Hindawi
Discrete Dynamics in Nature and Society
Volume 2018, Article ID 4950740, 25 pages
https://doi.org/10.1155/2018/4950740

Research Article

A Study on Evaluation of Modular Suppliers and Discussion of Stability

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Received 11 January 2018; Revised 24 March 2018; Accepted 3 May 2018; Published 2 July 2018

Academic Editor: Manuel De la Sen

Evaluation of modular suppliers is a crucial step towards building an effective modular production network. However, few studies focus on the salient features of modular production and discuss the selection and evaluation of modular suppliers. In this paper, the fuzzy evaluation method is used to make the evaluation. Regarding the method, this paper applies mathematical analysis to further discuss the stability of the method by introducing a dispersion degree and modifying the evaluation vector. Then, based on modularization theory, this paper adopts a factor analysis to identify the criteria for a modular supplier. This paper has two main findings: constructing an index system to evaluate modular suppliers and providing a way to test the stability of the method used. As such, the results of the paper contribute to helping enterprises involved in modular production to identify qualified modular suppliers and make reliable decision with regard to modular supplier evaluation.

1. Introduction

Since the 1970s and 1980s, the global manufacturing sector has undergone an extensive and profound change. In the past ten years, manufacturing companies tended to take the vertical integration strategy to produce. Namely, a company assumes control over several production or distribution steps involved in the creation of its product or service [1]. Vertical integration can help companies reduce costs and improve efficiencies by decreasing transportation expenses and reducing turnaround time, among other advantages [1–5]. Nevertheless, with the development of information technology and diversification of personal needs, manufacturing companies gradually disintegrate many activities and take the focus strategy. Big MNCs such as IBM, GM, GE, Toyota, Apple, P&G, Unilever, HP, and Philips now focus on a small number of core businesses (or areas) and outsource the noncore businesses through outsourcing and global sourcing and even sell their productive branches at home or abroad. The purpose of doing so is to reduce the operation risks, respond to the diversified market demands and adapt to the rapid development of information technology [6–9]. The vertical disintegration of industrial organizations does not mean that they simply return the integrated bureaucracy to the market. In fact by focusing on its core businesses and connected by the noncore businesses, these firms form network organizations which help the member firms to cooperate and obtain benefit through win-win activities. And it is called the networking of industrial organizations production network paradigm [10].

Furthermore, with the upsurge of modularity, namely, the use of exchangeable parts or options in the fabrication of an object, the internal production chain is decomposed and reorganized, which leads to the fragmentation of production process and the relocation of these fragments around the globe. Different procedures and processes of production are split up and assigned to different countries to produce. Then around a final product a series of companies are organized and connected and form the interorganizational network. Such new industrial organizing mode is called modular production network (MPN). Within functionally specialized value chain nodes activities tend to remain tightly integrated and based on tacit linkages [10]. Between these nodes, however, linkages are formed by the transfer of codified information. From such linkages the network architecture arises.

In a modular production network, the modular suppliers are always flexible and specialized. They can produce "the

capacity pooling effect". That is, brand manufacturers can easily integrate with the necessary modules and service capabilities and quickly turn their own ideas and designs into real products. According to the view of system economics, modular production network is actually an organic economic system which consists of system integrators and general/private module suppliers. Generally modular suppliers have the ability to independently develop and produce modules in accordance with system design rules. In some cases, they can even influence the system integrators who act as system designers in formulating and modifying the system design rules.

Therefore, in a modular production network the modular suppliers appear to have strong ability. The relationship between modular suppliers and system integrators is no longer a simple attached and dependent relationship. Instead, in order to achieve the optimality of modular production network, they have carried out extensive cooperation. So for a modular production network, it has dual subjects. One is production integrator and another is modular supplier. A production integrator usually acts as a convener and leader in the modular production network whereas a modular supplier is also indispensable and to some extent it is even of the same importance of production integrator. Both production integrator and modular supplier have relatively equal strong ability and this is the distinctive characteristic of modular production network that differentiates it from other production cooperation modes. Hence, for a production integrator, to build an effective modular production network the selection and evaluation of modular suppliers are of great importance.

However, few studies are carried out to discuss the selection of modular suppliers. Although there are already abundant researches of supplier evaluation and selection, very few studies discuss the selection of modular suppliers in the new modular production network. There lacks systematic study regarding the construction of the index system of modular supplier selection and the use of evaluation methods.

In fact, as analyzed above, there is a big difference between modular suppliers and common suppliers and such difference is mainly caused by the characteristics of modular production. On the premise of modularization, modular production is a production organizing mode that links module production enterprises and module assembly enterprises through relationships. In the context of such production cooperation, first of all the modular suppliers should possess powerful module production and R&D capability and can provide product modules which the production integrators need. At the same time, the compatibility of module suppliers will enable them to better communicate, cooperate, and innovate with production integrators under the guidance of "visible design rules". Nevertheless, these characteristics have not been fully considered in the evaluation of common suppliers.

To fill the research gap, first in this paper the fuzzy evaluation method is adopted and modified to evaluate the modular suppliers. Based on it, the stability of the method is discussed. Then based on the method, this paper conducts an empirical study on the index system of modular supplier selection. The index system can provide a comprehensive lens to study and select the potential modular suppliers. And the method as a whole is supposed to provide references for managers to make better selection decisions.

This paper is structured as follows: the second section is a literature review, in which relevant studies are reviewed and discussed; the third section is an introduction to the method we propose; the fourth section is an empirical study of the index system. By investigation and expert consultation, the questionnaires are designed and an empirical study is conducted; the fifth section is a case study. Based on the index system we built and by applying the fuzzy evaluation method, a modular supplier of JMC company is evaluated and the stability of the result is discussed.

2. Literature Review

2.1. An Overview on Indexes of Supplier Selection. The study on supplier selection can be traced to the 1960s. It was first examined in the studies about the selection of vendors in the US [11]. And he found that three factors are crucial in the choice of a vendor and they are the ability to meet quality standards, the ability to deliver the product on time, and performance history. Then many scholars respectively conducted studies on selection and evaluation of suppliers from different perspectives. For example, an empirical study was conducted on US auto industry and 8 indexes out of 26 were chosen to evaluate suppliers [12]. The indexes include quality, delivery, reliability, relationship, flexibility, price, and service. A study established an objective-orientation driven supplier customer satisfaction performance rating system [13]. In the study, the authors found four factors that are especially important for supplier selection and they are incoming inspection, line reject performance, supplier service quality, and product reliability. A study discussed the importance of suppliers' roles in new product development and suggested that supplier selection should be extended to consider the influence of supplier configuration [14]. A study examined the extension of the vendor evaluation methods with environmental, green issues [15]. By dividing the criteria into the traditional (managerial) and environmental (green) factors, they apply data envelopment analysis (DEA) with the common weights analysis (CWA) method to design a weight system, which helps to determine the environmental factors, as important decision factors. Until now the discussion of factors of supplier selection involves a wide range. We try to make a summary of the factors mentioned in previous studies and for the summary please see Table 1.

From the above research on the index of supplier selection and evaluation, we can see the early research of supplier selection index mostly focuses on factors such as cost, quality, price, delivery, and service. With the changes of environment and extension of supplier roles and capability, the former indexes can hardly completely evaluate the capability of suppliers. In such circumstances, some scholars begin to pay close attention to other factors, such as market agility, innovation ability, information reception and processing ability, and environmental management ability. The supplier selection index is gradually systematized and the evaluation criteria have been diversified and comprehensive.

Table 1: Indexes of supplier selection.

No.	Criteria	References	No.	Criteria	References
1	On time delivery	[16–20]	37	Total cost	[21]
2	Quality	[14, 16, 18, 22, 23]	38	Material management	[24]
3	Cost	[19–21, 25, 26]	39	Size of enterprise	[27]
4	After service	[27]	40	Procedural compliance	[11]
5	Product flexibility	[24, 27]	41	Customer relationship	[28]
6	Reputation	[11, 29–32]	42	Quality practices	[33]
7	Technical capability	[11, 32, 34, 35]	43	Trust	[21]
8	Flexibility	[21, 26, 34]	44	Resource utilization	[21]
9	Capacity and production facility	[11, 26, 30, 32, 34, 35]	45	ISO certification	[20]
10	Service	[21, 24, 26, 27, 36]	46	Advanced manufacturing technology	[30]
11	Financial position	[11, 20, 30, 32, 35]	47	Product configuration	[14]
12	Geographical location	[11, 27, 30, 35]	48	New technological identification	[34]
13	Responsiveness	[21, 37]	49	Support in product development	[20]
14	Communication	[11, 19, 20, 24]	50	Support in value analysis	[30]
15	Supplier's willingness to cooperate	[26]	51	Support in product simplification	[30]
16	Management and organization	[26, 30, 34, 35]	52	Support in modularization activity	[30]
17	Enterprise environment	[24]	53	Manufacturing process	[21]
18	R&D capability	[38, 39]	54	Loyalty	[40]
19	After sales service	[11, 24, 28]	55	Compatibility across levels and functions	[34]
20	Lead time	[19, 33]	56	Capability of new product development	[34]
21	Attitude	[11, 24, 35]	57	Cost saving measure adoption	[19]
22	Suppliers honesty	[24]	58	Process technology	[21]
23	Innovation	[26, 39]	59	Process management	[21]
24	Ability to keep promise	[24]	60	Purchasing management	[21]
25	Managerial capability	[26]	61	Factory management	[21]
26	Percentage defectiveness	[25]	62	Quality management	[26]
27	Design capability	[41]	63	Human resource management	[26]
28	Reliability	[20, 21, 28, 36]	64	Potential competence dimension	[21]
29	Payment terms	[40]	65	Testing capability	[35]
30	Warranties	[11]	66	Scope of resources	[35]
31	Operating controls	[11]	67	Industry knowledge	[32]
32	Product development	[20, 27]	68	Strategic importance of supplier	[30]
33	Clusters/grouping of attributes or criteria	[11]	69	Employee working conditions	[30]
34	Customer satisfaction level	[34]	70	Supplier's sale and administrative capabilities	[30]
35	Management system	[42]	71	Reciprocal arrangement	[11]
36	Transportation and storage	[27]			

2.2. An Overview on Methodologies of Supplier Selection. Regarding the methodology of supplier selection, both domestic and foreign scholars apply almost the same methods. And the main methods they use are analytic hierarchy process method (AHP), activity-based costing method (ABC), fuzzy theory, linear program method (LP), neural networks, and data envelopment analysis method (DEA).

For example, a study used Taguchi loss functions to measure performance of each supplier candidate with respect to the risks and benefits and adopted AHP method to determine the relative importance of these factors to the decision-maker, which provides a comprehensive decision tool for supplier selection [43]. Based on the analysis of the weakness of the existing ABC method, a study established a total cost of ownership matrix, which defined and classified all kinds of cost by extending the traditional ABC method [44]. Based on a case study, a study applied the fuzzy theory to design an integrated fuzzy model to discuss the supplier management issues [45]. By considering material preparation for outsourcing firms, technological transition, quality, lead time, and their interactions, a study adopted a linear programming model with fuzzy multiple goals for analyzing cost effectiveness during vendor selection [25]. Another study constructed a supplier quality evaluation index system under SCM environment [46]. On the basis of it, the BP neural network is used to conduct an empirical study on the supplier

quality space. A study presented a chance-constrained data envelopment analysis (CCDEA) approach in the presence of multiple performance measures that are uncertain and the effectiveness of application of CCDEA in the area of purchasing were demonstrated [28].

Regarding the methodology of supplier selection, in early research, some simple methods such as activity-based costing method (ABC) are mainly used. With the development of technology, some more advanced evaluation methods such as data envelopment analysis method (DEA) and neural networks method are applied to evaluate suppliers. One trend for the use of supplier selection method is the combination and synthesis of more than two methods. Another trend is the continuous modification of these methods. By overcoming the shortcomings of the methods, the essence of today's methodologies is to make the evaluation of a supplier have better relevance and veracity.

2.3. An Overview on Selection of Modular Supplier. Generally speaking modular production refers to such network organization that connects the module production enterprises and module assembly enterprises with the premise of modularization. Generally modular production incorporates two aspects: the decomposition of modules, namely, according to certain connection rules to decompose a complex system or process into self-disciplined subsystems; the integration of modules, namely, to connect the different independent subsystems into a complete system or process [47].

The main participants of a modular production network are system integrators, modular suppliers, and system designers. Usually the system integrator is the core enterprise in modular production. It has strong comprehensive strength and can satisfy the customers' needs according to the market demands by integrating different modules. System designers are responsible for formulating the rules. They decompose the complicated products, determine the configuration, interface and standard of the product system, and guarantee the independent submodules can be reorganized into an organic system. In this sense, system designers can also serve as the system integrators.

Modular suppliers are important participants in modular production network. According to Masahiko Aoki, the effective operation of a modular system lies in the "visible design rules" and the "implicit design rules". The visible rules mainly refer to the interfaces and standards while the invisible rules indicate the design and production rules embedded in a module. The visible rules enable the producers to decompose the complicated modular products into different modules and therefore design, purchase, and produce independently. So in a modular production network, a modular supplier has higher discretion than common supplier to produce as long as the module they produce can well connect other modules based on the standardized interfaces. On the other hand, a module is comprised of many components and is a complicated product too. According to the invisible rules, a modular supplier should have the capability to do R&D independently and decide how to organize these components to produce a module. As such, generally modular suppliers have relatively higher core competence than common suppliers. And such core competence mainly incorporates the R&D capability, design capability, and modularization capability. Besides, the capability of a modular supplier to manage a number of component suppliers also differentiates a modular supplier from a common supplier. In addition, the strong ability of modular suppliers also alters the relationship between modular suppliers and system integrators. It is no longer a mere dependent relationship but a mutually beneficial cooperation relationship built based on reciprocity [48]. In some cases, the modular suppliers can even influence the system integrators by participating in the R&D activities of a modular product and as a result formulating and modifying the system design rules [49].

So as an important actor in a modular production system, modular suppliers are quite different from common suppliers in a number of perspectives. At present, there are still rare studies on the selection of modular suppliers. A study carried out a fuzzy collaborative selection of modular suppliers from the perspective of the whole process of an enterprise [50]. Because the evaluation is built based on the whole process of enterprise production, it focuses on the evaluation of production and technical capabilities but fails to take full account of the modular and production cooperation capabilities of modular suppliers. In fact, these capabilities are very crucial capabilities for modular suppliers. As one of the very few studies on the selection of modular suppliers, this study provides a way of thinking about modular supplier selection issues but it lacks to provide a comprehensive picture of modular suppliers.

