Such a methodology is illustrated in the example shown in Figure 1. The system quality is then given by $R = \{Q_1 \times [1-(1-Q_2)^2] \times Q_3\} \times \{[1-(1-Q_4)^2] \times [1-(1-Q_5)^2]\} \times [1-(1-Q_6)^3] \times [1-(1-Q_7)^3]$.

3.2.3. Delivery Reliability of Final Product. Delivery reliability (DR) of the final product depends on the delivery reliability of all materials/components. The finished product's delivery reliability will be lowered when any material is not delivered on time. We define DR_i to be the delivery reliability of component i, which is computed by the probability of delivery on time. We assume that there are m items, which are made to order. Thus, the finished product is assembled or delivered on time and at the probability $\mathrm{DR} = \prod_{i=1}^{m} \mathrm{DR}_i$, which is between 0 and 1, and the greater the better.

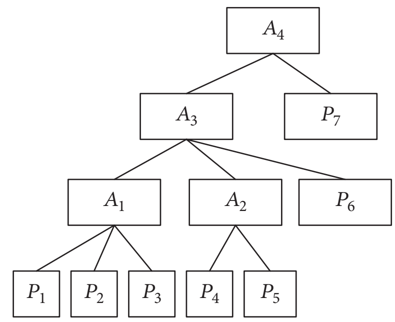


Figure 1: Product structure.

3.2.4. Total Delivery Lead Time. The popular manufacturing/assembly/delivery mode is a hybrid control between made to order (MTO) and made to stock (MTS). There are inventory and backlog costs when using MTS. However, manufacturing/assembly/delivery time is needed when using MTO, which is infeasible when its time is greater than the customer cycle time. In general, the shorter the time from customer orders arriving to fulfil them, the better. A company will choose different kinds of suppliers after it has chosen a MTO/MTS production mode. The company that uses the just-in-time strategy (a kind of MTO) requests its strategic suppliers to be located nearby in order to fulfil its orders quickly and reliably. Sun et al. [11] presented a model to determine the MTO/MTS mode among a supply network. In this paper, we assume that the firm has decided which component is made to stock or order. The total delivery lead time based on supplier delivery times is equal to a *critical path time* from start to end in the supply network [11]. The shorter the delivery lead time, the better the supply network. The supply network with a shorter delivery lead time can respond to the market quickly. Therefore, we use delivery lead time to evaluate the supply network's response performance to customer orders.

4. Case Study

4.1. Background. The case study is based on a real-life supplier selection problem in a large Chinese electronic OEM in Shenzhen. Its competitive advantages are low cost and short delivery lead time. The production of the electronic products is highly complicated and relies on the solid suppliers. After the analysis of component value and consumption, the key components are listed. We apply the proposed methodology to a finished product with seven key components to be purchased.

Figure 1 shows the product structure of the finished product. The finished product is made of seven key components, P_1 to P_7, which are purchased from different suppliers. A_1, A_2, and A_3 are semifinished products. The bill of materials shown in Table 1, such as one piece of P_1, two pieces of P_2, and one piece of P_3, is assembled to form one piece of A_1.

We assume that the company can decide on how to produce or assemble each component/semifinished product/finished product, using either MTO or MTS. Although

Table 1: Supplier information.

