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Description	

A Linguistic Screening Evaluation Model in New Product Development

Van-Nam Huynh, *Member, IEEE*, and Yoshiteru Nakamori, *Member, IEEE*

***Abstract*—The screening of new product ideas is critically very important in new product development (NPD). Due to the incompleteness of information available and the qualitative nature of most evaluation criteria regarding NPD process, a fuzzy linguistic approach may be necessary for new-product screening, making use of linguistic assessments and the fuzzy-set-based computation. However, an inherent limitation of such a fuzzy linguistic approach is the loss of information caused by approximation processes, which eventually implies a lack of precision in the final results. This limitation even becomes more critical when applying the approach to new product screening. This paper proposes an approach to new product go/stop evaluation at the front end in NPD, based on the 2-tuple linguistic representation and the so-called preference-preserving transformation. It is shown that the proposed approach always yields a consistent result, while maintaining the flexibility for managers in making their decisions as in the fuzzy-set-based approach. Ultimately, this approach enhances the fuzzy-logic-based screening model proposed in the previous studies by overcoming the mentioned limitation. A case study taken from the literature is used to illuminate the proposed technique and to compare with the previous technique based on fuzzy computation.**

***Index Terms*—Computing with words, decision making, linguistic multicriteria decision, new product go/stop evaluation, new product screening.**

I. Introduction

New PRODUCT development (NPD) is a dynamically complex and multistage process that ranges from idea generation through product lunch [4], [22]. As stated by Cooper [3], project selection is pivotal to effective risk reduction in NPD. Typically, the screening of new product ideas aims to help managers eliminating risky NPD projects at early stages of NPD before significant investments are made and opportunity costs incurred [21]. At the same time, terminating an inferior new product prior to commercialization results in unrecoverable sunk costs and resource consumption, which may, in turn, influence future screening decisions [6], [21]. These make the screening of a new product project critically very important [1]. However, it has been poorly or inadequately performed, as reported in the literature [2], [5], [6], [24].

During the last decades, we have witnessed many decision models and approaches already developed for tackling the process of screening new products. Good summaries of decision models for new product screening and their analysis can be referred to, e.g., [5]–[7]. The development of a particular decision model for the problem at hand is usually dependent on the nature of information and data available as well as the background of analysts involved. In the context of new product screening, the decision of a firm/organization on selecting a new product project for further development is not only depending on the profit maximization motive and characteristics of new product itself, but also depending on important aspects such as the firm's technological competency and marketing competition. Moreover, due to the qualitative nature of most evaluation criteria or features regarding new product screening process, the data available are mostly qualitative and may be expressed only by means of linguistic terms [5]. A fuzzy linguistic approach may then be realistic and necessary. Machacha and Bhattacharya [23] have developed a fuzzy reasoning system for selection of software projects. Liginlal *et al*. [5] have recently proposed a fuzzy measure theoretical framework for new product screening. In fact, their measure theoretical framework is essentially based on a multiattribute decision model that uses the Choquet integral as an aggregation functional associated with a fuzzy measure modeling relatively important weights of attributes. Lin and Chen [6], [7] have proposed a linguistic screening evaluation framework and developed a fuzzy multiple criteria decision model based on the notion of linguistic variables [27]–[29] and a fuzzy weighted average operator [18] for screening decision making. Basically, main features of Lin and Chen's linguistic screening model can be summarized as follows.

1) The problem of new product screening decision making is formulated as a multiexpert multicriteria decision-making problem.
2) Experts' assessments and the relative importance of criteria are expressed by linguistic terms semantically represented by fuzzy numbers.
3) A fuzzy weighted average operator is used to derive an overall value interpreted as fuzzy-possible-success rating (FPSR) of the new product project.
4) Finally, a process of linguistic approximation is applied to obtain the linguistic success level of the new product project as a suggestion to managers for making the screening decision.

While this fuzzy-logic-based screening model can efficiently support managers in dealing with both fuzzy uncertainty and complexity in new product screening decisions, it simultaneously has, as any fuzzy-computation-based approach, an unavoidable limitation of the loss of information caused by the process of linguistic approximation, which consequently

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implies a lack of precision in the final result. Note further that, as we observed from Lin and Chen [6], [7], the subjective definition of membership functions can sensitively influence the solution as well. In particular, with different definitions of membership functions of linguistic success levels (refer to Section V), different results are obtained in [6] and [7] for the same case study. These disadvantages of the fuzzy-computation-based approach would be especially and critically important in the context of new product screening as mentioned earlier.

