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A Fuzzy Evaluation Model for Sustainable Modular Supplier

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Abstract: The evaluation and selection of a sustainable modular supplier is a strategic decision towards sustainability of manufacturing. However, few related studies have been conducted, particularly in the modular production field. In this paper, a fuzzy evaluation method is used to evaluate sustainable modular suppliers. Different from previous studies, in designing the index system of the fuzzy evaluation method, this study introduces an organizational identity perspective. What is more, an empirical study based on a formative model is conducted to design the index system. Both measures ensure the appropriateness of the index system. The stability of the fuzzy evaluation method is also discussed. By introducing a dispersion degree and discussing the different circumstances of subjective judgment errors, the stability analysis helps us to better understand the reliability of the results. Lastly, this study applies this method and the index system to a practical case. The results show that the fuzzy evaluation method is effective and can be used to evaluate sustainable modular suppliers.

Keywords: supplier evaluation; formative model; stability analysis; sustainable modular supplier; organizational identity

1. Introduction

In the past ten years, modular production modes have been widely adopted in producing many complicated products such as automobiles, computers, and semiconductors. Taking the automobile manufacturing industry as an example, in 1997 a joint venture of Benz Corp and the SMH company launched a new type of car named the Smart Car. This car later proved to be a great success. To produce the car, the manufacturer used typical modular product development technology. The car is composed of five modules, which are supplied by seven first tier suppliers. In doing so this joint venture has fully realized modular production.

At the same time, with the proposal of the sustainability concept and society's increasing consciousness of environmental protection, sustainability of production is of great importance. For example, as car ownership continues to grow rapidly, the automobile industry is facing serious environmental problems and needs to make a response to these problems. For instance, some countries have set clear limits on the fuel consumption of automobiles. Such legal restrictions propel car manufacturers to continuously improve technology to produce vehicles with lower energy consumption.

Thus, considering manufacturers' aspirations for both sustainability and modular production, the evaluation of sustainable modular suppliers is a key strategic decision in the management of a sustainability-focused modular production network. In this paper, I focus on this topic and discuss the evaluation of sustainable modular suppliers, which has never been discussed before.

Different from previous studies, this study contributes to the current literature in the following aspects: (1) This paper introduces a new perspective into the design of the evaluation index system:

the organizational identity perspective. According to the organizational identity theory, organizational identity is the unanimous understanding of most members of an organization about "who we are as an organization" [1]. It is the central, enduring and distinctive cognition about an organization [2]. By learning about an organization's understanding of itself, the manufacturer can better judge and forecast the behaviors of the supplier and therefore further improve the effectiveness of supplier evaluation. (2) I use the formative model to evaluate the validity and reliability of the index system. Generally, there are reflective indicators and formative indicators, of which the former is said to reflect latent variables while the latter has formed the latent property in the past. Based on my analysis, the evaluation index system consists of three perspectives and the measurement model built in this paper would be a formative model. Different from previous factor analyses of the index system, the formative model better follows the design logic and is more appropriate for the index analysis of this paper. (3) Many of the factors of the evaluation system are qualitative and this qualitative information is in nature ambiguous. Based on fuzzy sets, the fuzzy evaluation method can solve this problem by providing a comprehensive evaluation. Furthermore, by introducing a dispersion degree, this paper modifies the evaluation vectors. Such analysis contributes to better understanding of the results.

This paper is structured as follows: Section 2 is a literature review, in which relevant studies are reviewed and discussed. Section 3 is an empirical study of the index system; by investigation and expert consultation, the questionnaires are designed and an empirical study is conducted. Section 4 introduces the fuzzy hierarchical method and sensitivity analysis; Section 5 is a case study. Based on the constructed index system and application of the fuzzy hierarchical method, a potential sustainable modular supplier of Jiangling Motors Co., Ltd. (JMC) company is evaluated and the stability of the method is discussed.

2. Literature Review

2.1. An Overview of Supplier Evaluation

Generally, there are two types of studies on supplier evaluation. One focuses on discussing the evaluation indexes while another centers on exploring the methodologies. Studies of supplier evaluation can be traced to 1960s. Dickson (1966) first examined the methods employed in studies about the selection of vendors in the U.S. [3]. Early research of supplier evaluation indices mainly focuses on factors such as cost, quality, price, delivery and service [4]. With changes of environment and extension of supplier roles and capability, some scholars started to pay close attention to other factors, such as market agility, innovation ability, information reception and processing ability, and environmental management ability [5–7]. The supplier selection index was gradually systematized and the evaluation criteria were diversified and became comprehensive. Concerning the methodology of supplier evaluation, both domestic and foreign scholars adopted almost the same methods. The main methods used are the analytic hierarchy process method (AHP) [8], activity-based costing method (ABC) [9], fuzzy theory [10], linear program method (LP) [11], neural networks [12,13], and data envelopment analysis method (DEA) [14]. In early research, some simple methods, such as the activity-based costing method (ABC), were mainly used. With the development of technology, some more advanced evaluation methods, such as data envelopment analysis method (DEA) and neural networks method, have been used. The trend for the use of supplier evaluation methods is the combination and synthesis of more than two methods. By overcoming the shortcomings of a single method, such a hybrid use of these methods can make the evaluation of suppliers more relevant and reliable.

2.2. An Overview of Sustainable Modular Supplier Evaluation

Generally speaking, modular production refers to such a network organization that connects module production enterprises and module assembly enterprises with the premise of the modularization of products. Usually the system integrator is the core enterprise in such modular production. It has a strong comprehensive strength and can satisfy customers' needs according to market demands by integrating different modules. Modular suppliers always conduct independent R&D activities according to the requirement of system integrators and possess certain high core competences. The relationship between modular suppliers and system integrators is no longer a mere dependent relationship but a mutually beneficial cooperative relationship [15–17].

At present, there are studies on the evaluation of modular suppliers are rare. Wang et al. (2016) carried out a fuzzy collaborative selection of strategic modular suppliers [18]. Because the evaluation is built on the entire process of enterprise production, it mainly focuses on production and technical capabilities, and fails to take full account of other characteristics of modular suppliers. Eggers et al. (2017) discussed supplier characteristics that are critical for module developments [19]. Based on case analysis, the authors found that technical factors, organizational factors and relationship factors are critical for supplier evaluation. The factors identified in Eggers et al. (2017) are more comprehensive, and provide an important reference for future research.

So far, a large proportion of studies have examined the issue of sustainable supplier evaluation [20–23]. For example, by using the qualitative research method, Walton et al. (1998) analyzed five companies in the furniture industry and identified a number of supply chain environmentally friendly practices [24]. By developing a novel approach first introduced by Li et al. (2008), Bai and Sarkis (2010) integrated the sustainability concept in their supplier selection model and the validity of the approach was further discussed [25]. Furthermore, taking account of sustainability in supplier selection, Büyükozkan and Çifçi, (2011) proposed a multi-criteria system that incorporated five criteria: service quality, financial performance, organization, technology and social responsibility, and environmental competencies [26]. By taking a triple-bottom-line approach, Sarkis and Dhavale (2015) further expanded the criteria for supplier selection and considered the environmental impacts [27]. To tackle complexities that arose, they developed a novel methodological approach.

Noticing the tendency for manufacturers to combine sustainability and modular production, some studies have explored such synthesis. For example, Ji et al. (2013) developed a systematic approach which put technical system modularity and material reuse modularity in a coherent framework [28]. In doing so, they discussed green modular design to increase material reuse efficiency. Ma and Kremer (2016) have reviewed more than 100 studies and elaborated how modular product design was associated with sustainability factors [29]. By reviewing these studies, this study finds that current research mainly focuses on the combination of modular design and sustainability. However, modular design is just a part of modular production. There is no study that particularly concentrates on the synthesis of modular supply activities and sustainability, and few studies have discussed the evaluation of sustainable modular suppliers.

2.3. An Overview of Organizational Identity

Albert and Whetten (1985) first proposed the concept "organizational identity (that is, OI)" [30]. They pointed out that organizational identity reflected the central, enduring and distinctive features of an organization, and mainly answers the question "who am I?". According to categorization, an organization should act based on its identity to avoid any inappropriate behavior [31]. This classical definition is, to different degrees, recognized by most scholars. However, there are still arguments about the definition of organizational identity. The enduring feature of organizational identity is especially criticized in contemporary studies [32].

Generally, the topics most discussed in the organizational identity field are (1) OI and organizational identification; (2) OI and change; (3) OI and management; and (4) OI and organizational image and reputation. In (1), organizational identification is a concept closely connected with OI. What is more, some similar but related concepts, such as social identification and inter-organizational identification, are also discussed; some interesting topics need to be further explored. For example, Rousseau (1998) discussed the link between organizational identification and organizational change and pointed out that a deep identification was hard to achieve with new forms of working [33]. Kreiner and Ashorth (2004) explicated the multiple outcomes of identification and argued that a positive reputation might prevent identification [34]. In (2), the research focus is moved to how organizational identity intertwines with organizational change, such as organizational growth, merger and acquisition, and entry into new markets. For example, Empson (2004) found that multiple identities existed after the acquisition of a company [35]. In an 18-year longitudinal study, Carlsen (2006) found that identity and organizational strategy are interlinked [36]. The results of Lowe et al. (2012) supported the view when studying a company's entry into international markets [37]. In (3), two kinds of management are focused on. One is the management of more than one identity. According to Albert and Whetten (2004), an organization is always developing more than one identity in its lifecycle [38]. Moreover, in many cases, an organization may have multiple identities. Hence, some scholars have suggested conducting active management of these identities [39]. Another type of management is the management of identity and identification of different stakeholders of an organization. Scott and Lane (2000) emphasized the importance of paying attention to stakeholders' identification [40]. By studying social venture capitalists' identification with different social components, Miller and Wesley (2010) proved that investment decisions both shape and are shaped by organizational identities [41]. In (4), the relationship between image and identity and identification are discussed in detail. For example, some scholars have suggested that image and identity are closely interlinked [2,32]. Whetten and Mackey (2002) emphasized that identity should be consistent with the images projected on others [42]. Further, Zachary et al. (2011) pointed out that projected organizational identity claims could be used to gain suitable franchise partners [43].