Component	Amount/production mode	Supplier candidates	Quality (%)	Total delivery lead-time (days)	Cost (RMB)	Delivery reliability (%)
P_1	1/MTS	S-11	98.5	5	24	99
		S-12	99.7	2	26	98.5
		S-13	99.8	14	36	98.8
		S-14	99.2	7	34	99.5
		S-15	99.6	5	12	99.5
		S-16	99.7	8	35	98.8
P_2	2/MTO	S-21	98	20	75	98
		S-22	98.8	13	70	97
		S-23	99.2	5	50	96.5
		S-24	99.7	25	55	99
		S-25	98.5	10	80	98
		S-26	99.2	3	90	99.5
P_3	1/MTS	S-31	99.2	8	150	99.5
		S-32	99.5	4	120	99
		S-33	98.8	5	130	98.6
		S-34	98.5	25	90	98.5
		S-35	98.8	12	80	99.5
		S-36	99	20	65	98.7
P_4	2/MTO	S-41	99.2	15	30	98.5
		S-42	97.6	45	95	96.5
		S-43	98.5	15	65	98.8
		S-44	98.4	27	83	96.5
		S-45	99.2	31	65	98.7
		S-46	99.5	18	65	98.6
P_5	2/MTO	S-51	99.2	8	200	98.5
		S-52	99.2	5	200	98.6
		S-53	98.5	12	250	98.3
		S-54	98.7	13	180	99
		S-55	98.7	12	160	99.5
		S-56	98.8	16	210	99
P_6	3/MTS	S-61	99.6	25	30	99.5
		S-62	98.8	13	36	98.7
		S-63	98.5	23	45	98.5
		S-64	99.2	25	48	98.8
		S-65	99.3	19	65	99.5
		S-66	99.2	15	55	98
P_7	3/MTO	S-71	98.8	12	35	98
		S-72	99.5	18	30	98.5
		S-73	98.5	18	40	99
		S-74	97.7	21	32	98.5
		S-75	99.5	5	38	99.5
		S-76	98.4	13	35	97.5

Notes. MTS means made to stock; MTO means made to order.

Table 2: Top ten supplier combinations.

Number	Supplier combination							Coupling values for final product				Score
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	Quality	Cost	Delivery lead-time	Delivery reliability	
85	S-15	S-23	S-36	S-41	S-55	S-61	S-72	87.23%	754	39	91.03%	1
87	S-15	S-23	S-36	S-41	S-55	S-62	S-72	85.14%	772	34	90.30%	0.9746
86	S-15	S-23	S-36	S-41	S-55	S-61	S-75	87.23%	778	39	91.95%	0.9713
21	S-12	S-23	S-36	S-41	S-55	S-61	S-72	89.19%	782	39	90.12%	0.9677
81	S-15	S-23	S-36	S-41	S-52	S-61	S-72	87.67%	794	39	90.21%	0.9512
88	S-15	S-23	S-36	S-41	S-55	S-62	S-75	85.14%	796	35	91.22%	0.9463
23	S-12	S-23	S-36	S-41	S-55	S-62	S-72	87.05%	800	35	89.39%	0.9427
22	S-12	S-23	S-36	S-41	S-55	S-61	S-75	89.19%	806	39	91.03%	0.9399
83	S-15	S-23	S-36	S-41	S-52	S-62	S-72	85.57%	812	35	89.48%	0.9274
82	S-15	S-23	S-36	S-41	S-52	S-61	S-75	87.67%	818	39	91.12%	0.9243

Notes. The top supplier combinations are obtained based on models (1)–(6) in order to analyze the differences among the individual supplier selections and combinations. However, only the best supplier combination calculated based on the model needs to be obtained.

different potential suppliers can have different delivery lead times, the in-house production lead times for A_1, A_2, A_3, and the finished product are fixed.

4.2. Combinatorial Analysis. As shown in Table 1, there are six potential suppliers for each component. The coupling values and the score of each combination are calculated by the proposed methodology in Section 3. Table 2 summarizes the top 10 supplier combinations.

For comparison, individual supplier selection using data envelopment analysis (DEA) has been carried out. The top two suppliers selected by DEA are S-12 and S-15 for P_1; S-26 and S-23 for P_2; S-32 and S-36 for P_3; S-41 and S-46 for P_4; S-52 and S-55 for P_5; S-61 and S-62 for P_6; S-72 and S-75 for P_7.

The optimal supplier combination is number 85, which is the first row in Table 1. It is noted that suppliers S-36 and S-55 are not the best ones for P_3 and P_5, according to the individual evaluation using DEA. Instead, S-32 and S-52 are the best suppliers, respectively, based on the methodology in Section 3. In other words, all the best individual suppliers may not form the best supplier combination for the finished product. One explanation is that when the whole production lead time is considered, it makes no difference if S-55 is replaced by S-52, which has a shorter lead time. The result is identical to that of number 81 in Table 2. The score of number 81 is smaller than the optimal score because its higher cost and lower reliability cannot be compensated by a slight improvement in quality.

