Private-label sustainable supplier selection using a fuzzy entropy-VIKOR-based approach

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Abstract

In recent decades, private labels have been the focus of great development in retail due to their price advantage and consumer-oriented production. With growing customer awareness of safety and health, private-label sustainable supplier selection has become a strategic issue for many retailers. Although there are many studies on supplier selection issues and evaluation methods, studies on the sustainability and consumption sectors are rather limited. Therefore, a novel three-phase MCDM model for private-label supplier selection compliance with sustainability criteria is proposed. First, the Delphi method is used to construct a criteria system based on a detailed literature review. Then, an integrated weight algorithm is suggested, in which objective weights are based on attributes' entropy measurements, and subjective weights are derived from decision-makers' preferences. Eventually, during evaluation, a fuzzy set extended in VIKOR is exploited by considering the vagueness of decision makers' expressions. The results from a case study then show that green packaging and labelling, relationship with manufacturing brand, order flexibility, and product traceability are the most important criteria in retail private-label supplier selection. The flexibility and reliability of the proposed model are also demonstrated in a practical case of supplier evaluation.

Keywords Supplier selection · Entropy · VIKOR · Sustainability · Private labels

Introduction

In modern times, the idea of improving organizational performance has changed significantly. Sustainability is becoming increasingly important for organizations with an emphasis on sustainable development through strict government guidance and growing green knowledge of customers [5, 34, 57]. Retailers acting as middlemen between manufacturers and consumers should be more concerned about ethical values while still creating economic values. Therefore, introducing sustainability as a core value is one of the most promising meanings to achieve maximum ecological-economic benefits [32, 54]. In view of the current retail market, a growing number of retailers are attempting to place their private labels (i.e., retailer brands or store brands) at the center of their strategies [20]. Retail private labels are owned

and/or licensed exclusively by retailers for distribution in their respective segments of the marketplace [24]. Retailers attempt to use exclusive brands to differentiate products from their competitors [29]. In North America and Europe, private-label product sales also increase dramatically to 22% and 30% market shares of consumer-packaged goods, respectively [37, 40]. Private-label goods are normally priced 20% or more below manufacturer brand market leaders. In large Western chain supermarkets, the objective quality gap between retailer brands and leading national brands is small-to-none. Lower prices and higher qualities of products are more in line with corporate and social sustainability.

Any strategy that relies on privately branded merchandise must also address a host of complex problems on the supply-chain side. Most private-label supply-chain research has concentrated on this topic, primarily including customers' behaviors [38] and marketing strategies [17]. However, the major challenges that retail private labels face focus on the upstream supply chain in product manufacturing, which begins with qualifying factories that create products. Private-label manufacturers differ from general manufacturers in that they have specific categories and characteristics. The Private Label Manufacturer's Association (PLMA) divides suppliers

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into four categories, as shown in Table 1 [41]; however, this process requires a specific criteria system to evaluate private-label suppliers' performance. Existing research has used supplier selection mechanisms in economic, green, and social concerns [3, 5, 28], and existing supplier selection criteria systems are primarily in the manufacturing industry. For example, in the textile industry, social-focused criteria, such as long working hours and employment of child labor, are critical [8]. In the motor industry, environmental factors have become the most critical criteria [28]. However, compared to manufacturing, more criteria should be published in the consumption sector.

This paper stresses private-label sustainability practices as criteria for supplier selection and evaluation in three dimensions: economic, environmental, and social. In this context, we propose a three-phase MCDM approach as the private-label sustainable supplier selection (PL-SSS) model. We investigate more than 60 supermarket chains and interview many relevant experts to establish PL-SSS criteria. Also, we markedly improve the effectiveness and efficiency of weight measurement by integrating both subjective and objective weights. Finally, the proposed PL-SSS is applied to a real and typical business case study of a Chinese grocery chain. The Chinese grocery industry is fragmented, and mainly consists of small- and medium-sized enterprises (SMEs), which are regional retailers that play important roles in the Chinese national economy and daily life. Although Chinese grocery chains and supermarket chains have been developing for many years, private labels in China are relatively new. Private-label categories and products are rare and typically focus on food items. A large proportion of regional retailers have no private-label products. To become more competitive, Chinese regional retailers must use supply-chain management practices to secure private-label product supply and minimize quality gaps with leading manufacturing brands. Compared to international supermarket chains, such as Walmart and Tesco, which have manufacturing expertise and factories, research of PL-SSS issues among Chinese regional retailers is more impactful [11].

The remainder of this paper is organized as follows. "Literature review" reviews relevant literature, and the proposed model and methods are described in "Methods".

"Results and discussion" then compares the results and provides a discussion based on a case study. Finally, "Conclusions" provides concluding observations, limitations, and suggestions for future work.

Literature review

The increase in research on supplier selection criteria and performance evaluation since the 1960s was encouraged by both academia and business. Dickson [21] is one of the first representatives in this research field and identified 23 criteria based on questionnaire research from organization managers in North America. In the subsequent decades, a significant impetus of just-in-time manufacturing strategies changed the procurement strategy, and implementation imposed a reordering of the vendor selection criteria. At that time, the preponderant criteria of vendor selection concentrated on economic factors, including quality, delivery, net price, production facilities, and capacity [10, 13, 35, 36].

Typically, a new strategic direction requires new criteria and/or the re-emphasis on existing criteria used in purchasing decisions necessary to use them [53]. Given the recent focus on sustainability issues, the main purpose of this section is to review documents about supplier selection issues published in the last decade and provide a systematic review of criteria (Table 2) related to sustainability practice. We use the triple bottom line (TBL) model to define sustainability in terms of economic, environmental, and social aspects, which is then described by various criteria [23].