In summary, we can find at present the research on supplier selection is more systematic and the design of the evaluation index is more comprehensive. The use of the evaluation methods is more inclined to overcome the judgment errors and other shortcomings as well. Under this research background, we reviewed related studies on modular supplier selection and found very few studies were conducted. To fill this research void, we endeavor to provide a systematic methodology from method test to index design to evaluate modular suppliers. To do that, first we adopt a modified fuzzy evaluation method and based on mathematical analysis we conduct a stability analysis to further discuss the modular supplier selection issue. Then we adopt a factor analysis method to identify the criteria for modular suppliers to construct an evaluation index system. And lastly by a practical case, the method is applied and tested.

3. Fuzzy Evaluation Method and the Stability Analysis

To select and evaluate modular suppliers we need to consider different factors. For the factor system please see Section 4. However, many of these factors are qualitative and this qualitative information is in nature ambiguous. Based on fuzzy sets, the fuzzy evaluation method can solve this problem by giving a comprehensive evaluation of the levels of the evaluated [51, 52]. By dividing the intervals, this method can deal with the ambiguity of the evaluation standards and consider the different levels of the objects. Besides, taking the advantages of experts' experiences makes the results more

Table 2: The pairwise comparison matrix of an expert.

	u_1	u_2	u_3	$\cdots$	u_m
u_1		1	0	$\cdots$	0
u_2	0		1	$\cdots$	1
u_3	1	0		$\cdots$	0
$\cdots$				$\cdots$	
u_m	1	0	1	$\cdots$	

objective and adaptable to the reality. So this paper adopts the fuzzy evaluation method to evaluate and select the modular suppliers.

However, this method depends much on experts' subjective judgment. If an expert underestimates or overestimates a factor, it may influence the final result. So in this paper we further discuss the stability of the method. That is, if an expert underestimates or overestimates a factor, whether the result is stable. In the stability analysis, a dispersion degree is introduced, which helps to further identify the differences of experts' subjective judgment. Based on it, mathematical analysis is adopted to discuss the influence of such difference on the final results. Generally mathematical analysis is a logical demonstration with strictness and continuity and therefore it can provide reliable argument for the topic discussed. As such, in the stability analysis, a mathematical analysis is adopted to provide a clear logic to judge the degree of reliability of the results.

3.1. Determining the Weights. Suppose $Q = (q_1, q_2, \ldots, q_t)$, where q_i denotes an expert consulted. $F = (f_1, f_2, \ldots, f_n)$, where f_i denotes a factor of modular supplier selection. $U = (u_1, u_2, \ldots, u_m)$, where u_i denotes a criterion of a factor of modular supplier selection. $V = (v_1, v_2, v_3, v_4)$, where v_1, v_2, v_3, v_4 respectively denote the "good", "general", "fairly weak", and "weak" comment of each criterion.

Each expert makes a series of judgments based on pairwise comparisons of the criteria of a factor. For two criteria of a factor, the relative important one is given 1 while the less important one is given 0. If the importance is considered as the same, then 0.5 is given to each index. So for any expert, we can have the following pairwise comparison table (see Table 2).

Then for each criterion we sum the values of all the experts (see Table 3).

Then we can calculate the weight of u_i:

$$a_{u_i} = \frac{\sum_{k=1}^{m}\sum_{j=1}^{t} x_{ikj}}{\sum_{k=1}^{m}\sum_{j=1}^{t} x_{1kj} + \sum_{k=1}^{m}\sum_{j=1}^{t} x_{2kj} + \cdots + \sum_{k=1}^{m}\sum_{j=1}^{t} x_{mkj}} \quad (1)$$

Using the pairwise comparison method, we can also calculate the weight of each factor.

Hence, the final weight of each criterion is $a_{U_i} = a_{f_i} \times a_{u_i}$

3.2. Establishing Membership and Conducting Comprehensive Evaluation. Although we can get definite comments on each criterion, the "boundary" is relatively ambiguous. Therefore,

Table 3: The pairwise comparison matrix of all experts.

	u_1	u_2	u_3	$\cdots$	u_m	sum
u_1		$\sum_{j=1}^{t} x_{12j}$	$\sum_{j=1}^{t} x_{13j}$		$\sum_{j=1}^{t} x_{1mj}$	$\sum_{k=1}^{m}\sum_{j=1}^{t} x_{1kj}$
u_2	$\sum_{j=1}^{t} x_{21j}$		$\sum_{j=1}^{t} x_{23j}$		$\sum_{j=1}^{t} x_{2mj}$	$\sum_{k=1}^{m}\sum_{j=1}^{t} x_{2kj}$
$\cdots$						
u_m	$\sum_{j=1}^{t} x_{m1j}$	$\sum_{j=1}^{t} x_{m2j}$	$\sum_{j=1}^{t} x_{m3j}$			$\sum_{k=1}^{m}\sum_{j=1}^{t} x_{mkj}$

the membership degree of each criterion to the evaluation set is calculated. In doing so, we need to grade each criterion based on specialist consultancy. We can get the membership vector R_j of criterion u_i to evaluation set V. $R_j = (r_{j1}, r_{j2}, r_{j3}, r_{j4})$, $j = 1, 2, \ldots, m \times n$, r_{jn} $(n = 1, 2, 3, 4)$ is the evaluation value of u_i. And we have $r_{ji} = v_{ji} / \sum v_{jn}$. $\sum v_{jn} = v_{j1} + v_{j2} + v_{j3} + v_{j4}$. We can get the evaluation membership matrix of the criteria of modular supplier selection.

Suppose $A = (a_1, a_2, \ldots, a_m)$, where a_i is the weight of u_i. Then we can calculate the comprehensive evaluation vector $P = A \times R = u_{A \bullet R} = \sum_{i=1}^{m} u_{A(u)} u_{R(u)}$.

3.3. Calculating the Dispersion Degree. According to the above method, we can get the comprehensive evaluation of a supplier. But if there are two suppliers and their comprehensive evaluation are similar. That is, more than 50% evaluation is general and good. But for one supplier, the evaluations of all the criteria are above general while for another supplier some criteria evaluations are good. The evaluations of some other criteria are below fairly weak. So we can easily find the first supplier is better than the second one because the second one does not develop evenly and therefore its risk is bigger than the first one.

Considering such circumstance, we introduce a dispersion degree to measure it. Based on probability theory, referring to the definition of variance in statistics, we use $L_j = \sum_{i=1}^{m} a_i (r_{ij} - b_j)^2$ to reflect the dispersion degree of criterion u_j, where $b_j = \sum_{i=1}^{m} a_i r_{ij}$. If L_j is big, then the comprehensive evaluation should move down. We construct $S_j = b_j - ZL_j$, where Z denotes the parameter which decision-maker can control. It is designed to reflect the adjustment that the dispersion causes to the evaluation judgment.

We suppose if the accumulative evaluation of level N is bigger than 0.5, then the comprehensive evaluation of the supplier is in N level. And it should satisfy $\sum_{j=1}^{N-1} p_j \le 0.5 \le \sum_{j=1}^{N} p_j$. Based on $S_j = b_j - ZL_j$, we can modify the judgment criterion as follows:

$$\sum_{j=1}^{N-1} S_j \le 0.5 - Z(N-1)\overline{L} \quad (2)$$

$$\sum_{j=1}^{N} S_j \ge 0.5 - ZN\overline{L}, \quad (3)$$

where $\overline{L} = (1/n)\sum_{j=1}^{n} L_j$. By the modification, the comprehensive evaluation of a supplier has both considered the membership matrix and the dispersion degree. It is more objective and comprehensive.

3.4. Stability Analysis. Experts' erroneous judgment may occur in adjacent levels or across levels. In this paper, to initiate the discussion on these situations and to simplify the problem, we mainly focus on the former circumstance. So we suppose the erroneous judgment of one criterion occurs in adjacent evaluation levels of the criterion. That is, suppose the positive error Δr occurs in r_{hk} and the negative error $-\Delta r$ occurs in $r_{hk'}$. Correspondingly, there are the following circumstances:

(1) Both positive and negative errors have impact on formula (2) and formula (3). Namely, $k \le N-1$, $k' \le N-1$.

(2) The positive error has impact on formula (2); both positive and negative errors have impact on formula (3). Namely, $k \le N-1$, $k' = N$.

(3) The negative error has impact on formula (2); both positive and negative error have impact on formula (3). Namely, $k = N$, $k' \le N-1$.

(4) Both positive and negative errors do not have impact on formula (2); the negative error has impact on formula (3). Namely, $k > N$, $k' = N$.

(5) Both positive and negative errors do not have impact on formula (2); the positive error has impact on formula (3). Namely, $k = N$, $k' > N$.

(6) Both positive and negative errors do not have impact on the two formulas. Namely, $k > N$, $k' > N$.

In this paper, L denotes the dispersion degree; b denotes the membership; r denotes the initial judgment matrix; a denotes the weight of a criterion; k denotes the evaluation level that the accumulative evaluation of a criterion is bigger than 0.5; k' denotes a level lower than k.

Then we make

$$\begin{aligned} A_h &= (1-a_h)\,a_h \\ B_{hk} &= 1 - 2Z(r_{hk} - b_k) \\ C_{hkk'} &= (r_{hk} - b_k) - (r_{hk'} - b_{k'}) \\ D_{N-1} &= 0.5 - (N-1)Z\overline{L} - \sum_{j=1}^{N-1} S_j \ge 0 \\ E_{hkk'(N-1)} &= \left[B_{hk} - B_{hk'} + \frac{2(N-1)ZC_{hkk'}}{n}\right] \\ F_{hkk'(N-1)} &= B_{hk} + \frac{2(N-1)ZC_{hkk'}}{n} \\ G_{hkk'} &= B_{hk'} - \frac{2(N-1)ZC_{hkk'}}{n} \\ H_N &= \sum_{j=1}^{N} S_j - 0.5 + NZ\overline{L} \ge 0. \end{aligned} \tag{4}$$

Then we conduct stability analysis as follows.

(1) Both positive and negative errors have impact on formula (2) and formula (3). Namely, $k \le N-1$, $k' \le N-1$.

Because $\sum_{j=1}^{N-1} S'_j \le 0.5 - Z(N-1)\overline{L'}$, by rearranging the formula we can get

$$\begin{aligned} &\frac{2(n-N+1)Z}{n} A_h \Delta r^2 \\ &\quad - \left[B_{hk} - B_{hk'} + \frac{2(N-1)ZC_{hkk'}}{n}\right] a_h \Delta r + D_{N-1} \\ &\ge 0 \end{aligned} \tag{5}$$

We make $E_{hkk'(N-1)} = [B_{hk} - B_{hk'} + 2(N-1)ZC_{hkk'}/n]$.

Then we can get the following.

If $(E_{hkk'(N-1)}a_h)^2 - 4(2(n-N+1)Z/n)A_hD_{N-1} < 0$, then the above inequality always holds.

If $(E_{hkk'(N-1)}a_h)^2 - 4(2(n-N+1)Z/n)A_hD_{N-1} \ge 0$,

$$\begin{aligned} 0 \le \Delta r &\le \frac{E_{hkk'(N-1)}a_h}{2(2Z(n-N+1)/n)A_h} \\ &\quad - \frac{\sqrt{(E_{hkk'(N-1)}a_h)^2 - 4(2Z(n-N+1)/n)A_hD_{N-1}}}{(2Z(n-N+1)/n)A_h}. \end{aligned} \tag{6}$$

Because $\sum_{j=1}^{N} S'_j \le 0.5 - ZN\overline{L'}$, by rearranging the formula, we can get $(2(n-N)Z/n)A_h\Delta r^2$:

$$-\left[B_{hk} - B_{hk'} + \frac{2NZC_{hkk'}}{n}\right] a_h \Delta r - H_N \le 0. \tag{7}$$

Therefore, if

$$\begin{aligned} &(E_{hkk'}a_h)^2 - 4\frac{2Z(n-N+1)}{n} A_hD_{N-1} < 0, \\ &0 \le \Delta r \\ &\quad \le \frac{E_{hkk'N}a_h}{2(2Z(n-N)/n)A_h} \\ &\qquad + \frac{\sqrt{(E_{hkk'N}a_h)^2 + 4(2Z(n-N)/n)A_hH_N}}{2(2Z(n-N)/n)A_h}. \end{aligned} \tag{8}$$

If $(E_{hkk'}a_h)^2 - 4(2Z(n-N+1)/n)A_hD_{N-1} \ge 0$,

$$\begin{aligned} 0 \le \Delta r \le \min\Bigg(&\frac{E_{hkk'N}a_h}{2(2Z(n-N)/n)A_h} \\ &+ \frac{\sqrt{(E_{hkk'N}a_h)^2 + 4(2Z(n-N)/n)A_hH_N}}{2(2Z(n-N)/n)A_h}, \\ &\frac{E_{hkk'(N-1)}a_h}{2(2Z(n-N+1)/n)A_h} \\ &- \frac{\sqrt{(E_{hkk'(N-1)}a_h)^2 - 4(2Z(n-N+1)/n)A_hD_{N-1}}}{2(2Z(n-N+1)/n)A_h}\Bigg) \end{aligned} \tag{9}$$

(2) The positive error has impact on formula (2); both positive and negative errors have impact on formula (3). Namely, $k \leq N-1$, $k' = N$.

Because $\sum_{j=1}^{N-1} S'_j \leq 0.5 - Z(N-1)\overline{L'}$, by rearranging the formula, we can get

$$\frac{n-2(N-1)Z}{n} A_h \Delta r^2 - \left[B_{hk} + \frac{2(N-1)ZC_{hkk'}}{n} \right] a_h \Delta r + D_{N-1} \geq 0. \tag{10}$$

We make $F_{hkk'(N-1)} = [B_{hk} + 2(N-1)ZC_{hkk'}/n]$.

Then we can get the following:

If $n - 2(N-1) \geq 0$,

$$\left(F_{hkk'(N-1)} a_h\right)^2 - 4\frac{n-2(N-1)Z}{n} A_h D_{N-1} < 0, \tag{11}$$

then the above inequality always holds.