By reviewing these studies, this study finds there are two types of research on organizational identity. One studies it from the individual perspective while the other type studies it from an organizational perspective. Comparatively, until now the former studies have been relatively abundant while the latter are a topical study issue in organizational identity research. Current studies mainly center on the influence of organizational identity on network identification, companies' competitive strategies and behaviors, companies' international investment behaviors, mergers and acquisitions, and growth of start-ups. However, there is no application of organizational identity to the selection and evaluation of suppliers. Hence, the present paper is such an attempt. By applying organizational identity perspective to supplier evaluation, it helps manufacturers to better learn about their suppliers, which helps them better forecast suppliers' behaviors and evaluate the possibility of task implementation.

In summary, by reviewing the literature, this study finds there are very few studies discussing the selection and evaluation of sustainable modular suppliers. The evaluation of sustainable modular suppliers is a relatively new topic in the field. Concerning the methods used to evaluate suppliers, this study also finds that even in the abundant studies about the selection of general suppliers, the formative model is seldom used to establish the index system and the stability of the fuzzy method is rarely discussed. Apart from that, by looking at organizational identity theory, this study finds there is a possibility to apply organizational identity to supplier evaluation. The application of the organizational identity perspective is new. By adding the organizational identity cognition criterion, the sustainable modular supplier evaluation is more comprehensive and predictive.

3. Empirical Study of Evaluation Criteria

The following parts of this paper follow the research process step by step. The corresponding methodology of each step is shown in Figure 1.

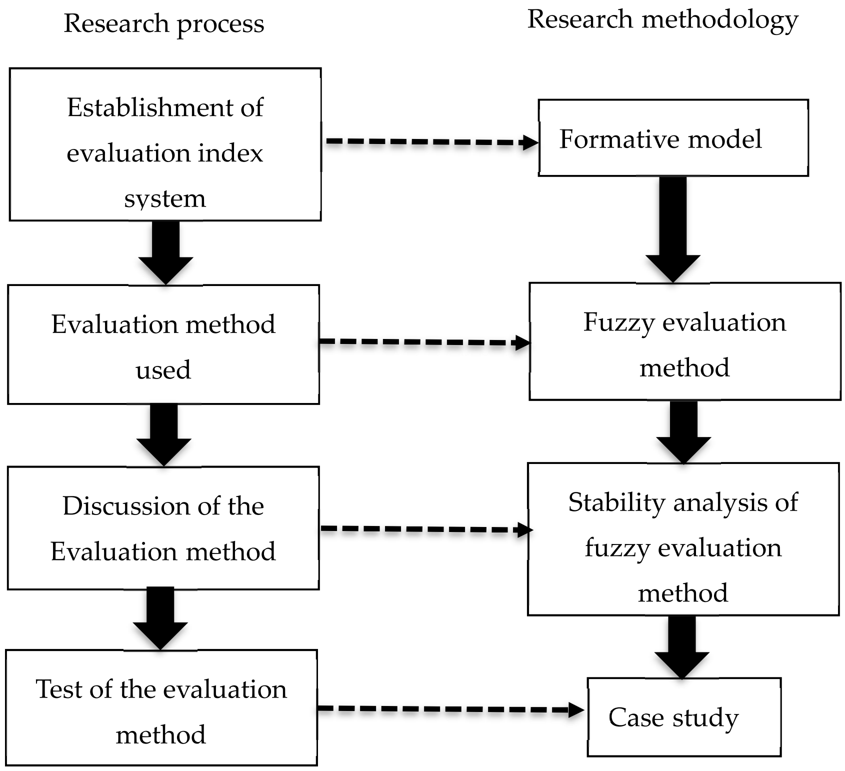

Figure 1. Research process and research methodologies.

First, in this section, this author builds the index system of sustainable modular supplier evaluation from three perspectives.

3.1. Item Primary Selection

Supplier selection and evaluation discussed in this paper is a process conducted by a manufacturer to use quantitative assessment to evaluate and approve potential suppliers. According to this line of thinking, the design of supplier evaluation criteria should be geared to the practical needs of the manufacturer. Hence, this is the basic logic of the design of the evaluation index system.

In practice, for manufacturers producing complicated modular products, suppliers' ability to satisfy their modular production requirements is a basic criterion to evaluate the potential suppliers. Sustainability requirements are another very important criterion. Firstly, society and government are attaching more importance to environmental protection and sustainable development. Correspondingly, sustainable regulations and legislation for manufacturers are being formulated. Hence, to undertake such obligations, manufacturers need the cooperation and support from their suppliers. Secondly, a sustainability criterion provides a perspective to reflect some important but often ignored qualities of suppliers, such as their credibility and integrity. It can also provide clues to further assess the production advancement of suppliers, such as the energy-saving ability of suppliers. Therefore, another dimension of the evaluation index system is sustainability. Moreover, this study takes suppliers' identity cognition into account to evaluate suppliers. According to organizational identity theory, organizational identity is the core, enduring and distinctive feature of an organization. Based on this, an organization categorizes itself and accordingly takes actions. By evaluating a supplier's cognition of its organizational identity, the manufacturer can know whether the supplier's understanding of its businesses and competitiveness is in line with the manufacturer. In doing so, the manufacturer can learn better about the supplier and therefore better forecast its behaviors and reduce the risk [43].

Based on the above analysis, this study divides the index system of sustainable modular supplier evaluation into three aspects: modular competency, sustainability, and organizational identity cognition. Then, an extensive literature review and enterprise interviews were conducted to identify the main elements in each aspect. The university where the author works has good alumni resources. Hence, the author took full advantage of these resources. Helped by the alumni associations in Guangdong province, the author was able to contact related modular production enterprises and conduct in-depth investigations of these enterprises to determine the primary set of the index. The author selected five modular production enterprises in Shenzhen to conduct field interviews. The basic information of the five enterprises is shown in Table 1.

Table 1. Basic information of enterprises interviewed.

No	Firm Name	Industry	Interviewees
1	BYD Company Limited	Automobile, new energy and rail transit	Executive director, deputy purchasing director, production director
2	Shenzhen Huaxun ark Science & Technology Co., Ltd.	Semiconductor devices, microwave systems, millimeter wave systems, and terahertz micro electronics systems	General manager, purchasing directors
3	Hasee Computer Co., Ltd.	Laptops, desktops, LCD computers, LCD LCDs, and smart TVs	Head of purchasing department, head of production department
4	Sunwoda Electronic Co., Ltd.	Lithium ion battery module	General manager, head of purchasing department, head of quality management department
5	Changan PSA Automobiles Co. Ltd.	Automobile	General manager, purchasing deputy directors, supply section chief

Before the formal interview, I confirmed the specific interview schedule with the managers. Then I carried out the semi-structured interviews. All interviews were conducted between January 2017 and May 2017. To avoid the fatigue of interviewees, I controlled the semi-structured interviews within 45–60 min. With the consent of the interviewees, I recorded the interviews and organized the recordings after the interviews. Regarding sustainable modular supplier evaluation criteria and index, this study addressed three types of questions: (1) questions about the features of modular suppliers, such as "what characteristics constitute a modular supplier?"; (2) questions about the sustainability of suppliers, such as "how do you judge your suppliers to be sustainable?"; and (3) questions about the organizational identity cognition such as "what do you think are the core features of a supplier?"

Combining the literature review and results of interviews, this study derived the indexes of sustainable modular suppliers. Finally, this study invited three professors from the school of business administration of Jiangxi University of Finance and Economics and two doctoral students majoring in operations management to discuss the clarity and effectiveness of the evaluation criteria. Taking account of their suggestions, the indexes were further condensed and were eventually modified from 25 to 21. Indexes of sustainable modular supplier evaluation are shown in Table 2. The sources of these indexes are also presented.

Table 2. Indexes of sustainable modular supplier evaluation.

First Tier Index	Second Tier Index	Third Tier Index	References
Modular Competency Criteria (MC)	Modular design and production competency (MCD)	Professional industry knowledge (MC1)	[44]
		Technical development capability (MC2)	[45,46]
		New technological identification (MC3)	[45]
		Value analysis capability (MC4)	[47]
	Modular management competency (MCM)	Engineering support (MC5)	[19]
		Integration capability (MC6)	[48]
		Relationship management capability (MC7)	[14,49]
		Compatibility capability (MC8)	[46]

Table 2. *Cont.*

First Tier Index	Second Tier Index	Third Tier Index	References
Sustainability Criteria (SC)	Social responsibility implementation (SCR)	Contribution to the government (SC1)	[25,50]
		Contribution to the investors (SC2)	[25,50]
		Contribution to the employees (SC3)	[51,52]
		Contribution to the suppliers (SC4)	[53]
		Contribution to the community (SC5)	[25,50]
	Environmental management (SCM)	Having environmental management certification (SC6)	[53,54]
		Protecting environmental resources (SC7)	[50,55]
		Implementing clean production (SC8)	[56]
		Passing ISO (International Organization for Standardization)14000 certification (SC9)	[57]
Organizational Identity Cognition Criteria (OI)	Cognition of the core features (OIC)	Cognition of the enterprise's core value (OI1)	[58–60]
		Cognition of the enterprise's vision and mission (OI2)	[58–60]
	Cognition of the distinctive features (OID)	Cognition of the enterprise's core competitiveness and businesses (OI3)	[58–60]
		Cognition of the resources needed in the enterprise's core businesses (OI4)	[58–60]

3.2. Item Optimization

In constructing the evaluation index system, the logic is in first designing the indexes of sustainable modular supplier based on the literature review and field study. In this step, this study mainly refers to the scale development theory. Then, these indexes are designed into scales and, by validity and reliability tests, these indexes are further purified and optimized.