This review will help define sustainability issues and focuses on private-label supplier selection in "Sustainability and supplier selection". We also review the literature over the last decade in "Sustainability and supplier selection" to identify important sustainable supplier selection criteria and effective supplier evaluation methods. Based on this review, "Research gaps" shows current research gaps and the contributions of this study.

Table 1 Private-label manufacturer's category

Private-label manufacturer's category	Features
Large national brand manufacturers (LNBMs)	Utilize their expertise and excess plant capacity to supply private labels
Small and quality manufacturers (SQMs)	Specialize in given product lines
	Nearly focus on private-label production
	Companies often own by LNBMs
Major retailers and wholesalers (MRWs)	Have self-developed capacity and own manufacturing facilities
Regional brand manufacturers (RBWs)	Produce store-brand products for specific markets

Table 2 Summary of sustainable supplier selection criteria

Dimension	Supplier selection criteria	Lee et al. [33]	Bai and Sarkis [6]	Büyükoğkan and Çifçi [15]	Govindan, Khodaverdi, and Jafarian [27]	Shen et al. [49]	Dou, Zhu, and Sarkis [22]	Sarkis and Dhavale [47]	Hashemi, Karimi, and Tavana [28]	Luthra et al. [34]
Economic	Price of product		*	*				*	*	*
	Profit on product		*						*	*
	Production/logistics cost		*		*		*	*	*	*
	Quality of product/service		*		*		*	*	*	*
	Quality management system									
	Quality-related certificates	*								
	Handling abnormal quality	*			*					
	Capability of R&D	*	*	*	*		*			
	Capability of design	*	*	*	*		*			
	Flexibility			*	*		*			*
	Delivery and service of product		*	*			*		*	*
	Lead time required		*					*		*
	Just-in-time inventory		*		*			*		*
Environmental	Cost of component disposal	*								
	Environment management		*		*	*	*			*
	Energy consumption	*	*			*	*	*	*	
	Use of harmful materials	*			*	*				
	Environment-related certificates	*			*	*				
	Green design and purchasing	*			*	*		*		*
	Green manufacturing	*			*		*			*
	Green image			*			*			*
	Green process planning	*		*						
	Staff environment training								*	
	Waste management	*						*		*
	Green R&D investment					*			*	*
	Recycle	*				*			*	*

Table 2 (continued)

Dimension	Supplier selection criteria	Lee et al. [33]	Bai and Sarkis [6]	Büyükoçkan and Çifçi [15]	Govindan, Khodaverdi, and Jafarian [27]	Shen et al. [49]	Dou, Zhu, and Sarkis [22]	Sarkis and Dhavale [47]	Hashemi, Karimi, and Tavana [28]	Luthra et al. [34]
Social	Occupational health		*		*					*
	Safety systems		*		*					*
	Flexible working arrangement				*					
	Career development				*					
	Discrimination				*					
	Stakeholder engagement				*					
	Service infrastructure				*					
	Economic welfare and growth						*			
	Child labor and forced labor							*		
	Employee turnover rate							*		
	Community responsibility		*					*		
	Information disclosure									
	Funds donation							*		

Sustainability and supplier selection

Many researchers and organizations attempt to define sustainability in various ways. The most originally and frequently cited definition is from the United Nations World Commission on Environment and Development, which states that “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own” [16]. However, this definition lacks a practical understanding of sustainability, particularly its application in specific situations. An important developing trend links sustainability to the TBL model, as described by Elkington [23], to incorporate economic, environmental, and social dimensions of sustainability into the supply chain and management practices [44].

In response to growing market pressures and stakeholders’ demands and compliance with strict sustainable development regulations, organizations review their supply chain, and firms have described the importance of their suppliers’ sustainable performance in sustainable supply-chain management [6]. Supplier selection and evaluation thus become some of the most significant strategic decisions that corporations make [14]. The requirement of organizations’ sustainable development for supplier selection and evaluation is to identify the most appropriate suppliers that consistently satisfy the firms’ sustainable demands at acceptable cost.

With private brand joining, the retail supply chain is shortened forward (Fig. 1); therefore, retailers are move closer to their suppliers. A new issue of PL-SSS arises in retail supply-chain management between manufacturers and retailers. According to Zimmer et al. [58], and Akman and Pışkın [2], PL-SSS is a process by which retailers evaluate suppliers and select the best supplier regarding sustainability to achieve competitiveness on products against national brands. The steps for the supplier selection process typically

Fig. 1 Retail and private-label supply-chain

begin with identifying overall objectives and specifications, continuing with criteria formulation [19, 31]. Then, through the first rough screening step with candidate submission, the final detailed evaluation procedures are enforced among qualified manufacturers. However, two types of problems tend to occur in sustainable supplier selection and evaluation processes arising from researchers: the lack of sustainable evaluation criteria [1] and the diversity of suppliers and criteria [6].

Sustainability and supplier selection

We review the most cited articles in the last decade that are associated with relevant keywords to construct a co-citation analysis network (see Fig. 2), and the 14 articles with the highest co-citations are then described. Based on the results of this review, we conducted a systemic analysis with these 14 articles. Supplier selection is a typical decision-making activity. Given the multiplicity and complexity of this process, we summarize the collected literature in Table 2, focusing on supplier selection criteria, and Table 3 in three aspects: (1) issues addressed, (2) industries involved, and (3) methodologies used.