If $n - 2(N-1) \geq 0$,

$$\left(F_{hkk'(N-1)} a_h\right)^2 - 4\frac{n-2(N-1)Z}{n} A_h D_{N-1} \geq 0,$$

$$0 \leq \Delta r \leq \frac{F_{hkk'(N-1)} a_h}{2((n-2(N-1))/n) ZA_h} - \frac{\sqrt{\left(F_{hkk'(N-1)} a_h\right)^2 - 4((n-2(N-1))/n) ZA_h D_{N-1}}}{2((n-2(N-1))/n) ZA_h}. \tag{12}$$

If $2(N-1) - n \geq 0$,

$$\frac{2(N-1)-n}{n} ZA_h \Delta r^2 + F_{hkk'(N-1)} a_h \Delta r - D_{N-1} \leq 0,$$

$$0 \leq \Delta r \leq \frac{-F_{hkk'(N-1)} a_h}{2((2(N-1)-n)/n) ZA_h} + \frac{\sqrt{\left(F_{hkk'(N-1)} a_h\right)^2 + 4((2(N-1)-n)/n) ZA_h D_{N-1}}}{2((2(N-1)-n)/n) ZA_h}. \tag{13}$$

Because both positive and negative errors have impact on formula (3), and according to the deduction of circumstance (1), to satisfy formula (3), it should have

$$0 \leq \Delta r \leq \frac{E_{hkk'N} a_h + \sqrt{\left(E_{hkk'N} a_h\right)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}. \tag{14}$$

Therefore, if $n - 2(N-1) \geq 0$,

$$0 \leq \Delta r \leq \frac{E_{hkk'N} a_h + \sqrt{\left(E_{hkk'N} a_h\right)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}. \tag{15}$$

If $n - 2(N-1) \geq 0$,

$$0 \leq \Delta r \leq \min\left(\frac{E_{hkk'N} a_h}{2(2Z(n-N)/n) A_h} + \frac{\sqrt{\left(E_{hkk'N} a_h\right)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}, \frac{a_h F_{hkk'(N-1)}}{2((n-2(N-1))/n) ZA_h} - \frac{\sqrt{a^2{}_h F^2{}_{hkk'(N-1)} - 4((n-2(N-1))/n) ZA_h D_{N-1}}}{2((n-2(N-1))/n) ZA_h} \right). \tag{16}$$

If $2(N-1) - n \geq 0$,

$$0 \leq \Delta r \leq \min\left(\frac{E_{hkk'N} a_h}{2(2Z(n-N)/n) A_h} + \frac{\sqrt{\left(E_{hkk'N} a_h\right)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}, \frac{-a_h F_{hkk'(N-1)}}{2((2(N-1)-n)/n) ZA_h} + \frac{\sqrt{a^2{}_h F^2{}_{hkk'(N-1)} + 4((2(N-1)-n)/n) ZA_h D_{N-1}}}{2((2(N-1)-n)/n) ZA_h} \right). \tag{17}$$

(3) The negative error has impact on formula (2); both positive and negative error have impact on formula (3). Namely, $k = N$, $k' \leq N-1$.

Because $\sum_{j=1}^{N-1} S'_j \leq 0.5 - Z(N-1)\overline{L'}$, by rearranging the formula, we can get

$$\frac{n-2(N-1)Z}{n} A_h \Delta r^2 + \left[B_{hk'} - \frac{2(N-1)ZC_{hkk'}}{n} \right] a_h \Delta r + D_{N-1} \geq 0. \tag{18}$$

We make $G_{hkk'} = [B_{hk'} - 2(N-1)ZC_{hkk'}/n]$.

Then we can get the following: if $n - 2(N-1) \geq 0$,

$$\left(G_{hkk'} a_h\right)^2 - 4\frac{n-2(N-1)Z}{n} A_h D_{N-1} < 0, \tag{19}$$

then the above inequality always holds.

If $n - 2(N-1) \geq 0$,

$$0 \leq \Delta r \leq \frac{-G_{hkk'} a_h - \sqrt{\left(G_{hkk'} a_h\right)^2 - 4((n-2(N-1))/n) ZA_h D_{N-1}}}{2((n-2(N-1))/n) ZA_h}. \tag{20}$$

If $2(N-1) - n \geq 0$,

$$0 \leq \Delta r \leq \frac{G_{hkk'} a_h + \sqrt{\left(G_{hkk'} a_h\right)^2 + 4((2(N-1)-n)/n) ZA_h D_{N-1}}}{2((2(N-1)-n)/n) ZA_h}. \tag{21}$$

Because both positive and negative errors have impact on formula (3), and according to the deduction of circumstance (1), to satisfy formula (3), it should have

$$0 \le \Delta r \le \frac{E_{hkk'N}a_h + \sqrt{\left(E_{hkk'N}a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right)A_hH_N}}{2\left(2Z\left(n-N\right)/n\right)A_h}. \tag{22}$$

Therefore, if $n - 2(N-1) \ge 0$,

$$0 \le \Delta r \le \frac{\left(E_{hkk'N}a_h + \sqrt{\left(E_{hkk'N}a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right)A_hH_N}\right)}{2\left(2Z\left(n-N\right)/n\right)A_h}. \tag{23}$$

If $n - 2(N-1) \ge 0$,

$$0 \le \Delta r \le \min\left(\frac{E_{hkk'N}a_h}{2\left(2Z\left(n-N\right)/n\right)A_h} + \frac{\sqrt{\left(E_{hkk'N}a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right)A_hH_N}}{2\left(2Z\left(n-N\right)/n\right)A_h}, \frac{-a_hG_{hkk'}}{2\left(\left(n-2\left(N-1\right)\right)/n\right)ZA_h} - \frac{\sqrt{a_h^2G_{hkk'}^2 - 4\left(\left(n-2\left(N-1\right)\right)/n\right)ZA_hD_{N-1}}}{2\left(\left(n-2\left(N-1\right)\right)/n\right)ZA_h}\right). \tag{24}$$

If $2(N-1) - n \ge 0$,

$$0 \le \Delta r \le \min\left(\frac{E_{hkk'N}a_h}{2\left(2Z\left(n-N\right)/n\right)A_h} + \frac{\sqrt{\left(E_{hkk'N}a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right)A_hH_N}}{2\left(2Z\left(n-N\right)/n\right)A_h}, \frac{a_hG_{hkk'}}{2\left(\left(2\left(N-1\right)-n\right)/n\right)ZA_h} + \frac{\sqrt{a_h^2G_{hkk'}^2 + 4\left(\left(2\left(N-1\right)-n\right)/n\right)ZA_hD_{N-1}}}{2\left(\left(2\left(N-1\right)-n\right)/n\right)ZA_h}\right). \tag{25}$$

(4) Both positive and negative errors do not have impact on formula (2); the negative error has impact on formula (3). Namely, $k > N$, $k' = N$.

Because $\sum_{j=1}^{N} S'_j \ge 0.5 - ZN\overline{L'}$, by rearranging the formula, we can get

$$\frac{n-2N}{n}ZA_h\Delta r^2 - \left[B_{hk'} - \frac{2NZC_{hkk'}}{n}\right]a_h\Delta r + H_N \ge 0. \tag{26}$$

Then we can get the following: if $n - 2N \ge 0$,

$$\left(G_{hkk'N}a_h\right)^2 - 4\frac{n-2N}{n}ZA_hD_{N-1} < 0, \tag{27}$$

then the above inequality always holds.

If $n - 2N \ge 0$,

$$0 \le \Delta r \le \frac{G_{hkk'N}a_h - \sqrt{\left(G_{hkk'N}a_h\right)^2 - 4\left(\left(n-2N\right)/n\right)ZA_hH_N}}{2\left(\left(n-2N\right)/n\right)ZA_h}. \tag{28}$$

If $2N - n \ge 0$,

$$0 \le \Delta r \le \frac{-G_{hkk'N}a_h + \sqrt{\left(G_{hkk'N}a_h\right)^2 + 4\left(2N-n/n\right)ZA_hH_N}}{2\left(2N-n/n\right)ZA_h}. \tag{29}$$

For formula (2), by rearranging the formula, we can get

$$\frac{2\left(N-1\right)Z}{n}A_h\Delta r^2 + \frac{2a_h\left(N-1\right)ZC_{hkk'}}{n}\Delta r - D_{N-1} \le 0.$$

$$0 \le \Delta r \le \frac{-2a_h\left(N-1\right)ZC_{hkk'}/n}{2\left(2\left(N-1\right)/n\right)ZA_h} + \frac{\sqrt{\left(2a_h\left(N-1\right)ZC_{hkk'}/n\right)^2 + 4\left(2\left(N-1\right)/n\right)ZA_hD_{N-1}}}{2\left(2\left(N-1\right)/n\right)ZA_h}. \tag{30}$$

Therefore, if $n - 2N \ge 0$,

$$0 \le \Delta r \le \frac{-2a_h\left(N-1\right)ZC_{hkk'}/n}{2\left(2\left(N-1\right)/n\right)ZA_h} + \frac{\sqrt{\left(2a_h\left(N-1\right)ZC_{hkk'}/n\right)^2 + 4\left(2\left(N-1\right)ZA_hD_{N-1}/n\right)}}{2\left(2\left(N-1\right)/n\right)ZA_h}. \tag{31}$$

If $n - 2N \ge 0$,

$$0 \le \Delta r \le \min\left(\frac{-2a_h\left(N-1\right)ZC_{hkk'}/n}{2\left(2\left(N-1\right)/n\right)ZA_h} + \frac{\sqrt{\left(2a_h\left(N-1\right)ZC_{hkk'}/n\right)^2 + 4\left(2\left(N-1\right)ZA_hD_{N-1}/n\right)}}{2\left(2\left(N-1\right)/n\right)ZA_h}, \frac{a_hG_{hkk'N} - \sqrt{a_h^2G_{hkk'N}^2 - 4\left(\left(n-2N\right)/n\right)ZA_hH_N}}{2\left(\left(n-2N\right)/n\right)ZA_h}\right) \tag{32}$$

If $2N - n \ge 0$,

$$0 \le \Delta r \le \min\left(\frac{-2a_h\left(N-1\right)ZC_{hkk'}/n}{2\left(2\left(N-1\right)/n\right)ZA_h} + \frac{\sqrt{\left(2a_h\left(N-1\right)ZC_{hkk'}/n\right)^2 + 4\left(2\left(N-1\right)ZA_hD_{N-1}/n\right)}}{2\left(2\left(N-1\right)/n\right)ZA_h}, \frac{-a_hG_{hkk'N} + \sqrt{a_h^2G_{hkk'N}^2 + 4\left(\left(2N-n\right)/n\right)ZA_hH_N}}{2\left(\left(2N-n\right)/n\right)ZA_h}\right) \tag{33}$$

(5) Both positive and negative errors do not have impact on formula (2); the positive error has impact on formula (3). Namely, $k = N, k' > N$.

Because $\sum_{j=1}^{N} S'_j \geq 0.5 - ZN\overline{L'}$, by rearranging the formula, we can get

$$\frac{n-2N}{n} ZA_h \Delta r^2 + \left[B_{hk} + \frac{2NZC_{hkk'}}{n} \right] a_h \Delta r + H_N \geq 0. \tag{34}$$

Then we can get the following: if $n - 2N \geq 0$,

$$\left(F_{hkk'N} a_h\right)^2 - 4\frac{n-2N}{n} ZA_h H_N < 0, \tag{35}$$

then the above inequality always holds.

If $n - 2N \geq 0$,

$$0 \leq \Delta r \leq \frac{-F_{hkk'N} a_h + \sqrt{\left(F_{hkk'N} a_h\right)^2 - 4\left((n-2N)/n\right) ZA_h H_N}}{2\left((n-2N)/n\right) ZA_h} \tag{36}$$

If $2N - n \geq 0$,

$$0 \leq \Delta r \leq \frac{F_{hkk'N} a_h + \sqrt{\left(F_{hkk'N} a_h\right)^2 + 4\left((2N-n)/n\right) ZA_h H_N}}{2\left((2N-n)/n\right) ZA_h} \tag{37}$$

For formula (2), by rearranging the formula, we can get

$$\frac{2(N-1)Z}{n} A_h \Delta r^2 + \frac{2a_h (N-1) ZC_{hkk'}}{n} \Delta r - D_{N-1} \leq 0.$$

$$0 \leq \Delta r \leq \frac{-2a_h (N-1) ZC_{hkk'}/n}{2\left(2(N-1)/n\right) ZA_h} + \frac{\sqrt{\left(2a_h (N-1) ZC_{hkk'}/n\right)^2 + 4\left(2(N-1) ZA_h D_{N-1}/n\right)}}{2\left(2(N-1)/n\right) ZA_h}. \tag{38}$$

Therefore, if $n - 2N \geq 0$,

$$0 \leq \Delta r \leq \frac{-2a_h (N-1) ZC_{hkk'}/n}{2\left(2(N-1)/n\right) ZA_h} + \frac{\sqrt{\left(2a_h (N-1) ZC_{hkk'}/n\right)^2 + 4\left(2(N-1) ZA_h D_{N-1}/n\right)}}{2\left(2(N-1)/n\right) ZA_h}. \tag{39}$$

If $n - 2N \geq 0$,

$$0 \leq \Delta r \leq \min\left(\frac{-2a_h (N-1) ZC_{hkk'}/n}{2\left(2(N-1)/n\right) ZA_h} + \frac{\sqrt{\left(2a_h (N-1) ZC_{hkk'}/n\right)^2 + 4\left(2(N-1) ZA_h D_{N-1}/n\right)}}{2\left(2(N-1)/n\right) ZA_h}, \frac{-a_h F_{hkk'N} + \sqrt{a_h^2 F_{hkk'N}^2 - 4\left((n-2N)/n\right) ZA_h D_{N-1}}}{2\left((n-2N)/n\right) ZA_h} \right) \tag{40}$$

If $2N - n \geq 0$,

$$0 \leq \Delta r \leq \min\left(\frac{-2a_h (N-1) ZC_{hkk'}/n}{2\left(2(N-1)/n\right) ZA_h} + \frac{\sqrt{\left(2a_h (N-1) ZC_{hkk'}/n\right)^2 + 4\left(2(N-1) ZA_h D_{N-1}/n\right)}}{2\left(2(N-1)/n\right) ZA_h}, \frac{a_h F_{hkk'N} + \sqrt{a_h^2 F_{hkk'N}^2 + 4\left((2N-n)/n\right) ZA_h H_N}}{2\left((2N-n)/n\right) ZA_h} \right) \tag{41}$$

(6) Both positive and negative errors do not have impact on the two formulas. Namely, $k > N, k' > N$.