4.3. Scenario Analysis. In this section, we reveal that the supplier selection is related to other components' suppliers and production modes. We should balance all the attributes of different components. The best supply network should harmonize itself with the supply network structure, production modes, and supplier attributes. The performance of a supply network will decrease if the coordination between suppliers is worse. One study of the US food industry estimated that poor coordination among supply chain partners wasted $30 billion annually [35]. Fisher also presented a matching matrix between supply chains and products. Functional products require an efficient process, while innovative products require a responsive process. We extend his claim to this: all suppliers should systematically match their supply chain network. The match among suppliers should be based on customer demand and supply network strategy. When producing functional products, such as staples, toothpaste, and soap, emphasis is on supplier cost and quality. However, more focus is given to delivery performance for innovative products, such as fashionable dress, laptops, and electronics.

4.3.1. Synergy among Component Attributes. In this subsection, which discusses synergy among component attributes, we change the attribute values of components by a trial-and-error approach in order to determine how the supplier combinations are affected. We adjust two attribute values of components to study their relationships provided that the best supplier combination remains unchanged. The attribute value of the first component is manipulated at discrete points. We calculate the range of attribute values of the second component to keep the best supplier combination unchanged provided that the values of other components are not changed. Figure 2 shows the relevant cost, quality, delivery reliability, and lead time effects of P_2 on P_1.

The four plots reveal the P_2 effects of quality, cost, delivery lead time, and reliability on P_1 in Figure 2. The cost range of P_2 is decreased when the cost P_1 is increased in order to provide a competitively priced finished product. Regarding quality, when P_1 quality increases from 90% to 99%, P_2 quality can decrease from 99% to 94.5%. We do not need to use extremely high-quality components for others if there is a quality trade-off in another component. In general, the cost is higher when the quality is higher. Therefore, we put more into cost for finished products when their quality is only slightly improved. P_1 is ordered to stock, and its lead time will not affect the total lead time. Therefore, the lead time range of P_2 is unchanged. The effects between other components can be similarly analyzed. This part numerically displays synergy