Research gaps

In supply-chain activities, building appropriate sustainability-focused criteria is important for organizations to achieve sustainable development. Several studies have incorporated green criteria [15, 22, 28, 33, 42, 49] and sustainable criteria [6, 14, 34, 47] during supplier selection. However, a few contribute to specific industries. Most research only applies a numerical example to verify the proposed supplier

Fig. 2 Co-citation analysis network

Table 3 Summary of issues, industries, and methodologies in the supply chain

Researchers	Issues addressed	Industries involved (or not)	Methodologies used (or not)	Weighting method	Supplier evaluation method
Lee et al. [33]	Green supplier selection	✓ Hi-tech industry	✓ Delphi method and a systematic literature review	✓ AHP	× –
Bai and Sarkis [6]	Integrate sustainability to supplier selection	× A case illustration (based on assumption)	✓ Literature review	× –	✓ Grey system and rough set
Büyüktürkkan and Çifçi [14]	Sustainable supplier selection with incomplete information	× A case study (Turkish white goods industry)	✓ Experts' opinions	✓ Preference of evaluators	✓ fuzzy ANP
Baskaran et al. [8]	India textile suppliers' sustainability evaluation	✓ Textile industry	✓ Literature review	✓ Identification by decision-makers	✓ Grey approach
Büyüktürkkan and Çifçi [15]	Evaluate green suppliers	× A case study (Ford Otosan)	✓ Literature search	✓ Fuzzy DEMATEL and fuzzy ANP	✓ Fuzzy TOPSIS
Govindan et al. [27]	Measure sustainability performance of a supplier	× A case illustration	✓ Literature review	✓ Experts' subjective preferences	✓ Fuzzy TOPSIS
Shen et al. [49]	Evaluate green supplier's performance in green supply chain	× A numerical example	✓ Literature review and discussion of experts	✓ Score of environmental and industrial experts	✓ Fuzzy TOPSIS
Dou et al. [22]	Evaluate green supplier development programs	× A real-world case	× –	✓ ANP	✓ A grey-based model
Kannan et al. [32]	Select green suppliers based on green supply-chain management (GSCM) practices	✓ Brazilian electronics company	✓ Literature review	✓ Preferences of decision-makers	✓ Fuzzy TOPSIS
Hashemi et al. [28]	Green supplier selection	× A case study in the automotive industry	✓ Literature review	✓ ANP	✓ Grey relational analysis (GRA)
Sarkis and Dhavale [47]	Supplier selection for sustainable operations	× An illustrative example	× –	× –	✓ Bayesian framework and MCMC (Monte Carlo Markov Chain)
Banaeian et al. [7]	Fuzzy group decision-making methods	× A case study from agri-food industry	× –	✓ Experts' opinions	✓ TOPSIS, VIKOR and GRA
Luthra et al. [34]	Sustainable supplier selection and evaluation in supply chains	× An application example	✓ Literature review and experts' inputs	✓ AHP	✓ VIKOR
Qin et al. [42]	Green supplier selection	× An illustrative example	× –	✓ Decision-makers' opinions	✓ TODIM in interval type-2 fuzzy environment

selection model [27, 34, 42, 47, 49]. Although certain studies focus on a particular industry, such as the hi-tech industry [33], textile industry [8], electronic industry [32], and steel industry [4], these studies primarily concentrate on upstream supply chains rather than downstream industries; thus, a significant lack of research has been conducted on the establishment of supplier selection criteria in retail industries.

Existing criteria systems are primarily based on literature reviews and a lack of empirical research that is likely due to limited research scopes or targets [27, 34, 42, 47, 49]. These facts may cause difficulty when applying these criteria to practical business decision-making tasks. Also, index weighting is primarily based on subjective assessments, such as AHP [33, 34], ANP [22, 28], preferences of decision-makers [14, 32, 42], and experts' opinions [7, 27, 47]. There thus remain subjective interference characteristics in these traditional weight methods.

To fill these gaps in research, we propose the PL-SSS model, which is an initial effort concentrated on the consumption sector. We first attempt to establish PL-SSS criteria system. Both theoretical and empirical models are used in criteria establishment, and the TBL method and a systematic literature review are used to build a rough criteria system (Table 2). The modified Delphi method is used to complete the criteria system, which helps focus and quantify the valuation of criteria. Then, a significant effort we made is to suggest a dynamic constitution evaluation that integrates subjective and objective weight assessments. To mitigate subjective bias, we use the entropy method to measure the objective weights of criteria, which is related to supplier performance rather than the judgement of decision-makers. Also, we use the fuzzy VIKOR method to evaluate suppliers and compare its results with TOPSIS. To the best of our knowledge, this research is an original attempt to propose a research framework for establishing a PL-SSS model and criteria system.

Methods

As mentioned above, applying the fuzzy entropy-VIKOR approach to solve the PL-SSS problem is viewed as a three-phase MCDM model, including criteria system establishment, weight computing, and supplier evaluation. In this study, the PL-SSS model is introduced (Fig. 3) and relates to mathematical preliminaries that can be divided into five parts: the Delphi method, fuzzy set theory, data pre-processing, entropy method, and VIKOR. The Delphi method is used to screen the criteria and establish an indicator system in "Delphi method". Then, "Linguistic variable and data pre-processing" introduces a triangular fuzzy number (TFN) to express decision-makers' judgements, in which we propose a data processing algorithm to manage linguistic variables.

The entropy method is used to obtain objective criteria, and the specific comprehensive weight measurement is described in "Weight measurement method". We use VIKOR as the evaluation approach in "Fuzzy VIKOR".

Delphi method

The Delphi method is a structural communication method that was initially developed for business forecasting based on the results of multiple rounds of interviews and/or questionnaires from a panel of experts [12, 18, 46]. In its application, the Delphi method has been developed from general forecasting to broad research subjects, such as reporting guidelines [52] and public policy-making [25].