For formula (2), by rearranging the formula, we can get

$$\frac{2(N-1)Z}{n} A_h \Delta r^2 + \frac{2a_h (N-1) ZC_{hkk'}}{n} \Delta r - D_{N-1} \leq 0.$$

$$0 \leq \Delta r \leq \frac{-2a_h (N-1) ZC_{hkk'}/n}{2\left(2(N-1)/n\right) ZA_h} + \frac{\sqrt{\left(2a_h (N-1) ZC_{hkk'}/n\right)^2 + 4\left(2(N-1)/n\right) ZA_h D_{N-1}}}{2\left(2(N-1)/n\right) ZA_h}. \tag{42}$$

For formula (3), by rearranging the formula, we can get

$$\frac{2NZ}{n} A_h \Delta r^2 + \frac{2a_h NZC_{hkk'}}{n} \Delta r + H_N \geq 0. \tag{43}$$

If $(2a_h NZC_{hkk'}/n)^2 - 4(2NZ/n)A_h H_N < 0$, then the above inequality always holds.

If $(2a_h NZC_{hkk'}/n)^2 - 4(2NZ/n)A_h H_N \geq 0$,

$$0 \leq \Delta r \leq \frac{-2a_h NZC_{hkk'}/n}{2\left(2N/n\right) ZA_h} - \frac{\sqrt{\left(2a_h NZC_{hkk'}/n\right)^2 - 4\left(2NZA_h H_N/n\right)}}{2\left(2N/n\right) ZA_h}. \tag{44}$$

Therefore, if $(2a_h NZC_{hkk'}/n)^2 - 4(2NZA_h H_N/n) < 0$,

$$0 \leq \Delta r \leq \frac{-2a_h (N-1) ZC_{hkk'}/n}{2\left(2(N-1)/n\right) ZA_h} + \frac{\sqrt{\left(2a_h (N-1) ZC_{hkk'}/n\right)^2 + 4\left(2(N-1) ZA_h D_{N-1}/n\right)}}{2\left(2(N-1)/n\right) ZA_h}. \tag{45}$$

If $(2a_h NZC_{hkk'}/n)^2 - 4(2NZA_h H_N/n) \geq 0$,

$$0 \leq \Delta r \leq \min\left(\frac{-2a_h (N-1) ZC_{hkk'}/n}{2\left(2(N-1)/n\right) ZA_h} + \frac{\sqrt{\left(2a_h (N-1) ZC_{hkk'}/n\right)^2 + 4\left(2(N-1) ZA_h D_{N-1}/n\right)}}{2\left(2(N-1)/n\right) ZA_h}, \frac{-2a_h NZC_{hkk'}/n + \sqrt{\left(2a_h NZC_{hkk'}/n\right)^2 - 4\left(2NZA_h H_N/n\right)}}{2\left(2NZA_h/n\right)} \right) \tag{46}$$

4. Empirical Study on Modular Supplier Selection Criteria

In this section, we adopt a factor analysis method to build the index system of modular supplier selection.

4.1. Research Method. In this section, a factor analysis method is used to construct the evaluation index system. From literature review, we find there are a number of criteria which are used to select modular suppliers. However, whether all these criteria are important or significantly influence the selection of modular suppliers is questionable. Besides, the discussions on the influencing factors of modular supplier selection are mainly qualitative analysis and there lacks quantitative support. Factor analysis is a statistical method which uses empirical data to make quantitative analysis. And one advantage of factor analysis is that it can analyze the interdependence of observed variables and can be used to reduce the set of variables in a dataset. Considering this, this paper adopts the factor analysis method to build the index system. By using the factor analysis, it can quantitatively test the significance of current criteria and help to cut down the superfluous and insignificant criteria. In doing so, the index system is more accurate to reflect the features of modular suppliers and provides reliable index for the next step evaluation.

Next we follow the procedure of index primary selection, index optimization, and index evaluation to conduct the factor analysis.

4.2. Index Primary Selection. Extensive literature review was conducted to conceptualize and identify the determinants of modular supplier selection. Based on the representative research of suppliers, modular suppliers, and strategic suppliers, the index of modular supplier selection and items of the questionnaire were identified (see Table 4).

The university the author affiliates has good alumni resources. So we take full advantage of these resources. Helped by the alumni associations in Shenzhen, Guangdong province, and Jiangsu province, we are able to contact related enterprises and conduct in-depth investigation of these enterprises to determine the primary set of the index. We selected 9 enterprises in Shenzhen which make modular production to conduct field interviews, telephone, or online interviews. For the basic information of these enterprises please see Table 5.

Before the formal interview, we confirm the specific interview schedule with the top management, vice president of procurement, and purchasing supervisors. Then we carried out the semistructured interviews and focus group discussions. All interviews were conducted between 2016.8 and 2016.11. To avoid the fatigue of interviewees, we controlled the semistructured interviews within 45-60 minutes and focus group interviews for no more than 90 minutes. With the consent of the interviewees, we recorded the interviews and sorted out the records after the interviews. Around the modular supplier selection criteria and index, we designed two types of questions: (1) the direct questions were such as "what are the requirements for modular supplier selection?" and "what features do you think a modular vendor should have?"; (2) the indirect questions were such as "please list the main activities a qualified modular suppliers may take" and "what events do you think represent the modular supplier can be trusted and therefore chosen?"

Finally we invited three professors of school of business administration of Jiangxi University of Finance and Economics and two Ph.D. students major in logistics and supply chain management to discuss the clarity and effectiveness of the evaluation criteria. Taking account of their suggestions, the indexes obtained through documentation and interviews were further condensed and were eventually modified from 30 to 27.

4.3. Index Optimization. First of all, we conduct exploratory factor analysis based on the survey of 27 items identified by the initial questionnaire. The subjects of the survey are 23 enterprises involved in the modular production of electronic manufacturing, computer manufacturing, and automotive manufacturing in Shenzhen and Guangzhou. A total of 223 questionnaires were sent and 182 valid questionnaires were collected with an effective rate of 81.6%.

Before factor analysis, the factor analysis fitness test was performed. Two judgment indexes, namely, the KMO value and Bartlett's test, were mainly taken into account [55]. If KMO < 0.5, we should not carry out the factor analysis. The data analysis results show that the KMO value was 0.908. The statistical significance of Bartlett's test is 0.000, which is smaller than 0.01 and reach the very significant level. All these show that it is suitable for conducting a factor analysis. In the exploratory analysis, the principal component analysis (PCA) was used with varimax rotation to arrive at the most interpretable and significant factor solution.

Secondly, the item-total correlation is calculated to obtain the internal consistency coefficient and to determine the quality of each item. Combining factor analysis and item analysis, we find that the initial questionnaire structure is not clear. The initial questionnaire is yet not an effective questionnaire and needs to be revised further.

The principles for questionnaire revision are as follows [56].

Firstly, referring to the results of factor analysis, we choose the items with high communality and high factor loading and delete the items with low communality and low factor loading. Secondly, also referring to the results of factor analysis, we delete items with significant double loadings (the difference between the two biggest values of the factor loading is less than 0.2) and items whose maximum value of the factor loading is less than 0.4. Then we adjust and delete the items with ambiguous meanings. Thirdly based on the scores of items we remove the items with low internal consistency reliability.

After the above modification, we identified 25 items from the initial questionnaire to form the formal questionnaire. Then we conduct a survey by using the formal questionnaire. We sent 472 questionnaires to 45 enterprises in Guangzhou, Shenzhen, Nanchang, Shanghai, Hangzhou, and Suzhou and collected 230 questionnaires with effective rate of 48.73%.

We conduct an exploratory factor analysis on the 230 questionnaires, using principal component analysis method

Table 4: Primary indexes of modular supplier selection.

No.	Criteria	References	No.	Criteria	References
1	Quality control	[14, 16, 18, 22, 23]	16	Support in modularization activity	[30]
2	Cost control	[19–21, 25, 26]	17	Integration capability	[36]
3	On time delivery	[16–20]	18	Process management	[21]
4	Service	[21, 24, 26, 27, 36]	19	Communication	[11, 19, 20, 24]
5	Financial situation	[11, 20, 30, 32, 35]	20	Responsiveness	[21, 37]
6	Reputation	[11, 29–32]	21	Customer satisfaction	[34]
7	Technical capability	[11, 32, 34, 35]	22	Loyalty	[40]
8	Innovation	[26, 39]	23	Follow up	[28]
9	ISO certification	[20]	24	Customer relationship	[28]
10	Product configuration	[14]	25	Trust	[21]
11	New technological identification	[34]	26	Customer support	[53]
12	Industry knowledge	[32]	27	Managerial capability	[26]
13	Commitment to continuous improvement	[40]	28	Compatibility across levels and functions	[34]
14	Support in product development	[20]	29	Desire of business	[54]
15	Support in value analysis	[30]	30	Reliability	[20, 21, 28, 36]

Table 5: Basic information of enterprises interviewed.

No.	Firm name	Industry	Interviewees
1	Epson engineering (Shenzhen) Ltd.	Printer, image projector, and liquid crystal display	Purchasing managers, business managers
2	BYD Company Limited	Automobile, new energy and rail transit	Executive director, deputy purchasing director, production director
3	Shenzhen Dazhong Science & Technology Co., Ltd.	Integrated circuit	Purchasing Managers, Quality Directors
4	Shenzhen Huaxun ark Science & Technology Co., Ltd.	Semiconductor devices, microwave systems, millimeter wave systems, and terahertz micro electronics systems	General manager, purchasing directors
5	Hasee Computer Co., Ltd	Laptops, desktops, LCD computers, LCD LCDs, and smart TVs	Chairman of the board, head of purchasing department, head of production department
6	Johnson Electric International Limited	Micro motor and parts, motor manufacturing machine	General manager, purchasing managers, Division Managers
7	Sunwoda Electronic Co., Ltd.	Lithium ion battery module	General manager, head of purchasing department, head of quality management department
8	Changan PSA Automobiles Co. Ltd.	Automobile	General manager, purchasing deputy directors, supply section chief
9	Super photoelectric (Shenzhen) Co. Ltd.	A-Silicon, /Poly-Silicon, TFT-LCD display panels for laptops, PC monitors and LCD TVs	Deputy general manager, QS Engineers

to extract factors and varimax method to rotate. Combining the use of the scree plot, we choose the factors whose eigenvalues are bigger than 1. Besides, we discuss the interpretability and meaningfulness of factors within the theoretical framework and finally deleted 4 items and left 21 items. Then the factors were extracted by principal component analysis and rotated by varimax. The result shows that the index system of modular supplier selection has a clear structure of four factors, whose cumulative contribution of variance accounted to 73.503%. For the loadings of items please see Table 6.

According to the survey results, we can find that the indexes of modular supplier selection include 4 main factors and the cumulative contribution of variance accounts to 73.503%. The four main factors are shown as follows.

Factor 1 is basic capability of modular supplier: quality control, cost control, on time delivery, service, financial situation, and reputation.

Table 6: Loadings of items.

No.	Item	Factor			
		F1	F2	F3	F4
Q1	Quality control	.821			
Q2	Cost control	.806			
Q3	On time delivery	.753			
Q4	Service	.738			
Q5	Financial situation	.713			
Q6	Reputation	.709			
Q7	Technical capability		.843		
Q8	Innovation		.826		
Q10	New technological identification		.742		
Q9	ISO certification		.703		
Q11	Industry knowledge		.664		
Q12	Support in product development			.763	
Q15	Integration capability			.747	
Q14	Support in modularization activity			.741	
Q13	Support in value analysis			.738	
Q16	Communication				.762
Q18	Customer satisfaction				.757
Q20	Trust				.751
Q19	Loyalty				.748
Q17	Responsiveness				.733
Q21	Customer support				.707
	Eigenvalue	3.935	1.591	1.287	1.116
	Variance contribution rate (73.503%)	34.621	17.193	11.727	9.962

Factor 2 is technological capability of modular supplier: technical capability, innovation, new technological identification, ISO certification, and industry knowledge.

Factor 3 is modular capability of modular supplier: support in product development, support in value analysis, support in modularization activity, and integration capability.

Factor 4 is cooperation capability of modular supplier: communication, responsiveness, customer satisfaction, loyalty, trust, and customer support.

4.4. Index Evaluation

4.4.1. Conceptual Model. Based on literature review, interviews, and expert consultation, through item analysis and exploratory factor analysis, we can obtain a four-factor model for modular supplier selection. This four-factor model modifies the preliminary index list of modular supplier selection and uncovers the underlying structure of these indexes. Thus it constructs the conceptual model for the confirmatory factor analysis. Please see Figure 1. Next confirmatory factor analysis is conducted to test the four-factor model.

4.4.2. Confirmatory Factor Analysis. In the confirmatory factor analysis, we sent 500 questionnaires to 41 enterprises in Guangzhou, Foshan, Shenzhen, Suzhou, Wuxi, and Nanchang. We received 278 questionnaires back and the effective rate is 55.6%.

Our conceptual model is a four-factor model while its competitive model can be the single-factor model, two-factor model, and three-factor model. There are 21 items in the questionnaires. Therefore, there is only one possibility for the single-factor model; there are 210 possibilities for the two-factor model; there are 1330 possibilities for the three-factor model. It is not possible for us to compare all of them. So the strategy we take is to find out the most reasonable model for each factor model and compare them.

As for the two-factor model, based on the exploratory factor analysis, we adopt varimax orthogonal rotation method to extract 2 factors from 21 items with compulsion and discuss whether the two-factor model is better than the four-factor model. In the two-factor model, Q1, Q2, Q5, Q7, Q8, Q10, Q11, Q12, Q13, and Q21 form the first factor while Q3, Q4, Q6, Q9, Q14, Q15, Q16, Q17, Q18, Q19, and Q20 form the second factor. The variance contribution rates of the two factors are respectively 28.458% and 9.902%. And the variance cumulative contribution rate is 38.361%.