As such, according to the scale development theory, it is noted that when we further test the scales, we should pay much attention to the relationship between the items (i.e., observed variables) and the construct (i.e., latent variable) [61]. Generally, there are reflective indicators and formative indicators, of which the former is said to reflect latent variable while the latter has formed the latent property in the past. From the analysis of Section 3.1, it is known that the evaluation index system consists of three perspectives: the modular production perspective, the sustainability perspective, and the organizational identity perspective. The items were mainly designed from the three perspectives. So according to Bollen (1989), the measurement model built in this paper would be a formative model [62]. Generally speaking, reflective measures are expected to have high intercorrelations. Hence, conventional exploratory and confirmatory factor analysis can be used as a test. However, different formative measures are not expected to correlate. Some scholars have pointed out that the traditional method is probably not suitable for testing a formative model [63].

Currently, a well-acknowledged method to analyze formative model is called partial least squares (PLS) [64]. Compared with the maximum likelihood covariance matrix method, PLS does not require interval scaling of the data. Moreover, the importance of sample size for maximum likelihood estimation is not relevant in PLS either. In addition, PLS can avoid factor indeterminacy and modeling with the existence of multicollinearity. Thus, it is easier to explain the regression coefficients of the variables [64]. PLS analysis was conducted by Smart-PLS software.

Next, this paper will first discuss the model identification issue and then apply the PLS method to test the validity and reliability of the indexes.

According to Bollen and Devis (2009), for a formative model to be identifiable, it should satisfy at least two principles: the t principle and the scaling rule [65]. From the model, it can be easily found that it satisfies both of these principles. Moreover, there is the third principle, that is, the 2+emitted paths principle [66]. One of the methods to satisfy the principle is to add two reflective indicators in a formative model based on theoretical analysis [65].

According to the principle, this study adds two general items which summarizes each aspect (MC01, MC02; SC01, SC02; OI01, OI02). In doing so, the model built is identifiable.

As for the validity, Bollen (1989) proposed that γ reflects the influence of formative indicators on the latent variables [62]. It is an indicator of validity. If a γ coefficient has not reached the significant level, then it indicates that the corresponding formative indicator is not valid and should be deleted. Moreover, according to Diamantopoulos and Winklhofer (2001), validity can be tested by calculating the correlations between the indicators and the criteria. This study can add a general indictor which summarizes the nature of the latent variable and it works as the "criterion" [63]. Then, this study calculates the correlation between the indicators and the criterion. This study remains the indicators with high correlation value and deletes those indicators with low or no correlation value.

I travelled to Shenzhen, Guangzhou, and Wuxi and sent 250 questionnaires to local modular production enterprises (The questionnaire please see Appendix B). Altogether, this study collected 174 valid questionnaires with an effective rate of 69.6%.

According to Bollen's (1989) method, by running the Smart-PLS software, this study calculated the γ coefficients and the t values [62] (Table 3). According to Diamantopoulos and Winklhofer (2001), for each aspect, this study added two global items that respectively summarizes one part of the aspect [63]. For modular competency criterion, this study added modular design and production competency (MCD0) and modular management competency (MCM0). For sustainable development capability, this study added social responsibility implementation (SCR0) and environmental management (SCM0). For identity cognition capability, this study added cognition of the core features (OIC0) and cognition of the distinctive features (OID0). Then this study calculated the correlations between the latent variables and the added global items as well as the correlations between the added global items and each aspect. Results are shown in Table 4. According to the criteria for judgment in Table 5, this study finds that the γ coefficients of MC3 and MC8 are much smaller than 0.6. Hence, this study should delete these two indicators. According to the criteria, except for MC3 and MC8, all the other indicators should be retained.

As for reliability, Diamantopoulos (2005) recommended the use of the retest method to test the reliability of a formative model [66]. The retest reliability refers to the degree of consistency by using the same questionnaires to test the same group of informants at two different times. Usually this study used the product moment correlation to calculate retest reliability: $R_{xx} = \frac{\frac{\sum X_1 X_2}{n} - X_1 X_2}{S_1 S_2}$, where X_1 and X_2, respectively, denote the value result of each test. S_1 and S_2 respectively denote the standard error of each test. n denotes the total number of informants.

The author travelled to the modular production enterprises that accepted the survey in June 2017 and sent them the questionnaires with the revised 19 items. The survey interval was two weeks. According to scholars, for retest reliability, the general intervals are 2–4 weeks [61]. Based on the data collected, following the above formula, this study could calculate the retest reliability; $R_{xx} = 0.815$, which indicates the reliability of the indexes is acceptable.

Table 3. Weights and *t* values of indicators.

Dimension	Indicator	Weight (γ Coefficient)	*t* Value	Dimension	Indicator	Weight (γ Coefficient)	*t* Value	Dimension	Indicator	Weight (γ Coefficient)	*t* Value
Modular competency (MC)	MC1	0.6539	4.503	Sustainability (SC)	SC1	0.7247	5.421	Organizational identity cognition (OI)	OI1	0.6739	4.363
	MC2	0.7841	6.364		SC2	0.6338	2.836		OI2	0.6224	3.048
	MC3	0.2753	2.067		SC3	0.5842	2.369		OI3	0.6593	4.604
	MC4	0.6037	2.573		SC4	0.6421	3.073		OI4	0.5881	2.348
	MC5	0.6439	2.936		SC5	0.5903	2.410				
	MC6	0.6328	2.745		SC6	0.6741	4.588				
	MC7	0.6080	2.594		SC7	0.6194	2.974				
	MC8	0.0710	0.7318		SC8	0.7003	5.422				
					SC9	0.6148	2.681				

Table 4. The coefficients, T values and R^2.

Path	Correlation	T Value	R^2	Path	Correlation	T Value	R^2
MCD → MCD0	0.6035	13.6841	0.3538	SCR → SCR0	0.6538	15.6372	0.3143
MCM → MCM0	0.6763	14.8935	0.3790	SCM → SCM0	0.5134	13.5129	0.3273
MCD0 → MC	0.2864	3.7042	0.3593	SCR0 → SC	0.2463	3.6937	0.3236
MCM0 → MC	0.1860	2.1743		SCM0 → SC	0.2153	3.4943	
OIC → OIC0	0.5283	11.3804	0.2639				
OID → OID0	0.5672	12.0319	0.2973				
OIC0 → OI	0.3045	5.2984	0.2851				
OID0 → OI	0.2841	3.7640					

Table 5. Criteria for formative model.

Category	Content	Standard
Statistical significance indicator	Significance of γ coefficient	T value should be bigger than 1.96
	Significance of path coefficient	T value should be bigger than 1.96
	Significance of Chi-Square test	It should not be significant
	GFI	It should be bigger than 0.9
Statistical validity indicator	γ coefficient	Generally, it should be bigger than 0.6. The ideal value should be bigger than 0.7.
	Path coefficient	Generally, it should be bigger than 0.2. The ideal value should be bigger than 0.3.
	R^2	Generally, it should be bigger than 0.2

4. Fuzzy Evaluation Method and Stability Analysis

Secondly, in this section, a fuzzy evaluation method is used and the stability analysis of the method is further discussed.

To select and evaluate sustainable modular suppliers, different factors must be considered. The factor system was discussed in Section 3. However, many of these factors are qualitative and this qualitative information is by nature ambiguous. Based on fuzzy sets, the fuzzy evaluation method can solve this problem by giving a comprehensive evaluation of levels [67]. Hence, this paper adopts the fuzzy evaluation method to evaluate and select the sustainable modular suppliers.

However, this method depends much on expert subjective judgments. If an expert underestimates or overestimates a factor, it may influence the final result. Hence, this study further discusses the stability of the method. That is, if an expert underestimates or overestimates a factor, whether the result is stable is discussed.

4.1. Determining the Weights

Suppose $Q = (q_1, q_2, \ldots\ldots, q_t)$, where q_i denotes an expert consulted. $P = (p_1, p_2, \ldots\ldots, p_n)$, where p_i denotes an evaluation perspective of sustainable modular supplier selection. $F = (f_1, f_2, \ldots\ldots, f_n)$, where f_i denotes a factor of a perspective of sustainable modular supplier selection. $U = (u_1, u_2, \ldots\ldots, u_m)$, where u_i denotes a criterion of a factor of sustainable 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 relatively important is given 1 while the less important is given 0. If the importance is considered the same, then 0.5 is given to each index. Thus, any expert can have the following pairwise comparison table (see Table 6).

Table 6. The pairwise comparison matrix of an expert.

	u_1	u_2	u_3	u_m
u_1		1	0	0
u_2	0		1	1
u_3	1	0		0
u_m	1	0	1	

Then, for each criterion, this study sums the values of all the experts (see Table 7).

Table 7. The pairwise comparison matrix of all experts.

	u_1	u_2	u_3	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	$\sum_{j=1}^{t} x_{21j}$		$\sum_{j=1}^{t} x_{23j}$	$\sum_{j=1}^{t} x_{2mj}$	$\sum_{k=1}^{m}\sum_{j=1}^{t} x_{2kj}$
u_3	$\sum_{j=1}^{t} x_{31j}$	$\sum_{j=1}^{t} x_{32j}$		$\sum_{j=1}^{t} x_{3mj}$	$\sum_{k=1}^{m}\sum_{j=1}^{t} x_{3kj}$
u_m	$\sum_{j=1}^{t} x_{m1j}$	$\sum_{j=1}^{t} x_{m2j}$	$\sum_{j=1}^{t} x_{m3j}$		$\sum_{k=1}^{m}\sum_{j=1}^{t} x_{mkj}$

Then the study can calculate the weight of u_i: $a_{u_i} = \frac{\sum_{k=1}^{m}\sum_{j=1}^{t} x_{ikj}}{\sum_{k=1}^{m}\sum_{j=1}^{t} x_{1kj}+\sum_{k=1}^{m}\sum_{j=1}^{t} x_{2kj}+\ldots\ldots+\sum_{k=1}^{m}\sum_{j=1}^{t} x_{mkj}}$. Using the pairwise comparison method, the study can also calculate the weight of each factor. Hence, the final weight of each criterion is $a_{U_i} = a_{p_i} \times a_{f_i} \times a_{u_i}$.