In this study, the Delphi method is embedded in supplier selection research to develop its criteria system. According to Saaty [45], if there are more than seven attributes at the same level, it is difficult for decision-makers to assess due to redundant standards; this problem could be resolved by combining or eliminating some criteria. Based on a literature review (Table 2), the Delphi method is used to reduce the number of irrelevant criteria and maintain effective evaluation attributes, and is performed as described in Fig. 4.

Linguistic variable and data pre-processing

In certain situations, crisp numbers cannot accurately model the judgement of decision-makers due to their vagueness and uncertainty. In such cases, fuzzy set theory is typically used to model decision-makers' opinions. Zadeh [56] introduced fuzzy set theory as an extension of classic set theory to manage imprecise information and expression by mapping linguistic terms to numerical variables. Also, Bellman and Zadeh [9] applied this theory to create fuzzy multiple-criteria decision-making (FMCDM) technology, which calculates weight assignments and alternative ranks compared to proposed criteria. The character of a fuzzy set is a membership function, which permits the gradual assessment of each element's membership within the interval [0, 1]. Thus, defined numerical intervals could be used to describe general linguistics terms, such as "good", "fair", or "bad", in fuzzy logic. The definitions and notations of fuzzy set theory used in this study are shown (Tables 4, 5, 6) (Figs. 5, 6).

The preliminary work of supplier evaluation defines a criteria evaluation matrix and a decision matrix. To simplify and eliminate repetitive computation, we conduct data pre-processing to obtain a crisp subjective matrix and decision matrix before the evaluation stage begins. Based on the foregoing fuzzy set, we assume that $\tilde{W}_k^s$ is a fuzzy criteria evaluation matrix, in which $\tilde{w}_{jk}^s$ represents k th decision-makers ($k = 1, 2, \dots, K$) which evaluate c_j criteria ($j = 1, 2, \dots, n$); $\tilde{D}_k$ is a fuzzy decision matrix; and $\tilde{r}_{ijk}^s$ indicates that the k th

Fig. 3 PL-SSS model framework

Fig. 4 Three-round Delphi method

decision-maker evaluates the A_i alternative based on c_j . The specific data process is shown in Table 7.

Weight measurement method

In the weighting process, there are two different weight measurements: subjective and objective. Subjective weight measurement is a conventional method is solely determined by decision-makers or experts, and objective weight

measurement is typically based on mathematical approaches, such as multiple objective programming and entropy methods. To establish a more reasonable and effective weight system, we integrate subjective and objective weights into a comprehensive weight system, in which the entropy method is introduced to determine objective weights.

Initially proposed by Shannon [48], entropy is a measurable physical property that represents the unavailability of a system's thermal energy for conversion into mechanical

Table 4 Notion and operational rules in fuzzy theory utilization

Fuzzy set notion and operational rules

Fuzzy set: A fuzzy set is a pair (X, m) , where X is the universe of discourse and $m : X \rightarrow [0, 1]$ is a membership function. Let A be a fuzzy set, and the function $m = \mu_A$. For a finite set $X = \{x_1, x_2, \dots, x_m\}$, $A = \{(\mu_A(x_1), x_1), (\mu_A(x_2), x_2), \dots, (\mu_A(x_m), x_m))\}$

Triangular fuzzy number: A triangular fuzzy number (TFN) is denoted as a triplet $A\{(a, b, c) | a, b, c \in R; a \leq b \leq c\}$, which respectively describes the smallest probable value, the most promising value, and the largest possible value to depict a fuzzy term. The membership function of a TFN $\mu_A(x)$ is defined and shown as follows:

$$\mu_A(x) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a < x \leq b \\ \frac{c-x}{c-b}, & b < x \leq c \\ 0, & x > c \end{cases}$$

Aggregate rules: Assuming a set $\tilde{r}_k = \{(a_k, b_k, c_k) | k = 1, 2, \dots, K\}$, the aggregate triangular fuzzy number $\tilde{r} = (a, b, c)$ is defined as:

$$\tilde{r} = \begin{cases} a = \min_k \{a_k\} \\ b = \frac{1}{K} \sum_{k=1}^K b_k \\ c = \max_k \{c_k\} \end{cases} \quad (1)$$

Defuzzy rules: Assuming a triangular fuzzy number $\tilde{r} = (a, b, c)$, defuzzification is computing as:

$$\tilde{r} = \frac{a+2b+c}{4}. \quad (2)$$

Linguistic variable: There are two set of proper linguistic variables: one for criteria evaluation (Table 5, Fig. 5), and another for supplier estimate (Table 6, Fig. 6).

Table 5 Linguistic variables for weighting criteria

Linguistic expression	Fuzzy numbers
Very low (VL)	(0, 0.2, 0.4)
Low (L)	(0.2, 0.4, 0.5)
Medium (M)	(0.4, 0.6, 0.8)
Hight (H)	(0.6, 0.8, 1)
Very high (VH)	(0.8, 0.9, 1)

Table 6 Linguistic variables for rate suppliers

Linguistic expression	Fuzzy numbers
Very poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very good (VG)	(9, 10, 10)

work that is most commonly associated with a state of randomness, disorder, or uncertainty. Entropy has been widely used in various fields, including spectral analysis [50], language modeling [43], and economics [26]. In this study, entropy is interpreted as dispersion, which is used to weight calculation, because it measures the relative contrast intensities of attributes to present average intrinsic information. According to Wang and Lee [51], the entropy

Fig. 5 TFNs for criteria **Fig. 6** TFNs for alternatives

method is used as an objective weight computing method. We propose a comprehensive weight model by merging the entropy method and decision-makers' judgements, and the specific algorithm is shown in Table 8.