As for the three-factor model, because the technological capability and modular capability of modular supplier to

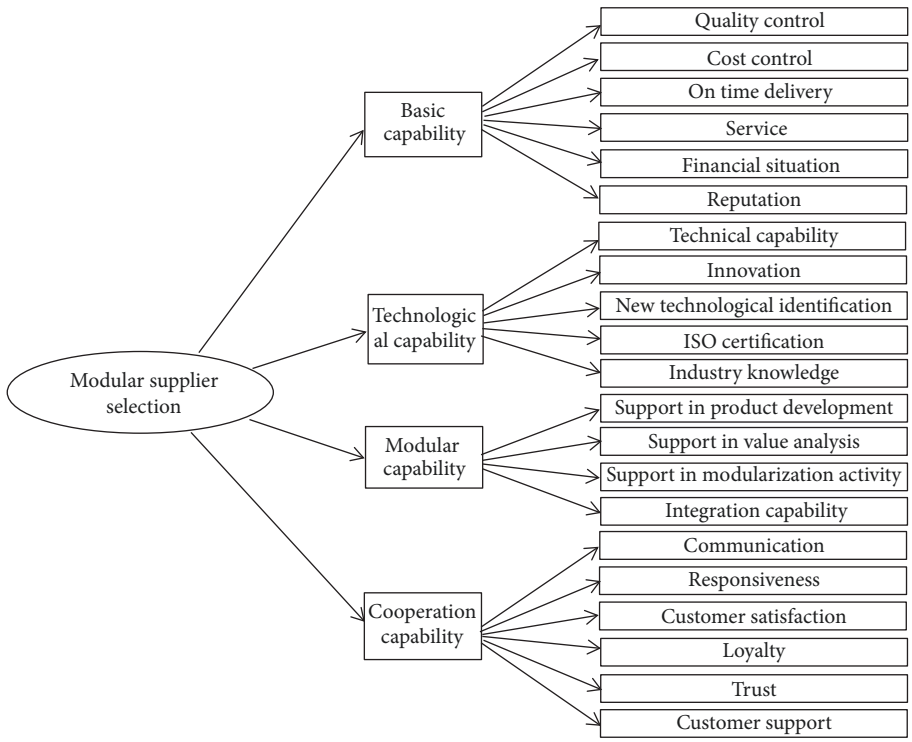

Figure 1: Conceptual model.

some extent incorporate the content of technology and innovation, the two concepts are relatively close to each other. In investigation, we also notice it. Therefore, in the three-factor model we suppose the technological capability and modular capability are in the same factor.

From Table 7 we can find the index such as RMSEA, GFI, CFI, NNFI, and PNFI of the single model, the two-factor model and the three-factor model have not reached an ideal level. Nevertheless, the indexes of the four-factor model all reach a relatively ideal level. Hence, the four-factor model is a better model for the index system of modular supplier selection.

4.4.3. Validity and Reliability Analysis. The reliability of the scale was checked by calculating the internal consistency coefficients (Cronbach Alpha Coefficients). From Table 8 we can see that apart from the fourth factor it is 0.693; the internal consistency coefficients of the other three factors are all above 0.700; and the total internal consistency coefficients are 0.833. Scholars posit that if the internal consistency coefficients are above 0.70, it shows the results are acceptable [57]. Therefore, the reliability of the questionnaire is acceptable and it indicates the results are reliable.

Validity refers to the effectiveness and correctness of questionnaires, that is, the degree of the questionnaires to measure what it wants to measure. It is an important criterion to evaluate the quality of the questionnaire. Generally it includes the content validity and construct validity. In the design of the questionnaire of modular supplier selection, we respectively ask the advices of the professors of business administration faculty and doctoral students in logistics and supply chain management and invite them to evaluate the questionnaire. At the same time, we choose the management of related enterprises to conduct a pretest. The data of the university circle and industry aids to improve the questionnaire. According to the results, we can see the questionnaire can basically reflect the content of modular supplier selection. Hence, the questionnaire has good content validity. As for the construct validity, firstly the results of both exploratory factor analysis and confirmatory factor analysis confirmed the validity of the structure of the questionnaire. The result shows that the factor structure is clear and each criterion matches the requirement of psychometrics. The results of confirmatory factor analysis are consistent with the theoretical model. Secondly, the item scores of each dimension are correlated with the total scores of the dimension. It also can verify the structure validity of the questionnaire. For the results please see Table 9. From the table we can see the correlation coefficients of each item and its dimension is between 0.669 and 0.766 and all reach the significant level. It indicates the items have good homogeneity, which from another perspective shows the questionnaire has good construct validity.

5. Case Analysis

In this section, we use the information of a modular supplier of Jiangling Motors Co., Ltd. (JMC), as an example to conduct a case analysis. By using fuzzy evaluation method and conducting the stability analysis, we discuss the evaluation of the supplier as well as the stability of the method.

Table 7: Comparison of fit indexes of models.

	χ^2/df	RMSEA	CFI	GFI	NNFI	PNFI
Null model	23.081					
Single model	4.877	0.103	0.717	0.852	0.673	0.579
Two factor model	4.131	0.093	0.753	0.873	0.712	0.602
Three factor model	3.879	0.089	0.807	0.881	0.771	0.633
Four factor model	2.281	0.059	0.901	0.929	0.881	0.685

Table 8: α coefficients of factors.

Factor	F1	F2	F3	F4	Total
α coefficient	0.757	0.716	0.702	0.693	0.833

Table 9: Correlations between criteria and factors.

Item	F1	F2	F3	F4
Q1	0.756^{**}			
Q2	0.741^{**}			
Q3	0.766^{**}			
Q4	0.712^{**}			
Q5	0.728^{**}			
Q6	0.734^{**}			
Q7		0.729^{**}		
Q8		0.712^{**}		
Q9		0.745^{**}		
Q10		0.708^{**}		
Q11		0.736^{**}		
Q12			0.762^{**}	
Q13			0.739^{**}	
Q14			0.757^{**}	
Q15			0.730^{**}	
Q16				0.739^{**}
Q17				0.683^{**}
Q18				0.669^{**}
Q19				0.724^{**}
Q20				0.691^{**}
Q21				0.716^{**}

5.1. Case Description. Jiangling Motors Co., Ltd. (JMC in abbreviation hereinafter), is a key player in China automotive industry with commercial vehicle as its core competitiveness. It was established in 1968 and went public in 1993. It has been ranked as one of China Top 100 Listed Companies for consecutive years. Currently there are 14036 people in the company. In the year 2014, JMC hit a high record in its business indexes with sales revenue reaching 25.5 billion RMB and volume over 276,000 units.

As we know, automobile is a typical modular product. Around the production of an automobile, an automobile manufacturer needs to build a modular production network and cooperate with various modular suppliers. In the modular production network, JMC company works as production integrator and it has built relationships with different modular suppliers. Each year it is a major task for the director of procurement department of JMC to select some of its modular suppliers. So we take JMC company as an example to discuss its selection of modular suppliers. In this company, we take pick-up truck as study object and discuss the evaluation of one of the suppliers.

5.2. Calculating the Weights. Based on the analysis of Section 3, the index system of modular supplier selection can be divided into 2 levels: the first level is the four factors of modular supplier selection and the second level is the items of each factor. For the index system please Table 10.

We employ pairwise comparison method to calculate the weights. 15 specialists are invited to make the pairwise comparison. Among them, 2 persons are professors, 4 persons are associate professors, and 9 persons are Ph.D. students. All of them are from the school of business administration of Jiangxi University of Finance and Economics.

For the pairwise comparison matrixes please see Tables 11–15.

5.3. Establishing Membership and Conducting Comprehensive Evaluation. Based on the above analysis, we select a group of 10 experts. They mainly come from two sources: 5 of them are managers of production and procurement departments of enterprises; 5 of them are college professors in logistics and supply chain management. The alternative answers include "good", "general", "fairly weak", and "weak" and we give each of them from 1 to 4 respectively. We send them the questionnaires and related information of the modular supplier by email and make sure they do not know each other's answer. Then we can get the fuzzy evaluation matrix of the modular supplier (see Table 16).

Then we can evaluate the supplier:

$$\begin{aligned} P_{B_1} &= A_{B_{11}-B_{16}} \times R_{B_{11}-B_{16}} \\ &= \begin{pmatrix} 0.178 & 0.178 & 0.193 & 0.129 & 0.162 & 0.16 \end{pmatrix} \\ &\quad \times \begin{bmatrix} 0.2 & 0.5 & 0.3 & 0 \\ 0.4 & 0.4 & 0.2 & 0 \\ 0.2 & 0.3 & 0.3 & 0.2 \\ 0.2 & 0.3 & 0.4 & 0.1 \\ 0.3 & 0.4 & 0.3 & 0 \\ 0.1 & 0.3 & 0.3 & 0.3 \end{bmatrix} \\ &= \begin{pmatrix} 0.2358 & 0.3696 & 0.2951 & 0.0995 \end{pmatrix} \end{aligned}$$

Table 10: Hierarchical structure of the index system of modular supplier selection.

The target layer	The first layer	The second layer
The index system of modular supplier selection A	Basic capability requirement for modular supplier B_1	Quality control B_{11}
		Cost control B_{12}
		On time delivery B_{13}
		Service B_{14}
		Financial situation B_{15}
		Reputation B_{16}
	Technological capability requirement for modular supplier B_2	Technical capability B_{21}
		Innovation B_{22}
		New technological identification B_{23}
		ISO certification B_{24}
		Industry knowledge B_{25}
	Modular capability requirement for modular supplier B_3	Support in product development B_{31}
		Integration capability B_{32}
		Support in modularization activity B_{33}
		Support in value analysis B_{34}
	Cooperation capability requirement for modular supplier B_4	Communication B_{41}
		Customer satisfaction B_{42}
		Trust B_{43}
		Loyalty B_{44}
		Responsiveness B_{45}
		Customer support B_{46}

Table 11: Judgment matrix of $B_1 - B_{1k}$.

B_1	B_{11}	B_{12}	B_{13}	B_{14}	B_{15}	B_{16}	Total	Weight
B_{11}		6	6.5	10	7.5	10	40	0.178
B_{12}	9		7	9	7	8	40	0.178
B_{13}	8.5	8		9	9	9	43.5	0.193
B_{14}	5	6	6		6	6	29	0.129
B_{15}	7.5	8	6	9		6	36.5	0.162
B_{16}	5	7	6	9	9		36	0.16

Table 12: Judgment matrix of $B_2 - B_{2k}$.

B_2	B_{21}	B_{22}	B_{23}	B_{24}	B_{25}	Total	Weight
B_{21}		7.5	10	11	9	37.5	0.25
B_{22}	7.5		8	10	7	32.5	0.217
B_{23}	5	7		9.5	6	27.5	0.183
B_{24}	4	5	5.5		9	23.5	0.157
B_{25}	6	8	9	6		29	0.193

$$P_{B_2} = A_{B_{21}-B_{25}} \times R_{B_{21}-B_{25}}$$
$$= \begin{pmatrix} 0.25 & 0.217 & 0.183 & 0.157 & 0.193 \end{pmatrix} \times \begin{bmatrix} 0.4 & 0.3 & 0.2 & 0.1 \\ 0.2 & 0.3 & 0.4 & 0.1 \\ 0.2 & 0.5 & 0.1 & 0.2 \\ 0.4 & 0.5 & 0.1 & 0 \\ 0.3 & 0.3 & 0.2 & 0.2 \end{bmatrix}$$
$$= \begin{pmatrix} 0.3007 & 0.368 & 0.2094 & 0.1219 \end{pmatrix}$$

$$P_{B_3} = A_{B_{31}-B_{34}} \times R_{B_{31}-B_{34}}$$
$$= \begin{pmatrix} 0.233 & 0.294 & 0.261 & 0.212 \end{pmatrix} \times \begin{bmatrix} 0.2 & 0.4 & 0.3 & 0.1 \\ 0.2 & 0.3 & 0.3 & 0.2 \\ 0.3 & 0.2 & 0.3 & 0.2 \\ 0.1 & 0.4 & 0.5 & 0 \end{bmatrix}$$
$$= \begin{pmatrix} 0.2049 & 0.3184 & 0.3424 & 0.1343 \end{pmatrix}$$

$$P_{B_4} = A_{B_{41}-B_{46}} \times R_{B_{41}-B_{46}}$$
$$= \begin{pmatrix} 0.171 & 0.142 & 0.2 & 0.12 & 0.193 & 0.174 \end{pmatrix} \times \begin{bmatrix} 0.3 & 0.4 & 0.2 & 0.1 \\ 0.4 & 0.4 & 0.2 & 0 \\ 0.2 & 0.3 & 0.3 & 0.2 \\ 0.3 & 0.3 & 0.3 & 0.1 \\ 0.3 & 0.4 & 0.3 & 0 \\ 0.2 & 0.3 & 0.3 & 0.2 \end{bmatrix}$$
$$= \begin{pmatrix} 0.2768 & 0.3506 & 0.2687 & 0.1039 \end{pmatrix}$$

$$P_A = A_{B_1-B_4} \times R_{B_1-B_4}$$

Table 13: Judgment matrix of $B_3 - B_{3k}$.

B_3	B_{31}	B_{32}	B_{33}	B_{34}	Total	Weight
B_{31}		5	7	9	21	0.233
B_{32}	10		7.5	9	26.5	0.294
B_{33}	8	7.5		8	23.5	0.261
B_{34}	6	6	7		19	0.212

Table 14: Judgment matrix of $B_4 - B_{4k}$.

B_4	B_{41}	B_{42}	B_{43}	B_{44}	B_{45}	B_{46}	Total	Weight
B_{41}		9	5.5	10	7	7	38.5	0.171
B_{42}	6		5	8	6	7	32	0.142
B_{43}	9.5	10		9	7.5	9	45	0.2
B_{44}	5	7	6		5	4	27	0.12
B_{45}	8	9	7.5	10		9	43.5	0.193
B_{46}	8	8	6	11	6		39	0.174

$$= \begin{pmatrix} 0.25 & 0.278 & 0.289 & 0.183 \end{pmatrix} \times \begin{bmatrix} 0.2358 & 0.3696 & 0.2951 & 0.0995 \\ 0.3007 & 0.368 & 0.2094 & 0.1219 \\ 0.2049 & 0.3184 & 0.3424 & 0.1343 \\ 0.2768 & 0.3506 & 0.2687 & 0.1039 \end{bmatrix} = \begin{pmatrix} 0.2524 & 0.3509 & 0.2801 & 0.1166 \end{pmatrix} \tag{47}$$

So

$$\begin{aligned} b_1 &= 0.2524, \\ b_2 &= 0.3509, \\ b_3 &= 0.2801, \\ b_4 &= 0.1166 \end{aligned} \tag{48}$$

And we can calculate the dispersion degree:

$$\begin{aligned} L_1 &= 0.008021, \\ L_2 &= 0.017891, \\ L_3 &= 0.008959, \\ L_4 &= 0.026638, \end{aligned} \tag{49}$$

$\overline{L} = 0.015377$ and we make $Z = 0.5$. According to $S_j = b_j - ZL_j$, we can get that the adjusted evaluation judgment vector is

$$\begin{pmatrix} 0.2484 & 0.3420 & 0.2756 & 0.1033 \end{pmatrix} \tag{50}$$

5.4. Stability Analysis. According to the calculation of Section 5.3, we can know $N = 2$. From the calculation of weights, we can know integration capability (B_{32}) has the highest weight among all the indexes. There are diverse circumstances of experts making erroneous judgments. In this case study, we choose one of them as an example to illustrate how the method discussed in the previous sections can be adopted to select the potential modular suppliers. Therefore, we suppose some experts overestimate the integration capability of the supplier. Then we discuss whether their judgment may influence the final results.