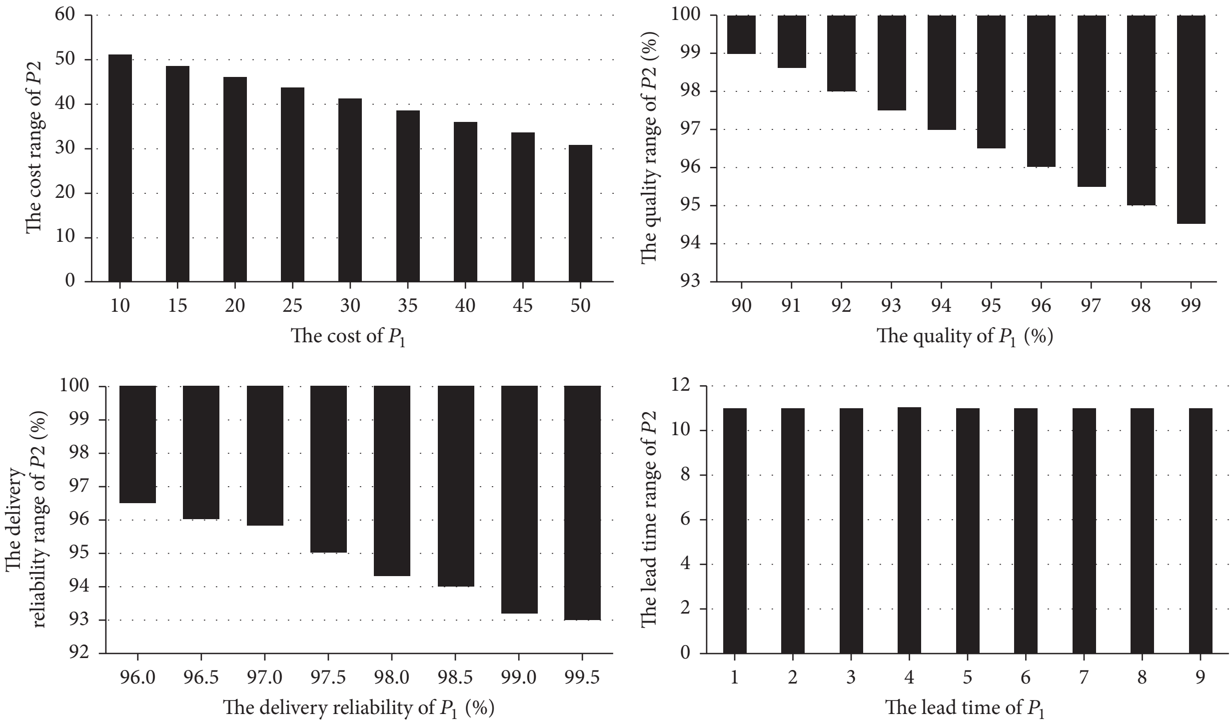


Figure 2: Synergy effect among components P_1 and P_2. *Notes*. The values of attributes for components P_3 to P_7 are unchanged. We use the data of S-36, S-41, S-55, S-61, and S-72.

among the component suppliers. The just-in-time principle requests the suppliers to set up their factories nearby to decrease the lead time systematically.

4.3.2. Production Mode. The manufacturing company should decide which component is made to order or stock. Sun et al. [11] provided a methodology for the production mode selection. They consider two factors in their paper: demand variability and customer delivery lead time. The objective is to minimize the supply chain cost. The production mode is related to supplier delivery lead time. In the rest of this paper, we will test the effect of the production mode on supplier selection. To the best of our knowledge, there is no paper concerning this issue in the literature.

We change a component's production mode, for example, by setting P_6 to be made to order. The potential suppliers of P_6 are S-61 and S-62. Their lead times are then 25 days and 13 days, respectively. Based on the new production mode, we change the total lead time of the supply network to 39 days and 37 days, respectively. Other attributes remain unchanged. In this case, the best supplier for component P_6 is S-62. As one can see, different production modes would be apt to select different suppliers. For example, a manufacturing company adopting the just-in-time strategy requests its strategic suppliers to be located within a one-hour radius in order to safeguard on-time delivery of components.

If the manufacturing company could obtain excellent, additional suppliers at a reasonable cost, it would change its production mode. Hewlett Packard manufactures its printers in the United States and delivers them to markets all over the world after several months of ocean shipping. In this situation, the total delivery lead time is so long that Hewlett Packard has to forecast the demand in advance and bear the risk of forecast error. After researching its supply chain and product design, Hewlett Packard successfully developed several of their printers around modular components to benefit from postponing the point of differentiation in their manufacturing and assembly processes. Finally, they postponed the last assembly into local markets [36], thus changing the final assembly from MTS to MTO.

We examine how the production mode will change when the production time of a component is changed. We divide the components into two groups: cost factors and production time. In order to find the relation between the lead time parameters and the optimal production mode, in one group these factors are fixed, and in another group they are varied. Table 3 shows the shift when the lead times of components A_1, P_1, and P_4 are changed. The rows from top to bottom show the increase in factor values. The string in the middle of the table represents the production mode of the components. The first, fourth, and eighth character in the code sequence describe the production mode of A_1. In each column, the discrepancies between the supply networks are marked in bold.

Table 3 reveals that more components are made to stock when the assembly time of A_1 is longer. The customer delivery time is fixed at 30 days. Since the assembly time of A_1 is longer, it is more difficult to meet the customer delivery time when using MTO. Thus, the production mode of A_1 has to be changed from MTO to MTS. What is more,

Table 3: What-if analysis based on the change of lead time of suppliers.