Table 7 Data pre-processing**Algorithm 1: Data pre-processing algorithm****Input:** Fuzzy criteria evaluation matrix $\tilde{W}_k^s = [\tilde{w}_{jk}^s]_n$ Fuzzy decision matrix $\tilde{D}_k = [\tilde{r}_{ijk}^s]_{m \times n}$ **Process:****For** $\tilde{w}_{jk}^s$ in $\tilde{W}_k^s$ **do**Aggregate $\tilde{w}_{jk}^s$ to $\tilde{W}^s = [\tilde{w}_j^s]_n$ called equation (1)Defuzzy $\tilde{W}^s$ to $\bar{W}^s = [\bar{w}_j^s]_n$ called equation (2)Normalize $\bar{W}^s$ to construct subjective weight matrix $W^s = [w_j^s]_n$ as:

$$w_j^s = \frac{\bar{w}_j^s}{\sum_{j=1}^n \bar{w}_j^s}$$

End for**For** $\tilde{r}_{ijk}^s$ in $\tilde{D}_k$ **do**Aggregate $\tilde{D}_k$ to $\tilde{D} = [\tilde{r}_{ij}]_{m \times n}$ called equation (1)Normalize $\tilde{D}$ to fuzzy supplier evaluation matrix $\tilde{D}^N = [\tilde{r}_{ij}^N]_{m \times n}$ where:

$$c_j^+ = \max_i \{c_{ij}\}, c_j \in B; a_j^- = \min_i \{a_{ij}\}, a_j \in C;$$

$$\tilde{r}_{ij}^N = \left\{ \left(\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+} \right), j \in B \right\}; \tilde{r}_{ij}^N = \left\{ \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right), j \in C \right\}$$

Defuzzy $\tilde{D}$ to obtain the decision matrix $D = [r_{ij}]_{m \times n}$ called equation (2)**End for****Output:** Subjective weight matrix W^s Decision matrix D **Table 8** Comprehensive weight measurement based on subjective and objective methods**Algorithm 2: Comprehensive weight algorithm****Input:** Decision matrix D Subjective weight matrix W^s **Process:****For** r_{ij} in D **do**Normalize decision matrix as the project value p_{ij} , where $p_{ij} = r_{ij} / \sum_{i=1}^n r_{ij}$ Calculate the entropy by $En_j = -k \sum_{i=1}^m p_{ij} \ln(p_{ij})$ and $k = 1/\ln(m)$ Define the divergence as $DG_j = 1 - En_j$ Obtain the objective matrix $W^o = [w_j^o]_n$ as $w_j^o = DG_j / \sum_{j=1}^n DG_j$ **End for****For** w_j^s, w_j^o in W^s, W^o **do**Compute geometric mean by $w_j^m = \sqrt{w_j^s \times w_j^o}$ Obtain the comprehensive weight matrix $W = [w_j]_n$ as $w_j = w_j^m / \sum_{j=1}^n w_j^m$ **End for****Output:** Comprehensive weight matrix**Fuzzy VIKOR**

Disagreements among decision-makers typically come from differences in subjective evaluations of alternatives. The VIKOR method is used to resolve potential divisions of opinions. Yu [55] introduced the idea of a compromise solution to minimize the group regret based on maximum group utility (S_i) and the minimum solution (R_i). Opricovic [39] extended the theory to extend the VIKOR

(Vlsekriterijumska Optimizacija I Kompromisno Resenje) method into multiple-criteria optimization, in which the notion of compromise programming was introduced to rank alternatives against probable conflicts. The specific VIKOR algorithm is shown in Table 9.

The alternative $A^{(1)}$ is a compromise solution that is ranked best in the Q minimum measurement when the following two conditions are satisfied:

Table 9 VIKOR method in the PL-SSS method**Algorithm 2: VIKOR algorithm****Input:** Decision matrix D Weight matrix W **Process:****For** r_{ij} in D **do**Determine the best r_j^* and the worst r_j^- as:

$$r_j^* = \max_i r_{ij}; r_j^- = \min_i r_{ij}$$

End for**For** r_{ij}, w_j in D, W **do**Calculate utility measure S_i and regret measure R_i where:

$$S_i = \sum_{j=1}^n w_j \frac{(r_j^* - r_{ij})}{(r_j^* - r_j^-)}; R_i = \max_j \left[w_j \frac{(r_j^* - r_{ij})}{(r_j^* - r_j^-)} \right]$$

Compute VIKOR index Q_i by:

$$Q_i = \frac{v(S_i - S^*)}{S^- - S^*} + \frac{(1 - v)(R_i - R^*)}{R^- - R^*}; v = 0.5$$

End for**Output:** S_i, R_i, Q_i in descending order

1. Acceptable advantage: $Q(A^{(2)}) - Q(A^{(1)}) \geq DQ$, where $A^{(2)}$ is the 2nd minimum in the Q rank; $DQ = 1/m - 1$; and m is the number of alternatives;
2. Acceptable stability: $A^{(1)}$ is stable and ranked best by S and/or R .

If one of the conditions cannot be satisfied, a set of compromise solutions is proposed, which include:

1. $A^{(1)}$ and $A^{(2)}$, if only condition (2) is not satisfied;
2. $A^{(1)}, A^{(2)}, \dots, A^{(k)}$, if condition (1) is not satisfied. $A^{(k)}$ is determined by the relation $Q(A^{(k)}) - Q(A^{(1)}) < DQ$ for maximum k (positions of alternative solutions are “in closeness”).

Results and discussion

We conducted an empirical study of a retail alliance that consisted of 68 regional retailers operating more than 2000 stores spread over 29 provinces in China. The members of the alliance serve 20% of Chinese customers, and their overall sales are approximately 80 billion RMB (1 USD $\cong$ 7.1 RMB). Member enterprises are devoted to developing their own-brand products and tend to achieve marked advantages over rivals via customized and differentiated products.