Table 15: Judgment matrix of $A - B$.

A	B_1	B_2	B_3	B_4	Total	Weight
B_1		7	5.5	10	22.5	0.25
B_2	8		8	9	25	0.278
B_3	9.5	7		9.5	26	0.289
B_4	5	6	5.5		16.5	0.183

According to the analysis of Section 4, in the circumstance that experts overestimate the integration capability (B_{32}), we know $k = 1$, $k' = 2$. There are four levels of evaluation. So $n = 4$. And we make $Z = 0.5$.

So $k \le N - 1$, $k' = N$. It is circumstance (2).

$$\begin{aligned} A_h &= (1 - a_h)\, a_h = (1 - 0.294) \times 0.294 = 0.2076 \\ B_{hk} &= 1 - 2Z(r_{hk} - b_k) = 1 - 2 \times 0.5 \times (0.2 - 0.2524) \\ &= 1.0524 \\ C_{hkk'} &= (r_{hk} - b_k) - (r_{hk'} - b_{k'}) \\ &= (0.2 - 0.2524) - (0.3 - 0.3509) = -0.0015 \\ D_{N-1} &= 0.5 - (N-1)\, Z\overline{L} - \sum_{j=1}^{N-1} S_j \\ &= 0.5 - (2-1) \times 0.5 \times 0.01538 - 0.248389 \\ &= 0.24392 \\ E_{hkk'(N-1)} &= \left[B_{hk} - B_{hk'} + \frac{2(N-1)\, ZC_{hkk'}}{n} \right] \\ &= (1.0524 - 1.0509) \\ &\quad + \frac{2 \times (2-1) \times 0.5 \times (-0.0015)}{4} = -0.00225 \\ F_{hkk'(N-1)} &= B_{hk} + \frac{2(N-1)\, ZC_{hkk'}}{n} \\ &= 1.0524 + \frac{2 \times (2-1) \times 0.5 \times (-0.0015)}{4} \\ &= 1.052025 \\ G_{hkk'} &= B_{hk'} - \frac{2(N-1)\, ZC_{hkk'}}{n} \\ &= 1.0509 - \frac{2 \times (2-1) \times 0.5 \times (-0.0015)}{4} \\ &= 1.051275 \end{aligned}$$

Table 16: Fuzzy evaluation matrix of the supplier.

	B_{11}	B_{12}	B_{13}	B_{14}	B_{15}	B_{16}	B_{21}	B_{22}	B_{23}	B_{24}	B_{25}	B_{31}	B_{32}	B_{33}	B_{34}	B_{41}	B_{42}	B_{43}	B_{44}	B_{45}	B_{46}
V_1	0.2	0.4	0.2	0.2	0.3	0.1	0.4	0.2	0.2	0.4	0.3	0.2	0.2	0.3	0.1	0.3	0.4	0.2	0.3	0.3	0.2
V_2	0.5	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.5	0.5	0.3	0.4	0.3	0.2	0.4	0.4	0.4	0.3	0.3	0.4	0.3
V_3	0.3	0.2	0.3	0.4	0.3	0.3	0.2	0.4	0.1	0.1	0.2	0.3	0.3	0.3	0.5	0.2	0.2	0.3	0.3	0.3	0.3
V_4	0	0	0.2	0.1	0	0.3	0.1	0.1	0.2	0	0.2	0.1	0.2	0.2	0	0.1	0	0.2	0.1	0	0.2

$$\begin{aligned}
H_N &= \sum_{j=1}^{N} S_j - 0.5 + NZ\overline{L} \\
&= (0.248389 + 0.341954) - 0.5 + 2 \times 0.5 \\
&\quad \times 0.0153773 = 0.10572 \\
n - 2(N-1) &= 4 - 2 \times (2-1) = 2 > 0, \\
a_h^2 F_{hkk'(N-1)}^2 - 4\frac{n-2(N-1)}{n} ZA_h D_{N-1} \\
&= 0.294^2 \times 1.052025^2 - 4 \times \frac{4-2(2-1)}{4} \times 0.5 \\
&\quad \times 0.2076 \times 0.24392 = 0.045022 > 0,
\end{aligned} \tag{51}$$

So

$$\begin{aligned}
&0 \le \Delta r \\
&\le \min\left(\frac{E_{hkk'N} a_h + \sqrt{(E_{hkk'N} a_h)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}, \right. \\
&\frac{a_h F_{hkk'(N-1)}}{2((n-2(N-1))/n) ZA_h} \\
&\left. - \frac{\sqrt{a^2{}_h F^2{}_{hkk'(N-1)} - 4((n-2(N-1))/n) ZA_h D_{N-1}}}{2((n-2(N-1))/n) ZA_h} \right)
\end{aligned} \tag{52}$$

By calculation, we can get $0 \le \Delta r \le 1.006025$.

5.5. Discussion. Based on the adjusted evaluation judgment vector we calculated in Section 5.3, we can know the results satisfy these two formulas $\sum_{j=1}^{N-1} S_j \le 0.5 - Z(N-1)\overline{L}$ and $\sum_{j=1}^{N} S_j \ge 0.5 - ZN\overline{L}$. So we can conclude that the supplier is a general modular supplier. In other words, the supplier has the basic characteristics of a modular supplier and can be taken into consideration to participate in the modular production.

But another important issue we need to consider is to which extent we can trust the result. So we refer to the stability analysis. There are 10 experts to make evaluations and hence$1.006025 \times 10 = 10.06025$. The result of the stability analysis indicates that even if all the 10 experts overestimate the integration capability, it would not influence the final results. So it is safe to say the comprehensive evaluation is stable. And we can trust the result.

As such, our method is divided into two parts. The first part is calculating the adjusted evaluation judgment vector. According to it, we can know whether the supplier is a good modular supplier or a general modular supplier or a fairly weak modular supplier or a weak modular supplier. This part gives us a basic evaluation of the supplier and helps us make a basic judgment on the supplier whether it is a modular supplier or not. The second part is about the stability analysis. Based on the first evaluation, if the supplier is a modular supplier, then we need to further to consider whether the result is stable or not. So the stability analysis can help us to estimate the maximum tolerant number of experts' erroneous judgments on a single index. In doing so, it helps us to estimate to which degree we can trust the results. If the tolerant number of experts' erroneous judgments is too small, say less than 3 which indicates that if three or less than three experts make erroneous judgments, the result will be greatly influenced. Then it shows the results are very sensitive to experts' judgment and they are not stable. And we perhaps need to reconsider the result or even to reconduct the evaluation. In doing so, the method discussed in this paper provides a relatively reliable way to evaluate whether a supplier is a modular supplier and supplements the current studies.

6. Conclusions

Based on an empirical study, this paper explores and further confirms the factor structure of modular supplier selection. On the basis of it, it applies the fuzzy evaluation method to evaluate the suppliers and the stability of the method is discussed. The main findings and contributions are as follows.

(1) Based on literature review, interviews, and open questionnaire, by adopting exploratory factor analysis and confirmatory factor analysis, this paper discusses the factor structure of the index system of modular supplier selection. The results show that the index system of modular supplier selection mainly includes four factors, that is, the basic capability requirement, technological capability requirement, modular capability requirement, and cooperation capability requirement. This finding contributes to building a comprehensive evaluation criteria system for modular suppliers and deepening the research on modular production.

From the results, we can have the implication that, different from general supplier evaluation, modular supplier evaluation needs to place particular emphasis on the modular capability of the suppliers. Modular suppliers' capability in product development, integration, and so on are important perspectives of a modular supplier and according to the empirical study they are emphasized by the manufacturers. Besides, the cooperation capability is also important criterion for evaluating whether the suppliers are competent and

suitable to take on modular production. Thus the index system provides comprehensive criteria and therefore can help managers to better identify the possible modular supplier.

(2) Based on it, this paper adopts the fuzzy evaluation method to evaluate and select the modular suppliers. Considering this method depending much on an expert's subjective judgment, the stability of the method is discussed. By introducing the dispersion degree, we modify the comprehensive evaluation vector, which considers the influence of both membership and dispersion. Lastly we apply this method to a practical case.

Based on the stability analysis, we discuss the range of subjective judgment errors in different circumstances. Such stability analysis can help managers to understand to which degree they can trust the results and therefore provides more precise and trustworthy evaluation. Thus by using the stability analysis, the managers is able to make more reliable decisions concerning modular supplier selection.

In a whole, this paper contributes to providing a systematic view to study the evaluation and selection of modular supplier by constructing an index system and proposing an evaluation method with stability analysis.

However, this paper also has some limitations. In the stability analysis, to simplify the problem, we mainly discuss the experts' erroneous judgment in adjacent levels and we only discuss the influence of erroneous judgment on one single index. In fact, the purpose of this paper is to initiate the discussion on the reliability of the fuzzy mathematical method. In further studies, more sophisticated mathematical models can be built to take more circumstances into account and then make the discussion more conducive.

Appendix

The followings are the detailed mathematical induction of the stability analysis.

(1) Both positive and negative errors have impact on formula (2) and formula (3). Namely, $k \le N-1$, $k' \le N-1$:

$$\begin{aligned}\sum_{j=1}^{N-1} S'_j &= \sum_{j\neq k,k'} S_j + S'_k + S'_{k'} \\ &= \sum_{j\neq k,k'} S_j + S_k - ZA_h\Delta r^2 + B_{hk}a_h\Delta r + S_{k'} \\ &\quad - ZA_h\Delta r^2 - B_{hk'}a_h\Delta r \\ &= \sum_{j=1}^{N-1} S_j - 2ZA_h\Delta r^2 + a_h\left(B_{hk} - B_{hk'}\right)\Delta r \end{aligned} \tag{A.1}$$

$$\begin{aligned}&0.5 - (N-1)Z\overline{L'} \\ &\quad = 0.5 - (N-1)Z\left(\overline{L} + \frac{2}{n}A_h\Delta r^2 + \frac{2a_hC_{hkk'}}{n}\Delta r\right) \\ &\quad = 0.5 - (N-1)Z\overline{L} - \frac{2(N-1)Z}{n}A_h\Delta r^2 \\ &\qquad - \frac{2(N-1)Za_hC_{hkk'}}{n}\Delta r\end{aligned}$$

Because $\sum_{j=1}^{N-1} S'_j \le 0.5 - Z(N-1)\overline{L'}$, by rearranging the formula we can get

$$\begin{aligned}&\frac{2(n-N+1)Z}{n}A_h\Delta r^2 \\ &\quad - \left[B_{hk} - B_{hk'} + \frac{2(N-1)ZC_{hkk'}}{n}\right]a_h\Delta r \\ &\quad + D_{N-1} \ge 0.\end{aligned} \tag{A.2}$$

We make

$$E_{hkk'(N-1)} = \left[B_{hk} - B_{hk'} + \frac{2(N-1)ZC_{hkk'}}{n}\right]. \tag{A.3}$$

Then

$$\begin{aligned}&\frac{2(n-N+1)Z}{n}A_h\Delta r^2 - E_{hkk'(N-1)}a_h\Delta r + D_{N-1} \\ &\quad \ge 0.\end{aligned} \tag{A.4}$$

Because $n - N + 1 \ge 0$, if

$$\left(E_{hkk'(N-1)}a_h\right)^2 - 4\frac{2(n-N+1)Z}{n}A_hD_{N-1} < 0, \tag{A.5}$$

then the above inequality always holds.

If $(E_{hkk'(N-1)}a_h)^2 - 4(2(n-N+1)Z/n)A_hD_{N-1} \ge 0$,

$$\begin{aligned}0 \le \Delta r &\le \frac{E_{hkk'(N-1)}a_h}{2(2Z(n-N+1)/n)A_h} \\ &\quad - \frac{\sqrt{\left(E_{hkk'(N-1)}a_h\right)^2 - 4(2Z(n-N+1)/n)A_hD_{N-1}}}{(2Z(n-N+1)/n)A_h}\end{aligned}$$

$$\begin{aligned}\sum_{j=1}^{N} S'_j &= \sum_{j\neq k,k'} S_j + S'_k + S'_{k'} \\ &= \sum_{j\neq k,k'} S_j + S_k - ZA_h\Delta r^2 + B_{hk}a_h\Delta r + S_{k'} - ZA_h\Delta r^2 \\ &\quad - B_{hk'}a_h\Delta r = \sum_{j=1}^{N} S_j - 2ZA_h\Delta r^2 + a_h\left(B_{hk} - B_{hk'}\right)\Delta r \end{aligned} \tag{A.6}$$

$$\begin{aligned}0.5 - NZ\overline{L'} &= 0.5 - NZ\left(\overline{L} + \frac{2}{n}A_h\Delta r^2 + \frac{2a_hC_{hkk'}}{n}\Delta r\right) \\ &= 0.5 - NZ\overline{L} - \frac{2NZ}{n}A_h\Delta r^2 - \frac{2NZa_hC_{hkk'}}{n}\Delta r.\end{aligned}$$

Because $\sum_{j=1}^{N} S'_j \le 0.5 - ZN\overline{L'}$, by rearranging the formula we can get

$$\begin{aligned}&\frac{2(n-N)Z}{n}A_h\Delta r^2 \\ &\quad - \left[B_{hk} - B_{hk'} + \frac{2NZC_{hkk'}}{n}\right]a_h\Delta r - H_N \le 0.\end{aligned} \tag{A.7}$$

That is $(2(n-N)Z/n)A_h\Delta r^2 - E_{hkk'N}a_h\Delta r - H_N \le 0$.

$$\begin{aligned} 0 &\le \Delta r \\ &\le \frac{E_{hkk'N}a_h}{2\left(2Z\left(n-N\right)/n\right)A_h} \\ &\quad + \frac{\sqrt{\left(E_{hkk'N}a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right)A_hH_N}}{2\left(2Z\left(n-N\right)/n\right)A_h}. \end{aligned} \tag{A.8}$$

Therefore, if

$$\begin{aligned} &\left(E_{hkk'}a_h\right)^2 - 4\frac{2Z\left(n-N+1\right)}{n}A_hD_{N-1} < 0, \\ &0 \le \Delta r \\ &\quad \le \frac{E_{hkk'N}a_h}{2\left(2Z\left(n-N\right)/n\right)A_h} \\ &\qquad + \frac{\sqrt{\left(E_{hkk'N}a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right)A_hH_N}}{2\left(2Z\left(n-N\right)/n\right)A_h}. \end{aligned} \tag{A.9}$$