The lead time of components	The production mode change		
	A_1	P_1	P_4
Short	**1**0**1**1000**1**111	**1**1010011111	0**1**011**001**111
	10**1**1000**1**111	**1**1010011111	0**1**011**001**111
	00**1**1000**1**111	**1**1010011111	0**1**011**001**111
↓	**0**0**1**1000**1**111	**1**1010011111	0**1**011**001**111
	001000**0**0111	**0**1010011111	0**1**000**000**111
	001000**0**0111	**0**1010011111	0**1**000**000**111
	001000**0**0111	**0**1010011111	0**1**000**000**111
Long	**00**1000**0**0111	**0**1010011111	0**1**000**000**111

Notes. Changed factors of component shown in bold character; "1" means MTO; "0" means MTS; the components are sequenced as P_1 P_2 P_3 P_4 P_5 P_6 P_7 A_1 A_2 A_3 A_4; the customer delivery time is fixed, equal to 30 days.

because the critical path of BOM is changed in order to satisfy customer delivery time requirements, the purchasing modes of P_1 and P_3 are also changed from MTO to MTS. From this case, we can hypothesize that the production mode of other components, whose factors are not changed, is perhaps changed.

The parameters of the supply network mode are integrated; thus, some functions of the supply network, such as supplier selection, should be considered from a whole system point of view. Most papers give the criteria based on a single supplier of product quality, price, and delivery time. In general, a supplier with a short delivery time should have a high price. However, this is a question of whether or not companies should pay higher prices for shorter delivery times. Based on our model, the total time to convert raw material to finished goods is related to the total production time of materials/components. Therefore, a supplier offering a shorter delivery time cannot always decrease the total time needed to convert raw materials to finished goods. For example, if a component is in a noncritical path of the supply network, the total time will be constant in a range of the component's lead time. This allows the product manager to choose an external raw material vendor with lower capability (i.e., with lower production cost and longer processing lead time).

5. Conclusions

This paper aims to develop an analytical model that describes the synergies among product components and supplier selection criteria that enhance supplier selection effectiveness. A max-max model was designed to facilitate the selection of the optional combination of suppliers. The synergies are identified using coupled-attribute analysis.

This paper integrates combinatorial optimization with coupling attributes of the final product, which is the real objective of the end user. Four coupling attributes are identified, including final product cost, final product quality, delivery reliability, and delivery lead time of final products. This paper also investigates the balance among component attributes and the effect on the production mode when selecting a supplier. The production time is calculated under the defined supply structure, lead time of suppliers, and production mode. The effect of supplier selection on the production mode is measured by using a different experimental scenario.

The model is applied to a real case and is shown to be an appropriate methodology for evaluating suppliers. The real case demonstrated that the best supply network should harmonize itself with the supply network structure, production modes, and supplier attributes. The what-if analysis showed that the parameters of the supply network mode are integrated; thus, some functions of the supply network, such as supplier selection, should be considered from a whole system point of view.

Further research into the problem of supplier selection may encourage the development of experimental design or heuristics algorithms to explore how to improve the performance supplier combination among many supplier candidates or multiple components considering numerous levels of supplier attributes.

Notation and Symbols Used in Section 3.1

- c: The number of components types
- ns: The number of suppliers for each component
- cs_i^k: The supplier k for component i
- V_p: The vector represents the supplier combination as sequenced p
- y_{rj}, x_{tj}: Representing the value of the rth output and the tth input for combination j respectively
- u: The number of inputs of supplier combination
- v: The number of outputs of supplier combination
- a_r, b_t: A set of factor weights given to the rth output and the tth input, respectively.

Conflicts of Interest

The author declares that he has no conflicts of interest.

Acknowledgments

This research was supported by Natural Science Foundation of Shaanxi (2017JM7009) and Young Talent Scheme of Xi'an Jiaotong University, China.

References

[1] L. de Boer, E. Labro, and P. Morlacchi, "A review of methods supporting supplier selection," *European Journal of Purchasing and Supply Management*, vol. 7, no. 2, pp. 75–89, 2001.

[2] M. N. Nobar and M. Setak, "A new approach for supplier selection process from the features of second layer suppliers point of view," *International Journal of Industrial Engineering and Production Research*, vol. 21, no. 1, pp. 35–44, 2010.