4.2. Establishing Membership and Conducting Comprehensive Evaluation

Although the study can get definite comments on each criterion, the "boundary" is relatively ambiguous. Therefore, the membership degree of each criterion to the evaluation set is calculated. In doing so, this study needs to grade each criterion based on specialist consultancy. The study can obtain 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 has $r_{ji} = \frac{v_{ji}}{\sum v_{jn}}$. $\sum v_{jn} = v_{j1} + v_{j2} + v_{j3} + v_{j4}$. The study can obtain the evaluation membership matrix of the criteria of modular supplier selection.

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

4.3. Calculating the Dispersion Degree

According to the above method, the study can get the comprehensive evaluation of a supplier. If there are two suppliers and their comprehensive evaluations are similar, then more than 50% of the evaluation is general and good. However, 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. Hence, the study can easily determine if the first supplier is better than the second because the second does not develop evenly and therefore its risk is bigger than the first one.

Considering such circumstances, this study introduces a dispersion degree. Referring to the definition of variance, the study uses $L_j = \sum_{i=1}^{m} a_i (r_{ij} - b_j)^2$ to reflect the dispersion degree of criterion

u_j, where $b_j = \sum_{i=1}^{m} a_i r_{ij}$. If L_j is large, then the comprehensive evaluation should move down. The study constructs $S_j = b_j - ZL_j$, where Z denotes the parameter which a decision maker can control. It is designed to reflect the adjustment that the dispersion causes to the evaluation judgment.

The study supposes if the accumulative evaluation of level N is bigger than 0.5, then the comprehensive evaluation of the supplier is N level and should satisfy: $\sum_{j=1}^{N-1} p_j \leq 0.5 \leq \sum_{j=1}^{N} p_j$. Based on $S_j = b_j - ZL_j$, the study can modify the judgment criterion as:

$$\sum_{j=1}^{N-1} S_j \leq 0.5 - Z(N-1)\overline{L} \tag{1}$$

$$\sum_{j=1}^{N} S_j \geq 0.5 - ZN\overline{L} \tag{2}$$

where $\overline{L} = \frac{1}{n}\sum_{j=1}^{n} L_j$. 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.

4.4. Stability Analysis

Because experts' erroneous judgment mainly occurs in adjacent levels, the study supposes that the erroneous judgment of one criterion occurs in adjacent evaluation levels of the criterion. 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 Equations (1) and (2). Namely, $k \leq N-1$, $k' \leq N-1$.
(2) The positive error has an impact on Equation (1), both positive and negative errors have impact on Equation (2). Namely, $k \leq N-1$, $k' = N$.
(3) The negative error has an impact on Equation (1), both positive and negative error have impact on Equation (2). Namely, $k = N$, $k' \leq N-1$.
(4) Both positive and negative errors do not have an impact on Equation (1), the negative error has an impact on Equation (2). Namely, $k > N$, $k' = N$.
(5) Both positive and negative errors do not have impact on Equation (1), the positive error has an impact on Equation (2). Namely, $k = N$, $k' > N$.
(6) Both positive and negative errors do not have impact on the two equations. Namely, $k > N$, $k' > N$.

This study makes:

$$A_h = (1 - a_h)a_h$$

$$B_{hk} = 1 - 2Z(r_{hk} - b_k)$$

$$C_{hkk'} = (r_{hk} - b_k) - (r_{hk'} - b_{k'})$$

$$D_{N-1} = 0.5 - (N-1)Z\overline{L} - \sum_{j=1}^{N-1} S_j \geq 0$$

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

$$F_{hkk'(N-1)} = B_{hk} + \frac{2(N-1)ZC_{hkk'}}{n}$$

$$G_{hkk'} = B_{hk'} - \frac{2(N-1)ZC_{hkk'}}{n}$$

$$H_N = \sum_{j=1}^{N} S_j - 0.5 + NZ\overline{L} \geq 0$$

Following the method proposed by He (2018) [68], this study conducts stability analysis. For detailed mathematical derivations of the stability analysis please see Appendix C.

5. Case Analysis

Thirdly, in this section, this study uses the information of a supplier of Jiangling Motors Co., Ltd. in Nanchang city of China as an example to conduct a case analysis. By using the fuzzy evaluation method and conducting the stability analysis, this study discusses the evaluation of the supplier as well as its stability.

5.1. Case Description

Jiangling Motors Co., Ltd. (abbreviated JMC hereafter), is a key player in China's automotive industry with commercial vehicle manufacture as its core competitiveness. It was established in 1968 and went public in 1993. It has been ranked as one of China's Top 100 Listed Companies for three consecutive years. Currently there are 14,036 people working for the company. Year 2014, JMC hit a record high in its business indexes with sales revenue reaching CNY 25.5 billion and volume exceeding 276,000 units.

An 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, the JMC company works as production integrator and has built relationships with different modular suppliers. In addition, JMC is pursuing sustainability development. In recent years, JMC has paid much attention to its effect on society and has received various environmental protection awards. To respond to such requirements, selecting suppliers who are capable of modular production activities while satisfying sustainability criteria appears particularly important. Hence, in this section, the index system and the fuzzy method are used to evaluate one of its potential suppliers.

5.2. Calculating the Weights

Based on the analysis of Section 3, the index system of modular supplier selection can be divided into two levels: the first level is the four factors of modular supplier selection and the second level is the items of each factor. The index system is shown in Table 8.

This study employs the pairwise comparison method to calculate the weights. A total of 15 specialists were invited to make the pairwise comparison. Among these, five were professors, five were associate professors and five were Ph.D. students. All were from the school of business administration of Jiangxi University of Finance and Economics.

The pairwise comparison matrixes please see Appendix A. The results are shown in Table 9.

Table 8. Hierarchical structure of the index system of modular supplier selection.

The Target Layer	The First Layer	The Second Layer	The Third Layer
The index system of sustainable modular supplier selection	Modular competency A_1	Modular design and production competency B_1	Professional industry knowledge C_1
			Technical development capability C_2
			Value analysis capability C_3
		Modular management competency B_2	Engineering support C_4
			Integration capability C_5
			Relationship management capability C_6
	Sustainability A_2	Social responsibility implementation B_3	Contribution to the government C_7
			Contribution to the investors C_8
			Contribution to the employees C_9
			Contribution to the suppliers C_{10}
			Contribution to the community C_{11}
		Environmental management B_4	Having environmental management certification C_{12}
			Protecting environmental resources C_{13}
			Implementing clean production C_{14}
			Passing ISO14000 certification C_{15}
	Organizational identity cognition A_3	Cognition of the core features B_5	Cognition of the enterprise's core value C_{16}
			Cognition of the enterprise's vision and mission C_{17}
		Cognition of the distinctive features B_6	Cognition of the enterprise's core competitiveness and businesses C_{18}
			Cognition of the resources needed in the enterprise's core businesses C_{19}

Table 9. Weights of factors.

Factor	First Tier Weight	Second Tier Weight	Third Tier Weight	Synthetic Weight
Professional industry knowledge	0.322	0.533	0.389	0.0668
Technical development capability	0.422	0.533	0.389	0.0875
Value analysis capability	0.256	0.533	0.389	0.0531
Engineering support	0.322	0.467	0.389	0.0585
Integration capability	0.389	0.467	0.389	0.0707
Relationship management capability	0.289	0.467	0.389	0.0525
Contribution to the government	0.213	0.433	0.289	0.0267
Contribution to the investors	0.2	0.433	0.289	0.0250
Contribution to the employees	0.223	0.433	0.289	0.0279
Contribution to the suppliers	0.194	0.433	0.289	0.0243
Contribution to the community	0.17	0.433	0.289	0.0213
Having environmental management certification	0.222	0.567	0.289	0.0364
Protecting environmental resources	0.211	0.567	0.289	0.0346
Implementing clean production	0.294	0.567	0.289	0.0482
Passing ISO14,000 certification	0.273	0.567	0.289	0.0447
Cognition of the enterprise's core value	0.6	0.533	0.322	0.1030
Cognition of the enterprise's vision and mission	0.4	0.533	0.322	0.0687
Cognition of the enterprise's core competitiveness and businesses	0.6	0.467	0.322	0.0902
Cognition of the resources needed in the enterprise's core businesses	0.4	0.467	0.322	0.0601

5.3. Establishing Membership and Conducting Comprehensive Evaluation

Based on the above analysis, this author selected a group of 10 experts. These mainly came from two sources: five were managers, directors or engineers of the production and procurement departments of the JMC company; the other fiver were college professors in logistics and supply chain management. The alternative answers include "good", "general", "fairly weak" and "weak" and the author assigned each answer a score from 1–4, respectively. The author sent questionnaires and related information (including business archives, financial records, and company website) of the supplier by email to ensure each respondent was not aware of other answers. The fuzzy evaluation matrix of the supplier was then determined (Table 10).