If $(E_{hkk'}a_h)^2 - 4(2Z(n-N+1)/n)A_hD_{N-1} \ge 0$,

$$\begin{aligned} 0 \le \Delta r \le \min\Bigg(&\frac{E_{hkk'N}a_h}{2\left(2Z\left(n-N\right)/n\right)A_h} \\ &+ \frac{\sqrt{\left(E_{hkk'N}a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right)A_hH_N}}{2\left(2Z\left(n-N\right)/n\right)A_h}, \\ &\frac{E_{hkk'(N-1)}a_h}{2\left(2Z\left(n-N+1\right)/n\right)A_h} \\ &- \frac{\sqrt{\left(E_{hkk'(N-1)}a_h\right)^2 - 4\left(2Z\left(n-N+1\right)/n\right)A_hD_{N-1}}}{2\left(2Z\left(n-N+1\right)/n\right)A_h}\Bigg). \end{aligned} \tag{A.10}$$

(2) The positive error has impact on formula (2); both positive and negative errors have impact on formula (3). Namely, $k \le N-1$, $k' = N$.

$$\begin{aligned} \sum_{j=1}^{N-1} S'_j &= \sum_{j\ne k} S_j + S'_k \\ &= \sum_{j\ne k} S_j + S_k - ZA_h\Delta r^2 + B_{hk}a_h\Delta r \\ &= \sum_{j=1}^{N-1} S_j - ZA_h\Delta r^2 + B_{hk}a_h\Delta r \\ 0.5 &- (N-1)Z\overline{L'} \\ &= 0.5 - (N-1)Z\left(\overline{L} + \frac{2}{n}A_h\Delta r^2 + \frac{2a_hC_{hkk'}}{n}\Delta r\right) \\ &= 0.5 - (N-1)Z\overline{L} - \frac{2(N-1)Z}{n}A_h\Delta r^2 \\ &\quad - \frac{2(N-1)Za_hC_{hkk'}}{n}\Delta r. \end{aligned} \tag{A.11}$$

Because $\sum_{j=1}^{N-1} S'_j \le 0.5 - Z(N-1)\overline{L'}$, by rearranging the formula, we can get

$$\begin{aligned} &\frac{n-2(N-1)Z}{n}A_h\Delta r^2 \\ &\quad - \left[B_{hk} + \frac{2(N-1)ZC_{hkk'}}{n}\right]a_h\Delta r + D_{N-1} \\ &\quad \ge 0. \end{aligned} \tag{A.12}$$

We make

$$F_{hkk'(N-1)} = \left[B_{hk} + \frac{2(N-1)ZC_{hkk'}}{n}\right]. \tag{A.13}$$

Then

$$\begin{aligned} &\frac{n-2(N-1)Z}{n}A_h\Delta r^2 - F_{hkk'(N-1)}a_h\Delta r + D_{N-1} \\ &\quad \ge 0. \end{aligned} \tag{A.14}$$

If $n-2(N-1) \ge 0$,

$$\left(F_{hkk'(N-1)}a_h\right)^2 - 4\frac{n-2(N-1)Z}{n}A_hD_{N-1} < 0, \tag{A.15}$$

then the above inequality always holds.

If $n-2(N-1) \ge 0$,

$$\begin{aligned} &\left(F_{hkk'(N-1)}a_h\right)^2 - 4\frac{n-2(N-1)Z}{n}A_hD_{N-1} \ge 0, \\ &0 \le \Delta r \le \frac{F_{hkk'(N-1)}a_h}{2\left(\left(n-2(N-1)\right)/n\right)ZA_h} \\ &\quad - \frac{\sqrt{\left(F_{hkk'(N-1)}a_h\right)^2 - 4\left(\left(n-2(N-1)\right)/n\right)ZA_hD_{N-1}}}{2\left(\left(n-2(N-1)\right)/n\right)ZA_h}. \end{aligned} \tag{A.16}$$

If $2(N-1)-n \ge 0$,

$$\begin{aligned} &\frac{2(N-1)-n}{n}ZA_h\Delta r^2 + F_{hkk'(N-1)}a_h\Delta r - D_{N-1} \le 0, \\ &0 \le \Delta r \le \frac{-F_{hkk'(N-1)}a_h}{2\left(\left(2(N-1)-n\right)/n\right)ZA_h} \\ &\quad + \frac{\sqrt{\left(F_{hkk'(N-1)}a_h\right)^2 + 4\left(\left(2(N-1)-n\right)/n\right)ZA_hD_{N-1}}}{2\left(\left(2(N-1)-n\right)/n\right)ZA_h}. \end{aligned} \tag{A.17}$$

Because both positive and negative errors have impact on formula (3), according to the deduction of circumstance (1), to satisfy formula (3), it should have

$$\begin{aligned} &0 \le \Delta r \\ &\quad \le \frac{E_{hkk'N}a_h + \sqrt{\left(E_{hkk'N}a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right)A_hH_N}}{2\left(2Z\left(n-N\right)/n\right)A_h} \end{aligned} \tag{A.18}$$

Therefore, if $n-2(N-1) \ge 0$, $a_h^2F_{hkk'(N-1)}^2 - 4((n-2(N-1))/n)ZA_hD_{N-1} < 0$,

$$\begin{aligned} &0 \le \Delta r \\ &\quad \le \frac{E_{hkk'N}a_h + \sqrt{\left(E_{hkk'N}a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right)A_hH_N}}{2\left(2Z\left(n-N\right)/n\right)A_h}. \end{aligned} \tag{A.19}$$

If $n-2(N-1) \geq 0$, $a_h^2 F_{hkk'(N-1)}^2 - 4((n-2(N-1))/n) Z A_h D_{N-1} \geq 0$,

$$0 \leq \Delta r \leq \min\left(\frac{E_{hkk'N} a_h}{2(2Z(n-N)/n) A_h} + \frac{\sqrt{(E_{hkk'N} a_h)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}, \frac{a_h F_{hkk'(N-1)}}{2((n-2(N-1))/n) Z A_h} - \frac{\sqrt{a^2{}_h F^2{}_{hkk'(N-1)} - 4((n-2(N-1))/n) Z A_h D_{N-1}}}{2((n-2(N-1))/n) Z A_h} \right). \tag{A.20}$$

If $2(N-1) - n \geq 0$,

$$0 \leq \Delta r \leq \min\left(\frac{E_{hkk'N} a_h}{2(2Z(n-N)/n) A_h} + \frac{\sqrt{(E_{hkk'N} a_h)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}, \frac{-a_h F_{hkk'(N-1)}}{2((2(N-1)-n)/n) Z A_h} + \frac{\sqrt{a^2{}_h F^2{}_{hkk'(N-1)} + 4((2(N-1)-n)/n) Z A_h D_{N-1}}}{2((2(N-1)-n)/n) Z A_h} \right). \tag{A.21}$$

(3) The negative error has impact on formula (2); both positive and negative error have impact on formula (3). Namely, $k = N$, $k' \leq N-1$:

$$\begin{aligned} \sum_{j=1}^{N-1} S'_j &= \sum_{j \neq k'} S_j + S'_{k'} \\ &= \sum_{j \neq k'} S_j + S_{k'} - Z A_h \Delta r^2 - B_{hk'} a_h \Delta r \\ &= \sum_{j=1}^{N-1} S_j - Z A_h \Delta r^2 - B_{hk'} a_h \Delta r. \end{aligned}$$

$$\begin{aligned} &0.5 - (N-1) Z \overline{L'} \\ &\quad = 0.5 \\ &\qquad - (N-1) Z \left(\overline{L} + \frac{2}{n} A_h \Delta r^2 + \frac{2 a_h C_{hkk'}}{n} \Delta r \right) \\ &\quad = 0.5 - (N-1) Z \overline{L} - \frac{2(N-1) Z}{n} A_h \Delta r^2 \\ &\qquad - \frac{2(N-1) Z a_h C_{hkk'}}{n} \Delta r. \end{aligned} \tag{A.22}$$

Because $\sum_{j=1}^{N-1} S'_j \leq 0.5 - Z(N-1)\overline{L'}$, by rearranging the formula we can get

$$\begin{aligned} &\frac{n-2(N-1)Z}{n} A_h \Delta r^2 \\ &\quad + \left[B_{hk'} - \frac{2(N-1) Z C_{hkk'}}{n} \right] a_h \Delta r + D_{N-1} \\ &\geq 0. \end{aligned} \tag{A.23}$$

We make $G_{hkk'} = [B_{hk'} - (2(N-1) Z C_{hkk'}/n)]$.

Then $((n-2(N-1)Z)/n) A_h \Delta r^2 + G_{hkk'} a_h \Delta r + D_{N-1} \geq 0$.

If $n - 2(N-1) \geq 0$,

$$(G_{hkk'} a_h)^2 - 4 \frac{n-2(N-1)Z}{n} A_h D_{N-1} < 0, \tag{A.24}$$

then the above inequality always holds.

If $n - 2(N-1) \geq 0$,

$$\begin{aligned} &(G_{hkk'} a_h)^2 - 4 \frac{n-2(N-1)Z}{n} A_h D_{N-1} \geq 0, \\ &0 \leq \Delta r \\ &\quad \leq \frac{-G_{hkk'} a_h - \sqrt{(G_{hkk'} a_h)^2 - 4((n-2(N-1))/n) Z A_h D_{N-1}}}{2((n-2(N-1))/n) Z A_h}. \end{aligned} \tag{A.25}$$

If $2(N-1) - n \geq 0$,

$$\begin{aligned} &\frac{2(N-1)-n}{n} Z A_h \Delta r^2 - G_{hkk'} a_h \Delta r - D_{N-1} \leq 0, \\ &0 \leq \Delta r \\ &\quad \leq \frac{G_{hkk'} a_h + \sqrt{(G_{hkk'} a_h)^2 + 4((2(N-1)-n)/n) Z A_h D_{N-1}}}{2((2(N-1)-n)/n) Z A_h}. \end{aligned} \tag{A.26}$$

Because both positive and negative errors have impact on formula (3), according to the deduction of circumstance (1), to satisfy formula (3), it should have

$$\begin{aligned} &0 \leq \Delta r \\ &\quad \leq \frac{E_{hkk'N} a_h + \sqrt{(E_{hkk'N} a_h)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}. \end{aligned} \tag{A.27}$$

Therefore, if $n - 2(N-1) \geq 0$, $a_h^2 G_{hkk'}^2 - 4((n-2(N-1))/n) Z A_h D_{N-1} < 0$,

$$\begin{aligned} &0 \leq \Delta r \\ &\quad \leq \frac{E_{hkk'N} a_h + \sqrt{(E_{hkk'N} a_h)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}. \end{aligned} \tag{A.28}$$

If $n-2(N-1) \geq 0$, $a_h^2 G_{hkk'}^2 - 4((n-2(N-1))/n) Z A_h D_{N-1} \geq 0$,

$$0 \leq \Delta r \leq \min\left(\frac{E_{hkk'N} a_h}{2(2Z(n-N)/n) A_h} + \frac{\sqrt{(E_{hkk'N} a_h)^2 + 4(2Z(n-N)/n) A_h H_N}}{2(2Z(n-N)/n) A_h}, \right.$$

$$\frac{-a_h G_{hkk'}}{2\left(\left(n-2\left(N-1\right)\right)/n\right) ZA_h} - \frac{\sqrt{a_h^2 G_{hkk'}^2 - 4\left(\left(n-2\left(N-1\right)\right)/n\right) ZA_h D_{N-1}}}{2\left(\left(n-2\left(N-1\right)\right)/n\right) ZA_h}\Bigg). \tag{A.29}$$

If $2(N-1)-n \geq 0$,

$$0 \leq \Delta r \leq \min\Bigg(\frac{E_{hkk'N} a_h}{2\left(2Z\left(n-N\right)/n\right) A_h} + \frac{\sqrt{\left(E_{hkk'N} a_h\right)^2 + 4\left(2Z\left(n-N\right)/n\right) A_h H_N}}{2\left(2Z\left(n-N\right)/n\right) A_h}, \frac{a_h G_{hkk'}}{2\left(\left(2\left(N-1\right)-n\right)/n\right) ZA_h} + \frac{\sqrt{a_h^2 G_{hkk'}^2 + 4\left(\left(2\left(N-1\right)-n\right)/n\right) ZA_h D_{N-1}}}{2\left(\left(2\left(N-1\right)-n\right)/n\right) ZA_h}\Bigg). \tag{A.30}$$

(4) Both positive and negative errors do not have impact on formula (2); the negative error has impact on formula (3). Namely, $k > N$, $k' = N$:

$$\begin{aligned}\sum_{j=1}^{N} S'_j &= \sum_{j\neq k'} S_j + S'_{k'} \\ &= \sum_{j\neq k'} S_j + S_{k'} - ZA_h \Delta r^2 - B_{hk'} a_h \Delta r \\ &= \sum_{j=1}^{N} S_j - ZA_h \Delta r^2 - B_{hk'} a_h \Delta r\end{aligned} \tag{A.31}$$

$$\begin{aligned}0.5 - NZ\overline{L'} &= 0.5 - NZ\left(\overline{L} + \frac{2}{n} A_h \Delta r^2 + \frac{2a_h C_{hkk'}}{n}\Delta r\right) \\ &= 0.5 - NZ\overline{L} - \frac{2NZ}{n} A_h \Delta r^2 - \frac{2NZa_h C_{hkk'}}{n}\Delta r.\end{aligned}$$

Because $\sum_{j=1}^{N} S'_j \geq 0.5 - ZN\overline{L'}$, by rearranging the formula we can get

$$\frac{n-2N}{n} ZA_h \Delta r^2 - \left[B_{hk'} - \frac{2NZC_{hkk'}}{n}\right] a_h \Delta r + H_N \geq 0. \tag{A.32}$$

That is $((n-2N)/n)ZA_h \Delta r^2 - G_{hkk'N} a_h \Delta r + H_N \geq 0$.

If $n - 2N \geq 0$,

$$\left(G_{hkk'N} a_h\right)^2 - 4\frac{n-2N}{n} ZA_h D_{N-1} < 0, \tag{A.33}$$

then the above inequality always holds.