Some of the major challenges that members encountered include a lack of production flexibility, low design capacity, and a lack of availability of guidelines for private-label development. Regional retailers depend on manufacturers to produce more total SKUs with lower volumes and to provide frequent changes to products to avoid obsolescence. This

process makes it difficult to ensure that vendor production meets strict quality standards while meeting retailer's ethical guidelines. To manage this complexity and provide high-quality products, retailers require expertise and evaluation criteria in supplier selection.

One of the alliance members, a regional retailer in Hefei city that operates more than 200 fresh food groceries, has used the proposed model as its decision-making technique to evaluate suppliers. We construct the evaluation criteria in "[PL-SSS Criteria system establishment](#)" and conduct the procedures of the weight and evaluation algorithm in "[Weight computing](#)" and "[Supplier evaluation](#)", respectively.

PL-SSS criteria system establishment

In the first phase, the Delphi method is used to generate consensus on the panel's opinions and extract the most appropriate PL-SSS criteria based on the literature research (Table 2). We invited eight experienced practitioners from the alliance to be industry experts. To select panelists, each expert had to stand for one specific perspective with regard to the research topic, considering that individual opinions may impact the study's results. Following this principle, the selected practitioners were from different departments. Also, six academics, including retail and sustainability professors, were included as panelists. Table 10 shows the demographics of the panelists.

A five-point scale was used in the Delphi questionnaire to gather panelists' feedback regarding their preferences about various topics, which were very important, important, ambivalent, unimportant, and very unimportant. We also appended several empty rows for experts to add new and

Table 10 Delphi panelists' information

Expert (no.)	Academic/practitioner	Job title/Area of expertise	Sector	Job experience
Expert 1	Academic	Professor for retail	Higher education	20 years
Expert 2	Academic	Professor for supply chain	Higher education	13 years
Expert 3	Academic	Dean of information technology	Higher education	17 years
Expert 4	Academic	Professor for retail	Higher education	15 years
Expert 5	Academic	Professor for corporate ethics	Higher education	7 years
Expert 6	Academic	Professor for private labels	Higher education	6 years
Expert 7	Practitioner	Chamber of retail alliance	Retail alliance	3 years
Expert 8	Practitioner	Head of private-label department	Retail alliance	2 years
Expert 9	Practitioner	Own-brand purchasing manager	Retail alliance	2 years
Expert 10	Practitioner	Purchasing advisor	Consulting	14 years
Expert 11	Practitioner	Procurement director	Chain supermarket	10 years
Expert 12	Practitioner	Senior manager	Chain supermarket	11 years
Expert 13	Practitioner	Shop manager	Chain supermarket	7 years
Expert 14	Practitioner	Marketing manager	Chain supermarket	10 years

Table 11 Excerpt of the Delphi questionnaire

Delphi questionnaire					
Criteria/sub-criteria	Importance of sub-criteria for private-label suppliers				
	Very important	Important	Ambivalent	Unimportant	Very unimportant
	5	4	3	2	1
Economic					
Price of product					
Profit on product					
Production/logistics cost					
Quality of product/service					
Quality management system					

significant criteria. An excerpt of the first-round questionnaire is shown in Table 11. A total of 14 experts were asked to complete the questionnaire. A summary of the first-round results were given to the panelists for reference, and then the panelists were asked to fill out the second-round questionnaire. To achieve stable results, we conducted a third round. Finally, the mean score of each criterion was computed as the final score, and the first 12 criteria were selected as the criteria system, as shown in Table 12.

After the opinions of the industry experts and academics were analyzed, we created 12 PL-SSS criteria using existing research and the practical requirements of the retail field. Three exclusive criteria are proposed: green packages and labels; relationships to manufacturing brands; and product traceability. According to the feedback from panelists, green packages and labels require using green materials and also designing green styles and expressing green hope, because private-label products are sold directly to consumers. Additionally, specialists think that product traceability indicates

reliability to consumers, particularly in food categories, such as eggs and milk. As technology progresses, it is becoming economically feasible for suppliers to include traceable devices in their products. Additionally, a close relationship to a national brand may imply that a product is of a high quality. Therefore, the developed criteria system is sustainable and practical. For all these reasons, these criteria are appropriate for regional retailers that lack manufacturing expertise.

Weight computing

The chief executive officer (D_1), purchasing manager (D_2), and marketing manager (D_3) form the committee as a decision group. After preliminary screening, five manufacturers (A_1, A_2, A_3, A_4, A_5) remained in the candidate list for further evaluation. The decision-making process shows the PL-SSS application of the weight measurement method

Table 12 Private-label SSS criteria

Sustainability dimensions	No	Criteria	Specification
Economic	1	Affordable price (AP)	The lowest market price that supplier can offer to the purchaser
	2	Quality-related certificate (QRC)	Whether the suppliers have quality-related certificates, such as ISO9000 and QS9000, etc
	3	Lead time required (LDE)	Lead time ensures that products are supplied within a marginal lead time
	4	Order flexibility (OF)	Suppliers are flexible to adapt the order quantity of retailers
	5	Design capacity (DC)	The capability of launching new products
Environmental	6	Green package and label (GPL)	The capability of suppliers to consider environmental issues with regard to packaging and labelling material and design
	7	Environment-related certificates (ERC)	Whether the supplier has environment-related certificates, such as ISO 14,000
	8	Green design and purchase (GDP)	Incorporate eco-friendly practices at the design and purchasing stages
	9	Green manufacturing (GM)	The production processes use fewer natural resources, reduce waste and pollution, reuse materials, recycle, and moderate emission
Social	10	Relationship to manufacturing brand (RMB)	Whether suppliers have a long-term relationship with the manufacturing brand
	11	Information disclosure (IS)	Whether the supplier provides information to their customers and stakeholders with regard to material used, carbon emissions and toxins released during production, etc
	12	Product traceability	Whether products can be traced to the place of origin

(Algorithm 2) and fuzzy VIKOR (Algorithm 3) compared to the 12 selected criteria (Table 12).