Table 10. Fuzzy evaluation matrix of the supplier.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}
V_1	0.3	0.4	0.2	0.5	0.3	0.2	0.4	0.2	0.2	0.3	0.3	0.4	0.2	0.3	0.6	0.3	0.4	0.3	0.4
V_2	0.5	0.3	0.3	0.3	0.4	0.3	0.4	0.4	0.3	0.3	0.2	0.3	0.4	0.4	0.4	0.4	0.3	0.4	0.3
V_3	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.3	0.3	0.2	0.3	0.3	0.3	0	0.3	0.2	0.2	0.3
V_4	0	0.1	0.2	0	0.1	0.2	0	0.2	0.2	0.1	0.3	0	0.1	0	0	0	0.1	0.1	0

Then the study was able to evaluate the supplier:

$$\begin{aligned}
P_{B_1} &= A_{C_1–C_3} \times R_{C_1–C_3} \\
&= \begin{pmatrix} 0.322 & 0.422 & 0.256 \end{pmatrix} \times \begin{bmatrix} 0.3 & 0.5 & 0.2 & 0 \\ 0.4 & 0.3 & 0.2 & 0.1 \\ 0.2 & 0.3 & 0.3 & 0.2 \end{bmatrix} \\
&= \begin{pmatrix} 0.3166 & 0.364 & 0.2256 & 0.0934 \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
P_{B_2} &= A_{C_4–C_6} \times R_{C_4–C_6} \\
&= \begin{pmatrix} 0.322 & 0.389 & 0.289 \end{pmatrix} \times \begin{bmatrix} 0.5 & 0.3 & 0.2 & 0 \\ 0.3 & 0.4 & 0.2 & 0.1 \\ 0.2 & 0.3 & 0.3 & 0.2 \end{bmatrix} \\
&= \begin{pmatrix} 0.3355 & 0.3389 & 0.2289 & 0.0967 \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
P_{B_3} &= A_{C_7–C_{11}} \times R_{C_7–C_{11}} \\
&= \begin{pmatrix} 0.213 & 0.2 & 0.223 & 0.194 & 0.17 \end{pmatrix} \times \begin{bmatrix} 0.4 & 0.4 & 0.2 & 0 \\ 0.2 & 0.4 & 0.2 & 0.2 \\ 0.2 & 0.3 & 0.3 & 0.2 \\ 0.3 & 0.3 & 0.3 & 0.1 \\ 0.3 & 0.2 & 0.2 & 0.3 \end{bmatrix} \\
&= \begin{pmatrix} 0.279 & 0.3243 & 0.2417 & 0.155 \end{pmatrix}
\end{aligned}$$

$$\begin{aligned}
P_{B_4} &= A_{C_{12}–C_{15}} \times R_{C_{12}–C_{15}} \\
&= \begin{pmatrix} 0.222 & 0.211 & 0.294 & 0.273 \end{pmatrix} \times \begin{bmatrix} 0.4 & 0.3 & 0.3 & 0 \\ 0.2 & 0.4 & 0.3 & 0.1 \\ 0.3 & 0.4 & 0.3 & 0 \\ 0.6 & 0.4 & 0 & 0 \end{bmatrix} \\
&= \begin{pmatrix} 0.383 & 0.3778 & 0.2181 & 0.021 \end{pmatrix}
\end{aligned}$$

$$
\begin{aligned}
P_{B_5} &= A_{C_{16}-C_{17}} \times R_{C_{16}-C_{17}} \\
&= \begin{pmatrix} 0.6 & 0.4 \end{pmatrix} \times \begin{bmatrix} 0.3 & 0.4 & 0.3 & 0 \\ 0.4 & 0.3 & 0.2 & 0.1 \end{bmatrix} \\
&= \begin{pmatrix} 0.34 & 0.36 & 0.26 & 0.04 \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
P_{B_6} &= A_{C_{18}-C_{19}} \times R_{C_{18}-C_{19}} \\
&= \begin{pmatrix} 0.6 & 0.4 \end{pmatrix} \times \begin{bmatrix} 0.3 & 0.4 & 0.2 & 0.1 \\ 0.4 & 0.3 & 0.3 & 0 \end{bmatrix} \\
&= \begin{pmatrix} 0.34 & 0.36 & 0.24 & 0.06 \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
P_{A_1} &= A_{B_1-B_2} \times R_{B_1-B_2} \\
&= \begin{pmatrix} 0.533 & 0.467 \end{pmatrix} \times \begin{bmatrix} 0.3166 & 0.3644 & 0.2256 & 0.0934 \\ 0.3355 & 0.3389 & 0.2289 & 0.0967 \end{bmatrix} \\
&= \begin{pmatrix} 0.3254 & 0.3525 & 0.2272 & 0.0949 \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
P_{A_2} &= A_{B_3-B_4} \times R_{B_3-B_4} \\
&= \begin{pmatrix} 0.433 & 0.567 \end{pmatrix} \times \begin{bmatrix} 0.279 & 0.3243 & 0.2417 & 0.155 \\ 0.383 & 0.3778 & 0.2181 & 0.021 \end{bmatrix} \\
&= \begin{pmatrix} 0.3380 & 0.3546 & 0.2283 & 0.0791 \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
P_{A_3} &= A_{B_5-B_6} \times R_{B_5-B_6} \\
&= \begin{pmatrix} 0.533 & 0.467 \end{pmatrix} \times \begin{bmatrix} 0.34 & 0.36 & 0.26 & 0.04 \\ 0.34 & 0.36 & 0.24 & 0.06 \end{bmatrix} \\
&= \begin{pmatrix} 0.34 & 0.36 & 0.2507 & 0.0493 \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
P_A &= A_{A_1-A_3} \times R_{A_1-A_3} \\
&= \begin{pmatrix} 0.389 & 0.289 & 0.322 \end{pmatrix} \times \begin{bmatrix} 0.3254 & 0.3525 & 0.2272 & 0.0949 \\ 0.3380 & 0.3546 & 0.2283 & 0.0791 \\ 0.34 & 0.36 & 0.2507 & 0.0493 \end{bmatrix} \\
&= \begin{pmatrix} 0.3337 & 0.3555 & 0.2351 & 0.0757 \end{pmatrix}
\end{aligned}
$$

So

$$b_1 = 0.3337,$$

$$b_2 = 0.3555,$$

$$b_3 = 0.2351,$$

$$b_4 = 0.0757$$

The study could also calculate the dispersion degree:

$$L_1 = 0.009951,$$

$$L_2 = 0.004230,$$

$$L_3 = 0.004961,$$

$$L_4 = 0.006288,$$

$\overline{L} = 0.0063575$ and $Z = 0.5$. According to $S_j = b_j - ZL_j$, the adjusted evaluation judgment vector is:

$$\begin{pmatrix} 0.3287 & 0.3534 & 0.2326 & 0.073 \end{pmatrix}$$

According to $\sum_{j=1}^{N-1} S_j \leq 0.5 - Z(N-1)\overline{L}$ and $\sum_{j=1}^{N} S_j \geq 0.5 - ZN\overline{L}$, it is known the results satisfies these two formulae. Hence, the study can conclude that the supplier is a generally sustainable modular supplier.

5.4. Stability Analysis

According to the calculation of Section 5.3, it is known that $N = 2$. From the calculation of weights, it is known that cognition of the enterprise's core value (C_{16}) has the highest weight among all the indexes. Hence, the study supposes some experts overestimated the index. Then the study discusses whether their judgment may influence the final results.

According to the analysis of Section 4, in the circumstance that experts overestimate the cognition of the enterprise's core value (C_{16}), it is known $k = 1, k' = 2$. There are four levels of evaluation, that is, $n = 4$, and $Z = 0.5$.

Hence, $k \leq N-1, k' = N$, that is, circumstance (2).

$$A_h = (1 - a_h)a_h = (1 - 0.103) \times 0.103 = 0.0924$$

$$B_{hk} = 1 - 2Z(r_{hk} - b_k) = 1 - 2 \times 0.5 \times (0.3 - 0.3337) = 1.0337$$

$$C_{hkk'} = (r_{hk} - b_k) - (r_{hk'} - b_{k'}) = (0.3 - 0.3337) - (0.4 - 0.3555) = -0.0782$$

$$D_{N-1} = 0.5 - (N-1)Z\overline{L} - \sum_{j=1}^{N-1} S_j = 0.5 - (2-1) \times 0.5 \times 0.0063575 - 0.3287 = 0.16812$$

$$E_{hkk'(N-1)} = \left[B_{hk} - B_{hk'} + \tfrac{2(N-1)ZC_{hkk'}}{n}\right] = (1.0337 - 0.9555) + \tfrac{2\times(2-1)\times 0.5\times(-0.0782)}{4} = 0.05865$$

$$F_{hkk'(N-1)} = B_{hk} + \frac{2(N-1)ZC_{hkk'}}{n} = 1.0337 + \frac{2 \times (2-1) \times 0.5 \times (-0.0782)}{4} = 1.01415$$

$$G_{hkk'} = B_{hk'} - \frac{2(N-1)ZC_{hkk'}}{n} = 0.9555 - \frac{2 \times (2-1) \times 0.5 \times (-0.0782)}{4} = 0.97505$$

$$H_N = \sum_{j=1}^{N} S_j - 0.5 + NZ\overline{L} = (0.3287 + 0.3534) - 0.5 + 2 \times 0.5 \times 0.0063575 = 0.18846$$

$$n - 2(N-1) = 4 - 2 \times (2-1) = 2 > 0$$

$$a^2{}_h F^2{}_{hkk'(N-1)} - 4\tfrac{n-2(N-1)}{n} ZA_h D_{N-1} = 0.103^2 \times 1.01415^2 - 4 \times \tfrac{4-2(2-1)}{4} \times 0.5 \times 0.0924 \times 0.16812 = -0.00462329 < 0$$

Hence, the inequality always holds.