If $n - 2N \geq 0$,

$$\begin{aligned}&\left(G_{hkk'N} a_h\right)^2 - 4\frac{n-2N}{n} ZA_h H_N \geq 0, \\ &0 \leq \Delta r \leq \frac{G_{hkk'N} a_h - \sqrt{\left(G_{hkk'N} a_h\right)^2 - 4\left(\left(n-2N\right)/n\right) ZA_h H_N}}{2\left(\left(n-2N\right)/n\right) ZA_h}.\end{aligned} \tag{A.34}$$

If $2N - n \geq 0$,

$$\begin{aligned}&\frac{2N-n}{n} ZA_h \Delta r^2 + G_{hkk'N} a_h \Delta r - H_N \leq 0, \\ &0 \leq \Delta r \leq \frac{-G_{hkk'N} a_h + \sqrt{\left(G_{hkk'N} a_h\right)^2 + 4\left(\left(2N-n\right)/n\right) ZA_h H_N}}{2\left(\left(2N-n\right)/n\right) ZA_h}\end{aligned} \tag{A.35}$$

For formula (2),

$$\begin{aligned}\sum_{j=1}^{N-1} S'_j = \sum_{j=1}^{N-1} S_j &\leq 0.5 - \left(N-1\right) Z\overline{L'} \\ &= 0.5 - \left(N-1\right) Z\left(\overline{L} + \frac{2}{n} A_h \Delta r^2 + \frac{2a_h C_{hkk'}}{n}\Delta r\right) \\ &= 0.5 - \left(N-1\right) Z\overline{L} - \frac{2\left(N-1\right) Z}{n} A_h \Delta r^2 - \frac{2\left(N-1\right) Za_h C_{hkk'}}{n}\Delta r.\end{aligned} \tag{A.36}$$

By rearranging the formula we can get

$$\begin{aligned}&\frac{2\left(N-1\right) Z}{n} A_h \Delta r^2 + \frac{2a_h\left(N-1\right) ZC_{hkk'}}{n}\Delta r - D_{N-1} \leq 0. \\ &0 \leq \Delta r \leq \frac{-2a_h\left(N-1\right) ZC_{hkk'}/n}{2\left(2\left(N-1\right)/n\right) ZA_h} + \frac{\sqrt{\left(2a_h\left(N-1\right) ZC_{hkk'}/n\right)^2 + 4\left(2\left(N-1\right)/n\right) ZA_h D_{N-1}}}{2\left(2\left(N-1\right)/n\right) ZA_h}.\end{aligned} \tag{A.37}$$

Therefore, if $n - 2N \geq 0$,

$$\begin{aligned}&a_h^2 G_{hkk'N}^2 - 4\frac{n-2N}{n} ZA_h H_N < 0, \\ &0 \leq \Delta r \leq \frac{-2a_h\left(N-1\right) ZC_{hkk'}/n}{2\left(2\left(N-1\right)/n\right) ZA_h} + \frac{\sqrt{\left(2a_h\left(N-1\right) ZC_{hkk'}/n\right)^2 + 4\left(2\left(N-1\right) ZA_h D_{N-1}/n\right)}}{2\left(2\left(N-1\right)/n\right) ZA_h}.\end{aligned} \tag{A.38}$$

If $n - 2N \geq 0$,

$$a_h^2 G_{hkk'N}^2 - 4\frac{n-2N}{n} ZA_h H_N \geq 0,$$

$$0 \leq \Delta r \leq \min\Bigg(\frac{-2a_h\left(N-1\right) ZC_{hkk'}/n}{2\left(2\left(N-1\right)/n\right) ZA_h}$$

$$+\frac{\sqrt{\left(2a_h(N-1)ZC_{hkk'}/n\right)^2+4\left(2(N-1)ZA_hD_{N-1}/n\right)}}{2\left(2(N-1)/n\right)ZA_h},$$
$$\frac{a_hG_{hkk'N}-\sqrt{a_h^2G_{hkk'N}^2-4\left((n-2N)/n\right)ZA_hH_N}}{2\left((n-2N)/n\right)ZA_h}\Bigg) \tag{A.39}$$

If $2N-n\geq 0$,

$$0\leq\Delta r\leq\min\Bigg(\frac{-2a_h(N-1)ZC_{hkk'}/n}{2\left(2(N-1)/n\right)ZA_h}$$
$$+\frac{\sqrt{\left(2a_h(N-1)ZC_{hkk'}/n\right)^2+4\left(2(N-1)ZA_hD_{N-1}/n\right)}}{2\left(2(N-1)/n\right)ZA_h},$$
$$\frac{-a_hG_{hkk'N}+\sqrt{a_h^2G_{hkk'N}^2+4\left((2N-n)/n\right)ZA_hH_N}}{2\left((2N-n)/n\right)ZA_h}\Bigg) \tag{A.40}$$

(5) Both positive and negative errors do not have impact on formula (2); the positive error has impact on formula (3). Namely, $k=N$, $k'>N$:

$$\begin{aligned}\sum_{j=1}^{N}S'_j&=\sum_{j\neq k}S_j+S'_k\\&=\sum_{j\neq k}S_j+S_k-ZA_h\Delta r^2+B_{hk}a_h\Delta r\\&=\sum_{j=1}^{N}S_j-ZA_h\Delta r^2+B_{hk}a_h\Delta r\end{aligned} \tag{A.41}$$

$$\begin{aligned}0.5-NZ\overline{L'}&=0.5-NZ\left(\overline{L}+\frac{2}{n}A_h\Delta r^2+\frac{2a_hC_{hkk'}}{n}\Delta r\right)\\&=0.5-NZ\overline{L}-\frac{2NZ}{n}A_h\Delta r^2-\frac{2NZa_hC_{hkk'}}{n}\Delta r.\end{aligned}$$

Because $\sum_{j=1}^{N}S'_j\geq 0.5-ZN\overline{L'}$, by rearranging the formula we can get

$$\frac{n-2N}{n}ZA_h\Delta r^2+\left[B_{hk}+\frac{2NZC_{hkk'}}{n}\right]a_h\Delta r+H_N\geq 0. \tag{A.42}$$

Then $((n-2N)/n)ZA_h\Delta r^2+F_{hkk'N}a_h\Delta r+H_N\geq 0$.

If $n-2N\geq 0$,

$$\left(F_{hkk'N}a_h\right)^2-4\frac{n-2N}{n}ZA_hH_N<0, \tag{A.43}$$

then the above inequality always holds.

If $n-2N\geq 0$,

$$\begin{aligned}&\left(F_{hkk'N}a_h\right)^2-4\frac{n-2N}{n}ZA_hH_N\geq 0,\\&0\leq\Delta r\\&\leq\frac{-F_{hkk'N}a_h+\sqrt{\left(F_{hkk'N}a_h\right)^2-4\left((n-2N)/n\right)ZA_hH_N}}{2\left((n-2N)/n\right)ZA_h}.\end{aligned} \tag{A.44}$$

If $2N-n\geq 0$,

$$\begin{aligned}&\frac{2N-n}{n}ZA_h\Delta r^2-F_{hkk'N}a_h\Delta r-H_N\leq 0,\\&0\leq\Delta r\\&\leq\frac{F_{hkk'N}a_h+\sqrt{\left(F_{hkk'N}a_h\right)^2+4\left((2N-n)/n\right)ZA_hH_N}}{2\left((2N-n)/n\right)ZA_h}.\end{aligned} \tag{A.45}$$

For formula (2),

$$\begin{aligned}\sum_{j=1}^{N-1}S'_j&=\sum_{j=1}^{N-1}S_j\leq 0.5-(N-1)Z\overline{L'}\\&=0.5\\&\quad-(N-1)Z\left(\overline{L}+\frac{2}{n}A_h\Delta r^2+\frac{2a_hC_{hkk'}}{n}\Delta r\right)\\&=0.5-(N-1)Z\overline{L}-\frac{2(N-1)Z}{n}A_h\Delta r^2\\&\quad-\frac{2(N-1)Za_hC_{hkk'}}{n}\Delta r.\end{aligned} \tag{A.46}$$

By rearranging the formula we can get

$$\begin{aligned}&\frac{2(N-1)Z}{n}A_h\Delta r^2+\frac{2a_h(N-1)ZC_{hkk'}}{n}\Delta r-D_{N-1}\leq 0.\\&0\leq\Delta r\leq\frac{-2a_h(N-1)ZC_{hkk'}/n}{2\left(2(N-1)/n\right)ZA_h}\\&\quad+\frac{\sqrt{\left(2a_h(N-1)ZC_{hkk'}/n\right)^2+4\left(2(N-1)/n\right)ZA_hD_{N-1}}}{2\left(2(N-1)/n\right)ZA_h}.\end{aligned} \tag{A.47}$$

Therefore, if $n-2N\geq 0$,

$$\begin{aligned}&a_h^2F^2{}_{hkk'N}-4\frac{n-2N}{n}ZA_hH_N<0.\\&0\leq\Delta r\leq\frac{-2a_h(N-1)ZC_{hkk'}/n}{2\left(2(N-1)/n\right)ZA_h}\\&\quad+\frac{\sqrt{\left(2a_h(N-1)ZC_{hkk'}/n\right)^2+4\left(2(N-1)ZA_hD_{N-1}/n\right)}}{2\left(2(N-1)/n\right)ZA_h}.\end{aligned} \tag{A.48}$$

If $n - 2N \geq 0$,

$$a_h^2 F^2{}_{hkk'N} - 4\frac{n-2N}{n} ZA_h H_N \geq 0,$$
$$0 \leq \Delta r \leq \min\left(\frac{-2a_h(N-1)ZC_{hkk'}/n}{2(2(N-1)/n)ZA_h} + \frac{\sqrt{(2a_h(N-1)ZC_{hkk'}/n)^2 + 4(2(N-1)ZA_h D_{N-1}/n)}}{2(2(N-1)/n)ZA_h}, \frac{-a_h F_{hkk'N} + \sqrt{a_h^2 F^2_{hkk'N} - 4((n-2N)/n)ZA_h D_{N-1}}}{2((n-2N)/n)ZA_h}\right) \tag{A.49}$$

If $2N - n \geq 0$,

$$0 \leq \Delta r \leq \min\left(\frac{-2a_h(N-1)ZC_{hkk'}/n}{2(2(N-1)/n)ZA_h} + \frac{\sqrt{(2a_h(N-1)ZC_{hkk'}/n)^2 + 4(2(N-1)ZA_h D_{N-1}/n)}}{2(2(N-1)/n)ZA_h}, \frac{a_h F_{hkk'N} + \sqrt{a_h^2 F^2_{hkk'N} + 4((2N-n)/n)ZA_h H_N}}{2((2N-n)/n)ZA_h}\right) \tag{A.50}$$

(6) Both positive and negative errors do not have impact on the two formulad. Namely, $k > N$, $k' > N$.

For formula (2),

$$\begin{aligned}\sum_{j=1}^{N-1} S'_j = \sum_{j=1}^{N-1} S_j &\leq 0.5 - (N-1)Z\overline{L'} \\ &= 0.5 - (N-1)Z\left(\overline{L} + \frac{2}{n}A_h\Delta r^2 + \frac{2a_h C_{hkk'}}{n}\Delta r\right) \\ &= 0.5 - (N-1)Z\overline{L} - \frac{2(N-1)Z}{n}A_h\Delta r^2 - \frac{2(N-1)Za_h C_{hkk'}}{n}\Delta r.\end{aligned} \tag{A.51}$$

By rearranging the formula we can get

$$\frac{2(N-1)Z}{n}A_h\Delta r^2 + \frac{2a_h(N-1)ZC_{hkk'}}{n}\Delta r - D_{N-1} \leq 0.$$
$$0 \leq \Delta r \leq \frac{-2a_h(N-1)ZC_{hkk'}/n}{2(2(N-1)/n)ZA_h} + \frac{\sqrt{(2a_h(N-1)ZC_{hkk'}/n)^2 + 4(2(N-1)/n)ZA_h D_{N-1}}}{2(2(N-1)/n)ZA_h}. \tag{A.52}$$

For formula (3),

$$\begin{aligned}\sum_{j=1}^{N} S'_j = \sum_{j=1}^{N} S_j &\geq 0.5 - NZ\overline{L'} \\ &= 0.5 - NZ\left(\overline{L} + \frac{2}{n}A_h\Delta r^2 + \frac{2a_h C_{hkk'}}{n}\Delta r\right) \\ &= 0.5 - NZ\overline{L} - \frac{2NZ}{n}A_h\Delta r^2 - \frac{2NZa_h C_{hkk'}}{n}\Delta r.\end{aligned} \tag{A.53}$$

By rearranging the formula we can get

$$\frac{2NZ}{n}A_h\Delta r^2 + \frac{2a_h NZC_{hkk'}}{n}\Delta r + H_N \geq 0. \tag{A.54}$$

If $(2a_h NZC_{hkk'}/n)^2 - 4(2NZ/n)A_h H_N < 0$, then the above inequality always holds.

If $(2a_h NZC_{hkk'}/n)^2 - 4(2NZ/n)A_h H_N \geq 0$,

$$0 \leq \Delta r \leq \frac{-2a_h NZC_{hkk'}/n}{2(2N/n)ZA_h} - \frac{\sqrt{(2a_h NZC_{hkk'}/n)^2 - 4(2NZA_h H_N/n)}}{2(2N/n)ZA_h}. \tag{A.55}$$

Therefore, if $(2a_h NZC_{hkk'}/n)^2 - 4(2NZA_h H_N/n) < 0$,

$$0 \leq \Delta r \leq \frac{-2a_h(N-1)ZC_{hkk'}/n}{2(2(N-1)/n)ZA_h} + \frac{\sqrt{(2a_h(N-1)ZC_{hkk'}/n)^2 + 4(2(N-1)ZA_h D_{N-1}/n)}}{2(2(N-1)/n)ZA_h}. \tag{A.56}$$

If $(2a_h NZC_{hkk'}/n)^2 - 4(2NZA_h H_N/n) \geq 0$,

$$0 \leq \Delta r \leq \min\left[\frac{-2a_h(N-1)ZC_{hkk'}/n}{2(2(N-1)/n)ZA_h} + \frac{\sqrt{(2a_h(N-1)ZC_{hkk'}/n)^2 + 4(2(N-1)ZA_h D_{N-1}/n)}}{2(2(N-1)/n)ZA_h}, \frac{-2a_h NZC_{hkk'}/n + \sqrt{(2a_h NZC_{hkk'}/n)^2 - 4(2NZA_h H_N/n)}}{2(2NZA_h/n)}\right] \tag{A.57}$$

Data Availability

The data underlying the findings of the study were mainly collected via questionnaires. Readers wishing to access these data can do so by contacting the corresponding author.

Conflicts of Interest

The author declares no conflicts of interest. The author has no financial and personal relationships with other people or organizations that can inappropriately influence the work.

Acknowledgments

This work was supported by the China Scholarship Council, the National Natural Science Foundations of China (Grants nos. 71462009 and 71361013), the Natural Science Foundations of Jiangxi Province (Grants nos. 20171BAA208013), and the Science and Technology Project of Jiangxi Provincial Department of Education (Grant no. GJJ160440).

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