First, three decision-makers are asked to complete the criteria and supplier evaluation. The results are shown in Tables 13 and 14. Their linguistic variables are transferred to TFNs to construct a fuzzy criteria evaluation matrix and fuzzy decision matrix. The data pre-processing algorithm is used to aggregate and defuzzy the subjective weight matrix and decision matrix (Table 15). Then, its results are input to Algorithm 2 to compute the comprehensive weight. The results of En_j , DG_j , w_j^o values are shown in Table 16.

The subjective weights, objective weights, and overall weights are shown in Table 17. Many factors in subjective weights exhibit equal importance, particularly in economic indexes. It is difficult to distinguish the importance of criteria using only subjective weights; therefore, the given entropy weight compensates for the weight coefficient that describes the criteria degree of differentiation. The subjective weight-replenishing objective weight is a reasonable and feasible weight measurement system. Also, although decision-makers tend to prefer to use affordable pricing as a criterion, the overall weight of affordable pricing is relatively low. Experts indicated that this result may be caused by the following reason: price is deemed the baseline for supplier evaluation; thus, only alternatives that meet the basic price requirement will be evaluated in more detail in other effects.

Regarding comprehensive weights, order flexibility; green packages and labels; relationships to manufacturing brands; and order traceability are important in PL-SSSs. These criteria are important to decision-makers' perspectives and exhibit a high degree of differentiation. Compared to the traditional manufacturing industry, PL-SSSs are more customer-oriented, allowing retailers to express their green image to customers. Also, the demand for private-label products is relatively low, which may require suppliers

Fig. 7 Supplier performance based on each criterion

to be flexible in how they produce low product quantities. Also, the production standardization of consumer goods is relatively lower than that of industrial products; therefore, the significance of criteria is embodied in the value added to products, such as traceability and green packages.

Supplier evaluation

To evaluate suppliers, the comprehensive weight matrix and decision matrix are used as the input to evaluate candidate performance via the VIKOR method (Algorithm 4). Table 18 shows the best (r^*) and worst (r^-) sub-criteria performance, and the final outputs of S , R , Q values are shown in Table 19. We also show the results produced by the TOPSIS (technique for order preference by similarity to ideal solution) method, which indicate that the best alternative has the longest distance to the negative ideal solution and the shortest distance to the positive ideal solution [30].

Although A_2 is ranked best in the S , R , Q values, it has no acceptable advantage: $Q(A_4) - Q(A_2) \not\geq DQ$ ($0.0765 - 0 \not\geq 0.25$). Therefore, A_2, A_4 are considered to be a set of compromise solutions by the VIKOR method. The TOPSIS method shows that A_2 is ranked best and should be chosen as the best supplier. Compared to the TOPSIS method, the VIKOR method provides a solution with acceptable advantages along with the best solution. According to Fig. 7, A_4 exhibits outstanding performance compared to the other three candidates. A more important fact in practical PL-SSS is that retailers tend to choose more than one foundry to guarantee supply stability and safety stock. Different from the motor and electronic industry, the retail industry, which is part of the consumption sector, has different requirements for suppliers, which focuses on product diversity rather than absolute standardization. Therefore, the VIKOR method's compromise solutions are more applicable when solving PL-SSS issues.

We investigated the selected suppliers and found that A_2 is a large national brand manufacturer, and A_4 is a state-owned enterprise. The results of this study also show that these two types of suppliers have strong competitive edges in environmental and social performance. Regional retailers also tend to choose manufacturers with endorsements of large national brands or government backgrounds according to feedback from decision-makers, perhaps because regional retailers lack manufacturing expertise and practices to regulate production.

Conclusions

Although private labels have long-term credibility and have been developed extensively in Europe and North America, they can be characterized as start-ups among Chinese

regional retailers. With today's fierce competitive environment in the retail industry, regional retailers must innovate boldly and differentiate their private-label products to reinforce their competitiveness. However, regional retailers, as downstream enterprises of the supply chain, lack production experience. Therefore, the selection of private-label product manufacturers has become an important factor. To our knowledge, a few studies have evaluated retail private-label suppliers. This paper proposes a three-phase integrated MCDM approach called the PL-SSS model, which combines the Delphi method with fuzzy entropy-VIKOR, to select sustainable suppliers for private-label product manufacturing. We complete four aspects of the study: (1) establish PL-SSS criteria system with 12 criteria; (2) propose a comprehensive weight algorithm with subjective and objective weights; (3) extend the VIKOR method to evaluate suppliers; and (4) compare and analyze the rank results of the VIKOR and TOPSIS methods. Finally, we use a case study to demonstrate the PL-SSS model, which is shown to be an easy and flexible method that can identify reliable and consistent solutions, particularly in customer-oriented and mass-customized private-label businesses. Based on the results of this study, foundry experience and green product packages are worthwhile criteria for retailers in PL-SSSs. The last two phases of the PL-SSS model could be used to evaluate private-label suppliers in practice.