In this case, it satisfies the conditions of circumstance 2. By calculation, this study finds the inequality always holds. The result indicates that even if all 10 experts overestimate the cognition of the enterprise's core value, it would not influence the final result. We can say the comprehensive evaluation is stable. In fact, according to Section 4 we can calculate the number of experts who make erroneous judgment but still can be trusted. In doing so, the stability analysis helps us to make further judgment about the validity of the results. The stability analysis is an exploration of such a question but it is quite inspiring. Following this line of thinking, it is possible to infer the maximum tolerable number of experts' erroneous judgments on multiple indexes. Such analysis has practical significance and can be used by managers to further estimate to which degree we can trust the results.

6. Conclusions

In this paper, based on a formative model, the author builds an index system for evaluating sustainable modular suppliers. It applies the fuzzy evaluation method to evaluate suppliers and its stability is discussed. The main findings and contributions are as follows:

(1) This paper introduces an organizational identity perspective into the design of the evaluation index system. According to the organizational identity theory, organizational identity is the unanimous understanding of most members of an organization about "who we are as an organization" [1]. It is the central, enduring and distinctive understanding about an organization [2]. An organization categorizes itself and accordingly takes actions by the cognition of its organizational identity. As such, the study proposes that by taking the supplier's cognition of its organizational identity into account, a manufacturer can learn more about a supplier and therefore better forecast the supplier's behaviors and reduce risk. Therefore, in designing the evaluation index system, the study adds the organizational identity perspective, which has not been discussed before.

(2) The study uses the formative model to evaluate the validity and reliability of the index system. In designing the index system, the author decomposes the concept of sustainable modular supplier into its three aspects: modular competency, sustainability, and organizational identity cognition. Based on a literature review and interviews, the author designs the indexes for each aspect. Different from previous factor analyses of the index system, the study adopts a formative model to build the index system, which better follows the design logic and is more appropriate for the index analysis.

(3) In this paper a fuzzy evaluation method is adopted to evaluate and select sustainable modular suppliers. Considering that this method depends largely on an expert's subjective judgment, the stability of the method is discussed. By introducing the dispersion degree, the study modifies the comprehensive evaluation vector. Based on this, the study discusses the different circumstances and the range of subjective judgment errors in each circumstance. Such stability analysis helps us to understand the degree to which results can be trusted. Lastly, by applying this method to a practical case, the author shows how the fuzzy evaluation method can help to evaluate sustainable modular suppliers and how stability analysis can help to test the reliability of the results.

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

However, this paper also has some limitations. In the stability analysis, the study only discusses the influence of the erroneous judgment of a single index. However, in practical scenarios, the judgmental error of multiple indices is very possible. Hence, the stability analysis of this paper is an exploration to discuss the influence of possible erroneous judgments on final results, and provides a line of thinking to solve this problem. In the future, more effort should be devoted to explore and discuss the synthetic influence of judgmental error of multiple indices and hence bring stability analysis closer to reality.

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Appendix A

Table A1. Judgment matrix of A–B.

A	B_1	B_2	B_3
B_1	1	3	4
B_2	1/3	1	2
B_3	1/4	1/2	1

Table A2. Judgment matrix of C_1–C_3.

B_1	C_1	C_2	C_3	Total	Weight
C_1		6	8.5	14.5	0.322
C_2	9		10	19	0.422
C_3	6.5	5		11.5	0.256

Table A3. Judgment matrix of C_4–C_6.

B_2	C_4	C_5	C_6	Total	Weight
C_4		6.5	8	14.5	0.322
C_5	8.5		9	17.5	0.389
C_6	7	6		13	0.289

Table A4. Judgment matrix of C_7–C_{11}.

B_3	C_7	C_8	C_9	C_{10}	C_{11}	Total	Weight
C_7		8	6.5	9	8.5	32	0.213
C_8	7		8	6	9	30	0.2
C_9	8.5	7		9	9	33.5	0.223
C_{10}	6	9	6		8	29	0.194
C_{11}	6.5	6	6	7		25.5	0.17

Table A5. Judgment matrix of C_{12}–C_{15}.

B_4	C_{12}	C_{13}	C_{14}	C_{15}	Total	Weight
C_{12}		8	6	6	20	0.222
C_{13}	7		6	6	19	0.211
C_{14}	9	9		8.5	26.5	0.294
C_{15}	9	9	6.5		24.5	0.273

Table A6. Judgment matrix of C_{16}–C_{17}.

B_5	C_{16}	C_{17}	Total	Weight
C_{16}		9	9	0.6
C_{17}	6		6	0.4

Table A7. Judgment matrix of C_{18}–C_{19}.

B_6	C_{18}	C_{19}	Total	Weight
C_{18}		9	9	0.6
C_{19}	6		6	0.4

Table A8. Judgment matrix of B_1–B_2.

A_1	B_1	B_2	Total	Weight
B_1		8	8	0.533
B_2	7		7	0.467

Table A9. Judgment matrix of B_3–B_4.

A_2	B_3	B_4	Total	Weight
B_3		6.5	6.5	0.433
B_4	8.5		8.5	0.567

Table A10. Judgment matrix of B_5–B_6.

A_3	B_5	B_6	Total	Weight
B_5		7	7	0.533
B_6	8		8	0.467

Table A11. Judgment matrix of A_1–A_3.

	A_1	A_2	A_3	Total	Weight
A_1		9	8.5	17.5	0.389
A_2	6		7	13	0.289
A_3	6.5	8		14.5	0.322

Appendix B

Supplier Evaluation Form

Evaluated Supplier:			**Code of supplier:**
Evaluating department or representative			
Purchasing and procurement department and representative		Production department and representative	Other departments and representative
Grades and definition of comments			
1 good (implement well, have good effect, obvious advantage) 2 general (implement basically, have general effect, partly advantage) 3 fairly weak (partly implement, have fairly weak effect, no advantage) 4 weak (no implementation, have weak effect, disadvantage)			
Evaluation Item			
Modular Competency (first tier index)			
Second tier index	Third tier index	Specific way	Comment
Modular design and production competency	Professional industry knowledge	Questionnaire	
	Technical development capability	Questionnaire	
	Value analysis capability	Questionnaire	
	Global item of MCD0	Questionnaire	
Modular management competency	Engineering support	Questionnaire	
	Integration capability	Questionnaire	
	Relationship management capability	Questionnaire	
	Global item of MCM0	Questionnaire	

MC01		Questionnaire	
MC02		Questionnaire	
Sustainability (first tier index)			
Second tier index	Third tier index	Specific way	Comment
Social responsibility implementation	Contribution to the government	National tax paid on time	
		Local tax paid on time	
		Number of people employed	
	Contribution to the investors	Dividends distributed	
		Return of investment	
	Contribution to the employees	Satisfied salaries and benefits paid	
		Sense of belonging	
		Sense of achievement	
	Contribution to the suppliers	Satisfied returns and profits	
		Long-term cooperation relationship	
	Contribution to the community	Money donated	
		Community activities undertaken	
	Global item of SCR0	Questionnaire	
Environmental management	Having environmental management certification	Questionnaire	
	Protecting environmental resources	Questionnaire	
	Implementing clean production	Questionnaire	
	Passing ISO14000 certification	Questionnaire	
	Global item of SCM0	Questionnaire	
SC01		Questionnaire	
SC02		Questionnaire	
Organizational identity cognition (first tier index)			
Second tier index	Third tier index	Specific way	Comment
Cognition of the core features	Cognition of the enterprise's core value	Questionnaire	
	Cognition of the enterprise's vision and mission	Questionnaire	
	Global item of OIC0	Questionnaire	
Cognition of the distinctive features	Cognition of the enterprise's core competitiveness and businesses	Questionnaire	
	Cognition of the resources needed in the enterprise's core businesses	Questionnaire	
	Global item of OID0	Questionnaire	
OI01		Questionnaire	
OI02		Questionnaire	

Appendix C

The detailed mathematical derivation of the stability analysis follows.

(1) Both positive and negative errors have an impact on Equations (1) and (2). Namely,

$$k \le N-1,\ k' \le N-1$$

$$\sum_{j=1}^{N-1} S'_j = \sum_{j\neq k,k'} S_j + S'_k + S'_{k'} = \sum_{j\neq k,k'} S_j + S_k - ZA_h\Delta r^2 + B_{hk}a_h\Delta r + S_{k'} - ZA_h\Delta r^2 - B_{hk'}a_h\Delta r$$
$$= \sum_{j=1}^{N-1} S_j - 2ZA_h\Delta r^2 + a_h(B_{hk} - B_{hk'})\Delta r$$

$$0.5 - (N-1)Z\overline{L'} = 0.5 - (N-1)Z(\overline{L} + \tfrac{2}{n}A_h\Delta r^2 + \tfrac{2a_hC_{hkk'}}{n}\Delta r)$$
$$= 0.5 - (N-1)Z\overline{L} - \tfrac{2(N-1)Z}{n}A_h\Delta r^2 - \tfrac{2(N-1)Za_hC_{hkk'}}{n}\Delta r$$

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

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

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

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

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

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

$$0 \le \Delta r \le \frac{E_{hkk'(N-1)}a_h - \sqrt{(E_{hkk'(N-1)}a_h)^2 - 4\frac{2Z(n-N+1)}{n}A_hD_{N-1}}}{2\frac{2Z(n-N+1)}{n}A_h}$$

$$\sum_{j=1}^{N} S'_j = \sum_{j\neq k,k'} S_j + S'_k + S'_{k'} = \sum_{j\neq k,k'} S_j + S_k - ZA_h\Delta r^2 + B_{hk}a_h\Delta r + S_{k'} - ZA_h\Delta r^2 - B_{hk'}a_h\Delta r$$
$$= \sum_{j=1}^{N} S_j - 2ZA_h\Delta r^2 + a_h(B_{hk} - B_{hk'})\Delta r$$

$$0.5 - NZ\overline{L'} = 0.5 - NZ(\overline{L} + \frac{2}{n}A_h\Delta r^2 + \frac{2a_hC_{hkk'}}{n}\Delta r) = 0.5 - NZ\overline{L} - \frac{2NZ}{n}A_h\Delta r^2 - \frac{2NZa_hC_{hkk'}}{n}\Delta r$$