[3] N. Aissaoui, M. Haouari, and E. Hassini, "Supplier selection and order lot sizing modeling: a review," *Computers & Operations Research*, vol. 34, no. 12, pp. 3516–3540, 2007.

[4] G. Bruno, E. Esposito, A. Genovese, and R. Passaro, "AHP-based approaches for supplier evaluation: problems and perspectives," *Journal of Purchasing and Supply Management*, vol. 18, no. 3, pp. 159–172, 2012.

[5] Z. Degraeve, E. Labro, and F. Roodhooft, "An evaluation of vendor selection models from a total cost of ownership perspective," *European Journal of Operational Research*, vol. 125, no. 1, pp. 34–58, 2000.

[6] A. Genovese, S. C. Koh, G. Bruno, and E. Esposito, "Greener supplier selection: state of the art and some empirical evidence," *International Journal of Production Research*, vol. 51, no. 10, pp. 2868–2886, 2013.

[7] W. Ho, X. Xu, and P. K. Dey, "Multi-criteria decision making approaches for supplier evaluation and selection: a literature review," *European Journal of Operational Research*, vol. 202, no. 1, pp. 16–24, 2010.

[8] , *Combinatorial Auctions*, P. Cramton, Y. Shoham, and R. Steinberg, Eds., MIT Press, Cambridge, Massachusetts and London, England, 2006.

[9] J. C. R. Giacon, H. T. Y. Yoshizaki, and G. Montibeller, "Supplier selection by multi-attribute combinatorial bidding," in *Proceedings of the 47th Hawaii International Conference on System Sciences, HICSS '14*, pp. 1132–1141, January 2014.

[10] M. H. Rothkopf, A. Pekeč, and R. M. Harstad, "Computationally manageable combinational auctions," *Management Science*, vol. 44, no. 8, pp. 1131–1147, 1998.

[11] X. Y. Sun, P. Ji, L. Y. Sun, and Y. L. Wang, "Positioning multiple decoupling points in a supply network," *International Journal of Production Economics*, vol. 113, no. 2, pp. 943–956, 2008.

[12] G. W. Dickson, "An analysis of vendor selection systems and decisions," *Journal of Purchasing*, vol. 2, no. 1, pp. 5–17, 1966.

[13] C. A. Weber, J. R. Current, and W. C. Benton, "Vendor selection criteria and methods," *European Journal of Operational Research*, vol. 50, no. 1, pp. 2–18, 1991.

[14] X. Y. Sun, L. Y. Sun, Y. L. Wang, and B. J. Wu, "An investigation on the application of advanced manufacturing mode in China," *Chinese Industrial Engineering and Management*, vol. 2, pp. 6–9, 2005.

[15] C.-J. Lin and H.-H. Kuo, "Multiple comparisons with the best for supplier selection," *Quality and Reliability Engineering International*, vol. 30, no. 7, pp. 1083–1092, 2014.

[16] S. Sharma and S. Balan, "An integrative supplier selection model using Taguchi loss function, TOPSIS and multi criteria goal programming," *Journal of Intelligent Manufacturing*, vol. 24, no. 6, pp. 1123–1130, 2013.

[17] C. A. Weber and J. R. Current, "A multiobjective approach to vendor selection," *European Journal of Operational Research*, vol. 68, no. 2, pp. 173–184, 1993.

[18] J. Chai, J. N. K. Liu, and E. W. T. Ngai, "Application of decision-making techniques in supplier selection: a systematic review of literature," *Expert Systems with Applications*, vol. 40, no. 10, pp. 3872–3885, 2013.

[19] F. T. S. Chan, N. Kumar, M. K. Tiwari, H. C. W. Lau, and K. L. Choy, "Global supplier selection: a fuzzy-AHP approach," *International Journal of Production Research*, vol. 46, no. 14, pp. 3825–3857, 2008.

[20] T. Wu and J. Blackhurst, "Supplier evaluation and selection: an augmented DEA approach," *International Journal of Production Research*, vol. 47, no. 16, pp. 4593–4608, 2009.