The PL-SSS model can improve the sustainability of private-label manufacturers and make retailers stand out in competitive markets. Other industries could also use this supplier selection model as a reference and tailor the criteria according to their particular business situation. Procurement strategies derived from the results of this study with proper performance will foster better and smoother relationships between private-label manufacturers and retailers. Incorporating sustainability into each part of the retail supply chain will promote the sustainable development of societies, and future studies should develop investigate case studies in different retail settings to complement and refine the criteria described in this study. Additionally, other MCDM techniques, such as TOPSIS and PROMETHEE, could also be used to solve this problem in comparative studies.

Appendix

See Tables 13, 14, 15, 16, 17, 18 and 19.

Table 13 Importance weight of each criterion

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
	AP	QRC	LTR	OF	DC	GPL	ERC	GDP	GM	RMB	IC	PT
D1	VH	VH	M	H	H	VH	M	H	M	VH	M	H
D2	VH	H	H	VH	H	VH	M	M	M	H	L	H
D3	H	VH	H	VH	VH	H	H	H	H	H	L	VH

Table 14 Rates of alternatives

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
D1	A1	VG	F	F	MP	F	MG	MP	MP	MP	P	F	P
	A2	VG	G	VG	MG	VG	VG	G	G	VG	VG	G	VG
	A3	G	F	MG	MP	MG	VG	MG	MG	G	F	VG	VG
	A4	G	G	VG	G	VG	G	G	G	VG	G	MG	MG
	A5	VG	MG	MG	VG	F	MP	F	MP	G	MP	MG	F
D2	A1	VG	F	F	F	G	P	F	MP	F	P	F	P
	A2	G	VG	G	MG	G	VG	G	G	VG	VG	VG	VG
	A3	G	F	F	P	G	G	F	G	VG	F	VG	G
	A4	VG	G	G	MG	G	G	G	VG	G	MG	G	G
	A5	VG	F	G	G	MG	F	MG	F	F	MP	G	MG
D3	A1	VG	G	MG	MP	G	VP	F	F	F	MP	MP	MP
	A2	G	VG	VG	G	VG	G	VG	G	VG	VG	VG	G
	A3	G	MG	F	MP	G	G	F	G	G	MG	VG	G
	A4	VG	VG	G	MG	G	G	G	G	G	G	G	G
	A5	VG	MG	G	G	MG	MP	MG	F	MG	F	G	F

Table 15 Defuzzy subjective weights and fuzzy decision rates

w_j^s		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
		0.83	0.83	0.72	0.83	0.82	0.83	0.68	0.72	0.68	0.82	0.48	0.82
r_{ij}	A1	0.98	0.64	0.58	0.38	0.79	0.11	0.42	0.38	0.42	0.21	0.58	0.21
	A2	0.89	0.91	0.91	0.76	0.91	0.91	0.89	0.88	0.98	0.98	0.91	0.91
	A3	0.88	0.58	0.58	0.24	0.79	0.89	0.58	0.79	0.89	0.58	0.98	0.89
	A4	0.91	0.89	0.89	0.76	0.89	0.88	0.88	0.89	0.89	0.79	0.79	0.79
	A5	0.98	0.62	0.79	0.89	0.62	0.38	0.53	0.42	0.68	0.38	0.79	0.58

Table 16 Entropy measure, divergence, and objective weights

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
En_j	0.9994	0.9885	0.9885	0.9419	0.9946	0.8957	0.9741	0.963	0.9763	0.9278	0.9912	0.9439
DG_j	0.0006	0.0115	0.0115	0.0581	0.0054	0.1043	0.0259	0.037	0.0237	0.0722	0.0088	0.0561
w_j^0	0.0015	0.0278	0.0277	0.1398	0.0131	0.2512	0.0624	0.0892	0.0571	0.174	0.0211	0.1352

Table 17 PL-SSS criteria weights

No. 1	Criteria	Subjective weight		Objective weight		Comprehensive weight	
C1	AP	0.0919	1st	0.0015	12th	0.0133	12th
C2	QRC	0.0919	1st	0.0278	8th	0.0564	8th
C3	LTR	0.0790	8th	0.0277	9th	0.0522	9th
C4	OF	0.0919	1st	0.1398	3rd	0.1265	3rd
C5	DC	0.0901	5th	0.0131	11th	0.0383	10th
C6	GPL	0.0919	1st	0.2512	1st	0.1696	1st
C7	ERC	0.0754	10th	0.0624	6th	0.0765	6th
C8	GDP	0.0790	8th	0.0892	5th	0.0937	5th
C9	GM	0.0754	10th	0.0571	7th	0.0732	7th
C10	RMB	0.0901	5th	0.1740	2nd	0.1397	2nd
C11	IC	0.0533	12th	0.0211	10th	0.0374	11th
C12	PT	0.0901	5th	0.1352	4th	0.1231	4th

Table 18 r^+ and r^- for each criterion

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
r^+	0.975	0.908	0.9083	0.8917	0.9083	0.9083	0.8917	0.8917	0.975	0.975	0.975	0.9083
r^-	0.875	0.5833	0.5833	0.2417	0.6167	0.1083	0.4167	0.3833	0.4167	0.2083	0.5833	0.2083

Table 19 VIKOR and TOPSIS results

	VIKOR results							TOPSIS results	
	S_i		R_i		Q_i			Closeness coefficient	
A1	0.926	5th	0.1696	5th	1	5th	0.1154	4th	
A2	0.0465	1st	0.0259	1st	0	1st	6.2322	1st	
A3	0.4206	3rd	0.1265	3rd	0.5627	3rd	2.2338	3rd	
A4	0.1347	2nd	0.0334	2nd	0.0761	2nd	4.1934	2nd	
A5	0.5861	4th	0.1113	4th	0.6038	4th	0.9098	5th	

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Declarations

Conflict of interest The authors declare no conflict of interest. We ensure the availability of data and material and code.

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