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

$$\frac{2(n-N)Z}{n}A_h\Delta r^2 - \left[B_{hk} - B_{hk'} + \frac{2NZC_{hkk'}}{n}\right]a_h\Delta r - H_N \le 0$$

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

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

Therefore, if $(E_{hkk'}a_h)^2 - 4\frac{2Z(n-N+1)}{n}A_hD_{N-1} < 0$,

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

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

$$0 \leq \Delta r \leq \min\left[\begin{array}{c}\frac{E_{hkk'N}a_h+\sqrt{(E_{hkk'N}a_h)^2+4\frac{2Z(n-N)}{n}A_h H_N}}{2\frac{2Z(n-N)}{n}A_h}, \\ \frac{E_{hkk'(N-1)}a_h-\sqrt{(E_{hkk'(N-1)}a_h)^2-4\frac{2Z(n-N+1)}{n}A_h D_{N-1}}}{2\frac{2Z(n-N+1)}{n}A_h}\end{array}\right]$$

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

$$\sum_{j=1}^{N-1} S'_j = \sum_{j \neq k} S_j + S'_k = \sum_{j \neq k} S_j + S_k - ZA_h\Delta r^2 + B_{hk}a_h\Delta r = \sum_{j=1}^{N-1} S_j - ZA_h\Delta r^2 + B_{hk}a_h\Delta r$$

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

Because $\sum_{j=1}^{N-1} S'_j \leq 0.5 - Z(N-1)\overline{L'}$, by rearranging the formula one can get $\frac{n-2(N-1)Z}{n}A_h\Delta r^2 - \left[B_{hk} + \frac{2(N-1)ZC_{hkk'}}{n}\right]a_h\Delta r + D_{N-1} \geq 0$.

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

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

If $n - 2(N-1) \geq 0$, $(F_{hkk'(N-1)}a_h)^2 - 4\frac{n-2(N-1)Z}{n}A_h D_{N-1} < 0$, then the above inequality always holds.

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

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

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

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

Because both positive and negative errors have an impact on Equation (2), according to the deduction of circumstance (1), to satisfy Equation (2), it should have

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

Therefore, if $n - 2(N-1) \geq 0$, $a^2{}_h F^2{}_{hkk'(N-1)} - 4\frac{n-2(N-1)}{n}ZA_h D_{N-1} < 0$,

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

If $n-2(N-1)\geq 0$, $a^2{}_h F^2{}_{hkk'(N-1)} - 4^{\frac{n-2(N-1)}{n}} ZA_h D_{N-1} \geq 0$,

$$0 \leq \Delta r \leq \min\left[\begin{array}{c} \frac{E_{hkk'N}a_h + \sqrt{(E_{hkk'N}a_h)^2 + 4^{\frac{2Z(n-N)}{n}} A_h H_N}}{2^{\frac{2Z(n-N)}{n}} A_h}, \\ \frac{a_h F_{hkk'(N-1)} - \sqrt{a_h^2 F^2{}_{hkk'(N-1)} - 4^{\frac{n-2(N-1)}{n}} ZA_h D_{N-1}}}{2^{\frac{n-2(N-1)}{n}} ZA_h} \end{array}\right]$$

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

$$0 \leq \Delta r \leq \min\left[\begin{array}{c} \frac{E_{hkk'N}a_h + \sqrt{(E_{hkk'N}a_h)^2 + 4^{\frac{2Z(n-N)}{n}} A_h H_N}}{2^{\frac{2Z(n-N)}{n}} A_h}, \\ \frac{-a_h F_{hkk'(N-1)} + \sqrt{a_h^2 F^2{}_{hkk'(N-1)} + 4^{\frac{2(N-1)-n}{n}} ZA_h D_{N-1}}}{2^{\frac{2(N-1)-n}{n}} ZA_h} \end{array}\right]$$

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

$$\sum_{j=1}^{N-1} S'_j = \sum_{j\neq k'} S_j + S'_{k'} = \sum_{j\neq k'} S_j + S_{k'} - ZA_h\Delta r^2 - B_{hk'}a_h\Delta r = \sum_{j=1}^{N-1} S_j - ZA_h\Delta r^2 - B_{hk'}a_h\Delta r$$

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

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

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

The study makes $G_{hkk'} = \left[B_{hk'} - \frac{2(N-1)ZC_{hkk'}}{n}\right]$.
Then $\frac{n-2(N-1)Z}{n}A_h\Delta r^2 + G_{hkk'}a_h\Delta r + D_{N-1} \geq 0$.
If $n-2(N-1)\geq 0$, $(G_{hkk'}a_h)^2 - 4\frac{n-2(N-1)Z}{n}A_hD_{N-1} < 0$, then the above inequality always holds.
If $n-2(N-1)\geq 0$, $(G_{hkk'}a_h)^2 - 4\frac{n-2(N-1)Z}{n}A_hD_{N-1} \geq 0$,

$$0 \leq \Delta r \leq \frac{-G_{hkk'}a_h - \sqrt{(G_{hkk'}a_h)^2 - 4\frac{n-2(N-1)}{n}ZA_hD_{N-1}}}{2\frac{n-2(N-1)}{n}ZA_h}$$

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

$$0 \leq \Delta r \leq \frac{G_{hkk'}a_h + \sqrt{(G_{hkk'}a_h)^2 + 4\frac{2(N-1)-n}{n}ZA_hD_{N-1}}}{2\frac{2(N-1)-n}{n}ZA_h}$$

Because both positive and negative errors have impact on Equation (2), according to the deduction of circumstance (1), to satisfy Equation (2), it should have

$$0 \leq \Delta r \leq \frac{E_{hkk'N}a_h + \sqrt{(E_{hkk'N}a_h)^2 + 4\frac{2Z(n-N)}{n}A_hH_N}}{2\frac{2Z(n-N)}{n}A_h}$$

Therefore, if $n-2(N-1) \geq 0$, $a^2{}_h G^2{}_{hkk'} - 4\frac{n-2(N-1)}{n} Z A_h D_{N-1} < 0$, $0 \leq \Delta r \leq \frac{E_{hkk'N}a_h + \sqrt{(E_{hkk'N}a_h)^2 + 4\frac{2Z(n-N)}{n} A_h H_N}}{2\frac{2Z(n-N)}{n} A_h}$.

If $n-2(N-1) \geq 0$, $a^2{}_h G^2{}_{hkk'} - 4\frac{n-2(N-1)}{n} Z A_h D_{N-1} \geq 0$,

$$0 \leq \Delta r \leq \min \left[\begin{array}{c} \frac{E_{hkk'N}a_h + \sqrt{(E_{hkk'N}a_h)^2 + 4\frac{2Z(n-N)}{n} A_h H_N}}{2\frac{2Z(n-N)}{n} A_h}, \\ \frac{-a_h G_{hkk'} - \sqrt{a^2{}_h G_{hkk'}{}^2 - 4\frac{n-2(N-1)}{n} Z A_h D_{N-1}}}{2\frac{n-2(N-1)}{n} Z A_h} \end{array} \right]$$

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

$$0 \leq \Delta r \leq \min \left[\begin{array}{c} \frac{E_{hkk'N}a_h + \sqrt{(E_{hkk'N}a_h)^2 + 4\frac{2Z(n-N)}{n} A_h H_N}}{2\frac{2Z(n-N)}{n} A_h}, \\ \frac{a_h G_{hkk'} + \sqrt{a^2{}_h G_{hkk'}{}^2 + 4\frac{2(N-1)-n}{n} Z A_h D_{N-1}}}{2\frac{2(N-1)-n}{n} Z A_h} \end{array} \right]$$

(4) Both positive and negative errors do not have an impact on Equation (1), the negative error has impact on Equation (2). Namely, $k > N$, $k' = N$

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

$$0.5 - NZ\overline{L'} = 0.5 - NZ(\overline{L} + \frac{2}{n} A_h \Delta r^2 + \frac{2a_h C_{hkk'}}{n} \Delta r) = 0.5 - NZ\overline{L} - \frac{2NZ}{n} A_h \Delta r^2 - \frac{2NZa_h C_{hkk'}}{n} \Delta r$$

Because $\sum\limits_{j=1}^{N} S'_j \geq 0.5 - ZN\overline{L'}$, by rearranging the formula one can get $\frac{n-2N}{n} Z A_h \Delta r^2 - \left[B_{hk'} - \frac{2NZC_{hkk'}}{n} \right] a_h \Delta r + H_N \geq 0$.

That is $\frac{n-2N}{n} Z A_h \Delta r^2 - G_{hkk'N} a_h \Delta r + H_N \geq 0$.

If $n-2N \geq 0$, $(G_{hkk'N}a_h)^2 - 4\frac{n-2N}{n} Z A_h D_{N-1} < 0$, then the above inequality always holds.