[21] C.-T. Lin, C.-B. Chen, and Y.-C. Ting, "An ERP model for supplier selection in electronics industry," *Expert Systems with Applications*, vol. 38, no. 3, pp. 1760–1765, 2011.

[22] C. N. Liao and H. P. Kao, "An integrated fuzzy TOPSIS and MCGP approach to supplier selection in supply chain management," *Expert Systems with Applications*, vol. 38, no. 9, pp. 10803–10811, 2011.

[23] Y.-T. Lin, C.-L. Lin, H.-C. Yu, and G.-H. Tzeng, "A novel hybrid MCDM approach for outsourcing vendor selection: a case study for a semiconductor company in Taiwan," *Expert Systems with Applications*, vol. 37, no. 7, pp. 4796–4804, 2010.

[24] R. Hlioui, A. Gharbi, and A. Hajji, "Joint supplier selection, production and replenishment of an unreliable manufacturing-oriented supply chain," *International Journal of Production Economics*, vol. 187, pp. 53–67, 2017.

[25] W. D. Cook, J. Zhu, G. Bi, and F. Yang, "Network DEA: additive efficiency decomposition," *European Journal of Operational Research*, vol. 207, no. 2, pp. 1122–1129, 2010.

[26] C. Chen and H. Yan, "Network DEA model for supply chain performance evaluation," *European Journal of Operational Research*, vol. 213, no. 1, pp. 147–155, 2011.

[27] S. Park, C. Ok, and C. Ha, "A stochastic simulation-based holistic evaluation approach with DEA for vendor selection," *Computers & Operations Research*, 2017.

[28] M. R. Asadabadi, "A customer based supplier selection process that combines quality function deployment, the analytic network process and a Markov chain," *European Journal of Operational Research*, vol. 263, no. 3, pp. 1049–1062, 2017.

[29] X. Chen and J. Zhang, "Production control and supplier selection under demand disruptions," *Journal of Industrial Engineering and Management*, vol. 3, no. 3, pp. 421–446, 2010.

[30] S. Talluri and R. Narasimhan, "Vendor evaluation with performance variability: a max-min approach," *European Journal of Operational Research*, vol. 146, no. 3, pp. 543–552, 2003.

[31] Z. Sinuany-Stern, A. Mehrez, and Y. Hadad, "An AHP/DEA methodology for ranking decision making units," *International Transactions in Operational Research*, vol. 7, no. 2, pp. 109–124, 2000.

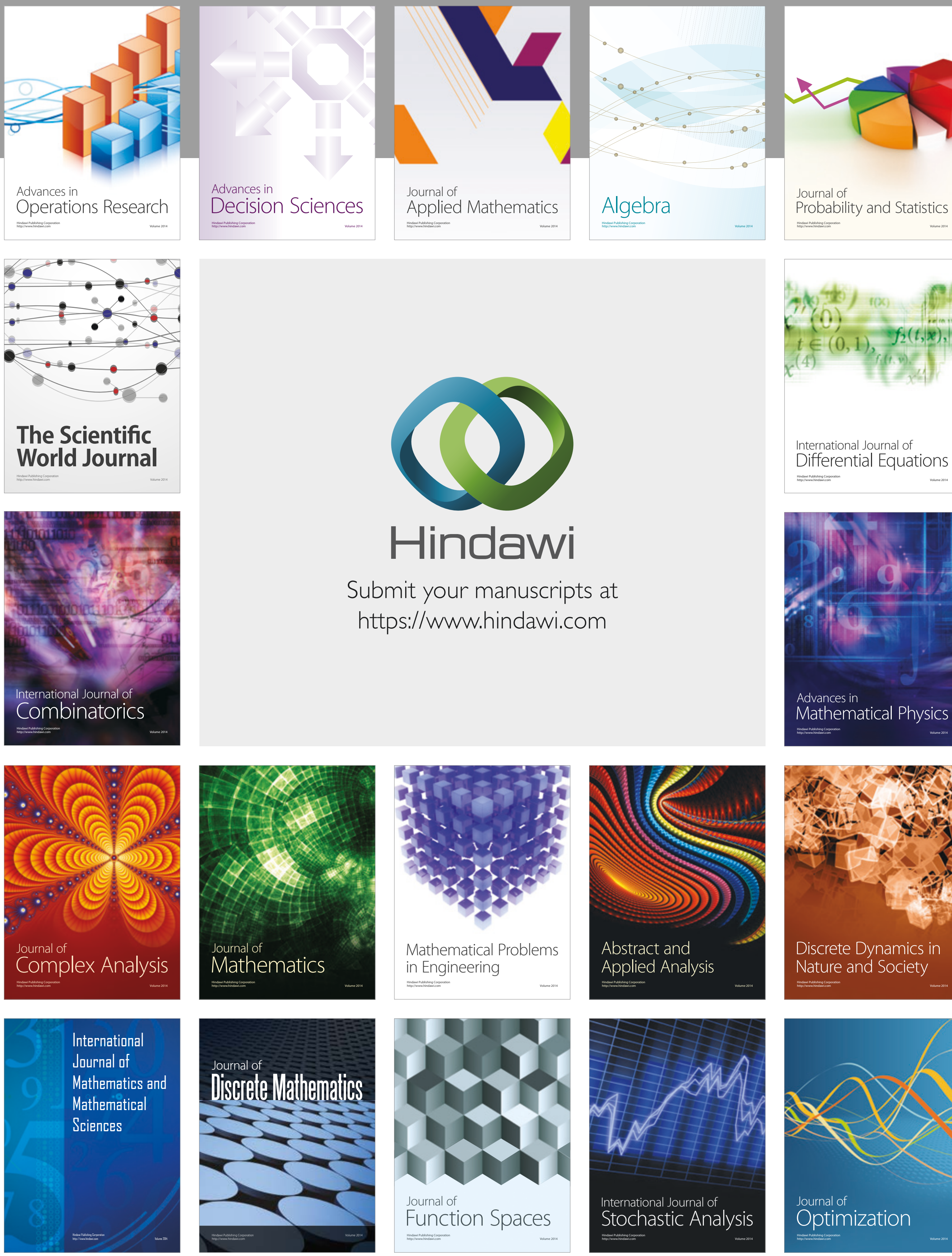
[32] A. Charnes, W. W. Cooper, and E. Rhodes, "Measuring the efficiency of decision making units," *European Journal of Operational Research*, vol. 2, no. 6, pp. 429–444, 1978.

[33] Y.-M. Wang and P. Jiang, "Alternative mixed integer linear programming models for identifying the most efficient decision making unit in data envelopment analysis," *Computers & Industrial Engineering*, vol. 62, no. 2, pp. 546–553, 2012.

[34] A. Lisnianski, "Extended block diagram method for a multi-state system reliability assessment," *Reliability Engineering & System Safety*, vol. 92, no. 12, pp. 1601–1607, 2007.

[35] M. L. Fisher, "What is the right supply chain for your product," *Harvard Business Review*, vol. 75, no. 2, pp. 105–116, 1997.

[36] E. Feitzinger and H. L. Lee, "Mass customization at Hewlett-Packard: the power of postponement," *Harvard Business Review*, vol. 75, no. 1, pp. 116–121, 1997.


Advances in Operations Research
Advances in Decision Sciences
Journal of Applied Mathematics
Algebra
Journal of Probability and Statistics
The Scientific World Journal
Hindawi
Submit your manuscripts at https://www.hindawi.com
International Journal of Differential Equations
International Journal of Combinatorics
Advances in Mathematical Physics
Journal of Complex Analysis
Journal of Mathematics
Mathematical Problems in Engineering
Abstract and Applied Analysis
Discrete Dynamics in Nature and Society
International Journal of Mathematics and Mathematical Sciences
Journal of Discrete Mathematics
Journal of Function Spaces
International Journal of Stochastic Analysis
Journal of Optimization