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

$$0 \leq \Delta r \leq \frac{G_{hkk'N}a_h - \sqrt{(G_{hkk'N}a_h)^2 - 4\frac{n-2N}{n} Z A_h H_N}}{2\frac{n-2N}{n} Z A_h}$$

If $2N-n \geq 0$, $\frac{2N-n}{n} Z A_h \Delta r^2 + G_{hkk'N} a_h \Delta r - H_N \leq 0$,

$$0 \leq \Delta r \leq \frac{-G_{hkk'N}a_h + \sqrt{(G_{hkk'N}a_h)^2 + 4\frac{2N-n}{n} Z A_h H_N}}{2\frac{2N-n}{n} Z A_h}$$

For Equation (1),

$$\sum_{j=1}^{N-1} S'_j = \sum_{j=1}^{N-1} S_j \leq 0.5 - (N-1)Z\overline{L'} = 0.5 - (N-1)Z(\overline{L} + \frac{2}{n} A_h \Delta r^2 + \frac{2a_h C_{hkk'}}{n} \Delta r)$$
$$= 0.5 - (N-1)Z\overline{L} - \frac{2(N-1)Z}{n} A_h \Delta r^2 - \frac{2(N-1)Za_h C_{hkk'}}{n} \Delta r$$

By rearranging the formula, one can get

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

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

Therefore, if $n-2N \ge 0$, $a^2{}_hG^2{}_{hkk'N} - 4\frac{n-2N}{n}ZA_hH_N < 0$,

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

If $n-2N \ge 0$, $a^2{}_hG^2{}_{hkk'N} - 4\frac{n-2N}{n}ZA_hH_N \ge 0$,

$$0 \le \Delta r \le \min\left[\begin{array}{l} \frac{-\frac{2a_h(N-1)ZC_{hkk'}}{n} + \sqrt{\left(\frac{2a_h(N-1)ZC_{hkk'}}{n}\right)^2 + 4\frac{2(N-1)ZA_hD_{N-1}}{n}}}{2\frac{2(N-1)}{n}ZA_h}, \\ \frac{a_hG_{hkk'N} - \sqrt{a^2{}_hG^2{}_{hkk'N} - 4\frac{n-2N}{n}ZA_hH_N}}{2\frac{n-2N}{n}ZA_h} \end{array}\right]$$

If $2N-n \ge 0$,

$$0 \le \Delta r \le \min\left[\begin{array}{l} \frac{-\frac{2a_h(N-1)ZC_{hkk'}}{n} + \sqrt{\left(\frac{2a_h(N-1)ZC_{hkk'}}{n}\right)^2 + 4\frac{2(N-1)ZA_hD_{N-1}}{n}}}{2\frac{2(N-1)}{n}ZA_h}, \\ \frac{-a_hG_{hkk'N} + \sqrt{a^2{}_hG^2{}_{hkk'N} + 4\frac{2N-n}{n}ZA_hH_N}}{2\frac{2N-n}{n}ZA_h} \end{array}\right]$$

(5) Both positive and negative errors do not have impact on Equation (1), the positive error has impact on Equation (2). Namely, $k = N$, $k' > N$

$$\sum_{j=1}^{N} S'_j = \sum_{j \ne k} S_j + S'_k = \sum_{j \ne k} S_j + S_k - ZA_h\Delta r^2 + B_{hk}a_h\Delta r = \sum_{j=1}^{N} S_j - ZA_h\Delta r^2 + B_{hk}a_h\Delta r$$

$$0.5 - NZ\overline{L'} = 0.5 - NZ(\overline{L} + \frac{2}{n}A_h\Delta r^2 + \frac{2a_hC_{hkk'}}{n}\Delta r) = 0.5 - NZ\overline{L} - \frac{2NZ}{n}A_h\Delta r^2 - \frac{2NZa_hC_{hkk'}}{n}\Delta r$$

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

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

Then $\frac{n-2N}{n}ZA_h\Delta r^2 + F_{hkk'N}a_h\Delta r + H_N \ge 0$.
If $n-2N \ge 0$, $(F_{hkk'N}a_h)^2 - 4\frac{n-2N}{n}ZA_hH_N < 0$, then the above inequality always holds.
If $n-2N \ge 0$, $(F_{hkk'N}a_h)^2 - 4\frac{n-2N}{n}ZA_hH_N \ge 0$,

$$0 \le \Delta r \le \frac{-F_{hkk'N}a_h + \sqrt{(F_{hkk'N}a_h)^2 - 4\frac{n-2N}{n}ZA_hH_N}}{2\frac{n-2N}{n}ZA_h}$$

If $2N-n \ge 0$, $\frac{2N-n}{n}ZA_h\Delta r^2 - F_{hkk'N}a_h\Delta r - H_N \le 0$,

$$0 \le \Delta r \le \frac{F_{hkk'N}a_h + \sqrt{(F_{hkk'N}a_h)^2 + 4\frac{2N-n}{n}ZA_hH_N}}{2\frac{2N-n}{n}ZA_h}$$

For Equation (1),

$$\begin{aligned}&\sum_{j=1}^{N-1} S'_j = \sum_{j=1}^{N-1} S_j \leq 0.5-(N-1)Z\overline{L'} = 0.5-(N-1)Z(\overline{L}+\tfrac{2}{n}A_h\Delta r^2+\tfrac{2a_hC_{hkk'}}{n}\Delta r)\\ &= 0.5-(N-1)Z\overline{L}-\tfrac{2(N-1)Z}{n}A_h\Delta r^2-\tfrac{2(N-1)Za_hC_{hkk'}}{n}\Delta r\end{aligned}$$

By rearranging the formula one can get $\frac{2(N-1)Z}{n}A_h\Delta r^2+\frac{2a_h(N-1)ZC_{hkk'}}{n}\Delta r-D_{N-1}\leq 0.$

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

Therefore, if $n-2N\geq 0$, $a^2{}_hF^2{}_{hkk'N}-4\frac{n-2N}{n}ZA_hH_N<0$,

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

If $n-2N\geq 0$, $a^2{}_hF^2{}_{hkk'N}-4\frac{n-2N}{n}ZA_hH_N\geq 0$,

$$0\leq\Delta r\leq\min\left[\begin{array}{c}\frac{-\frac{2a_h(N-1)ZC_{hkk'}}{n}+\sqrt{\left(\frac{2a_h(N-1)ZC_{hkk'}}{n}\right)^2+4\frac{2(N-1)ZA_hD_{N-1}}{n}}}{2\frac{2(N-1)}{n}ZA_h},\\ \frac{-a_hF_{hkk'N}+\sqrt{a^2{}_hF_{hkk'N}{}^2-4\frac{n-2N}{n}ZA_hD_{N-1}}}{2\frac{n-2N}{n}ZA_h}\end{array}\right]$$

If $2N-n\geq 0$,

$$0\leq\Delta r\leq\min\left[\begin{array}{c}\frac{-\frac{2a_h(N-1)ZC_{hkk'}}{n}+\sqrt{\left(\frac{2a_h(N-1)ZC_{hkk'}}{n}\right)^2+4\frac{2(N-1)ZA_hD_{N-1}}{n}}}{2\frac{2(N-1)}{n}ZA_h},\\ \frac{a_hF_{hkk'N}+\sqrt{a^2{}_hF_{hkk'N}{}^2+4\frac{2N-n}{n}ZA_hH_N}}{2\frac{2N-n}{n}ZA_h}\end{array}\right].$$

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

For Equation (1),

$$\begin{aligned}&\sum_{j=1}^{N-1} S'_j = \sum_{j=1}^{N-1} S_j \leq 0.5-(N-1)Z\overline{L'} = 0.5-(N-1)Z(\overline{L}+\tfrac{2}{n}A_h\Delta r^2+\tfrac{2a_hC_{hkk'}}{n}\Delta r)\\ &= 0.5-(N-1)Z\overline{L}-\tfrac{2(N-1)Z}{n}A_h\Delta r^2-\tfrac{2(N-1)Za_hC_{hkk'}}{n}\Delta r\end{aligned}$$

By rearranging the formula one can get

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

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

For Equation (2),

$$\begin{aligned}\sum_{j=1}^{N} S'_j = \sum_{j=1}^{N} S_j \geq & 0.5 - NZ\overline{L'} = 0.5 - NZ(\overline{L} + \tfrac{2}{n}A_h\Delta r^2 + \tfrac{2a_hC_{hkk'}}{n}\Delta r) \\ &= 0.5 - NZ\overline{L} - \tfrac{2NZ}{n}A_h\Delta r^2 - \tfrac{2NZa_hC_{hkk'}}{n}\Delta r\end{aligned}$$

By rearranging the formula one can get $\frac{2NZ}{n}A_h\Delta r^2 + \frac{2a_hNZC_{hkk'}}{n}\Delta r + H_N \geq 0$.
If $\left(\frac{2a_hNZC_{hkk'}}{n}\right)^2 - 4\frac{2NZ}{n}A_hH_N < 0$, then the above inequality always holds.
If $\left(\frac{2a_hNZC_{hkk'}}{n}\right)^2 - 4\frac{2NZ}{n}A_hH_N \geq 0$, $0 \leq \Delta r \leq \frac{-\frac{2a_hNZC_{hkk'}}{n} - \sqrt{\left(\frac{2a_hNZC_{hkk'}}{n}\right)^2 - 4\frac{2NZA_hH_N}{n}}}{2\frac{2N}{n}ZA_h}$.
Therefore, if $\left(\frac{2a_hNZC_{hkk'}}{n}\right)^2 - 4\frac{2NZA_hH_N}{n} < 0$,

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

If $\left(\frac{2a_hNZC_{hkk'}}{n}\right)^2 - 4\frac{2NZA_hH_N}{n} \geq 0$,

$$0 \leq \Delta r \leq \min\left[\begin{array}{l}\frac{-\frac{2a_h(N-1)ZC_{hkk'}}{n} + \sqrt{\left(\frac{2a_h(N-1)ZC_{hkk'}}{n}\right)^2 + 4\frac{2(N-1)ZA_hD_{N-1}}{n}}}{2\frac{2(N-1)}{n}ZA_h}, \\ \frac{-\frac{2a_hNZC_{hkk'}}{n} + \sqrt{\left(\frac{2a_hNZC_{hkk'}}{n}\right)^{2;} - 4\frac{2NZA_hH_N}{n}}}{2\frac{2NZA_h}{n}}\end{array}\right]$$

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