Motivated by overcoming these disadvantages in the linguistic new product screening framework, this paper presents an alternative linguistic screening evaluation model with the computation solely based on the order-based semantics of the linguistic terms and the 2-tuple linguistic representation proposed in [10]. The main contribution of this paper is to introduce a new concept of preference-preserving 2-tuple transformation serving (see Section IV-B) for unification of linguistic information expressed by different term sets, which then allows us to develop the linguistic screening evaluation model based upon 2-tuple representation of linguistic information. It is worth noting that by performing direct computation on linguistic terms in the proposed approach, the burden of quantifying qualitative concepts is eliminated, and particularly, as illustrated with the case study, the result yielded by this method is consistent and comparable to previous work in terms of efficiency and flexibility.

The rest of the paper is organized as follows. Section II briefly describes the linguistic screening evaluation framework and main tasks for implementation of the screening evaluation. Section III presents Lin and Chen's fuzzy-computation-based evaluation model. In Section IV, after introducing the Herrera and Martinez's 2-tuple linguistic representation model, we introduce the notion of a preference-preserving 2-tuple transformation and then develop a 2-tuple linguistic evaluation model for new product screening. Section V presents a comparative study conducted with the same case study used by Lin and Chen [6] for illuminating the proposed method. Finally, Section VI concludes the paper with some concluding remarks.

II. New Product Screening: The Linguistic Assessment-Based Framework

The linguistic screening evaluation framework proposed by Lin and Chen [6] is graphically depicted in Fig. 1. It basically consists of three main parts as briefly described in the following.

A. Selecting Criteria for Evaluation

Typically, a new product project is characterized by a variety of features or characteristics of both quantitative and qualitative in nature. Moreover, a new product screening evaluation depends not only on the new product's characteristics but also on a firm's technological competency and marketing competition, which would play essentially important roles in creating the success of new product. With a comprehensive reference to the most factors proposed in previous studies, Lin and Chen [6], [7] have proposed a selected set of criteria regarding the screening evaluation for an NPD project, as shown in Table I.

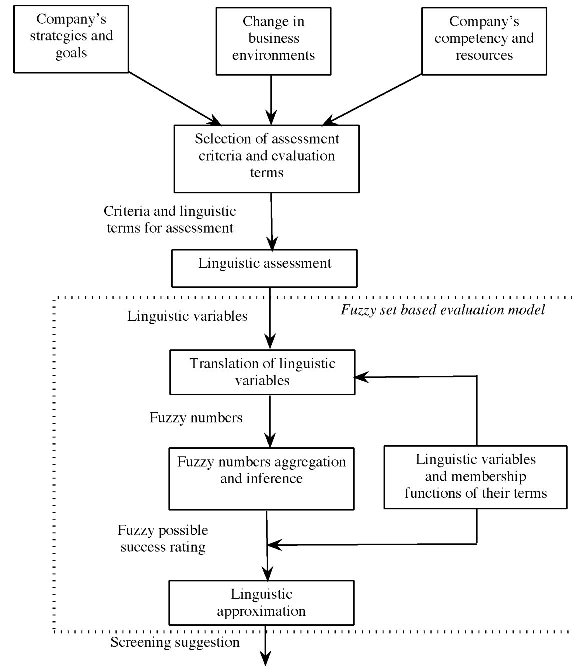

Fig. 1. New product screening evaluation framework.

B. Selecting Linguistic Term Sets and Their Associated Semantics

Essentially, in any linguistic approach to solving a problem, term sets of involved linguistic variables and their associated semantics must be defined first to supply users with an instrument by which they can naturally express their information. In accomplishing this objective, one of main approaches often used in the literature is to directly define, for each linguistic variable involved, a finite linguistic term set associated with a fuzzy set representation of its linguistic terms distributing on a scale on which a total order is defined (see [11] for more details). This approach has been used by Lin and Chen [6], [7] in developing their fuzzy-logic-based screening model. In particular, they have designed four linguistic term sets with associated fuzzy set semantics for use as follows.

1) The first term set for linguistically rating different criteria of the factors regarding the product-marketing competitive advantages, product superiority, and technological suitability:

$$\mathcal{S}_1 = \{s_0^1(\text{Worst}), s_1^1(\text{Very Poor}), s_2^1(\text{Poor}), s_3^1(\text{Fair}), s_4^1(\text{Good}), s_5^1(\text{Very Good}), s_6^1(\text{Best})\} \tag{1}$$

and the associated fuzzy set semantics is shown in Fig. 2.

2) The second term set for linguistically assessing risky factors, such as market competitive, technological uncertainty, and monetary risk regarding an NPD project

$$\mathcal{S}_2 = \{s_0^2(\text{Low}), s_1^2(\text{Fairly Low}), s_2^2(\text{Medium}), s_3^2(\text{Fairly High}), s_4^2(\text{High}), s_5^2(\text{Very High}), s_6^2(\text{Extremely High})\} \tag{2}$$

with the associated fuzzy set semantics shown in Fig. 3.

TABLE I
PRODUCT EVALUATION AND SELECTED CRITERIA [6]

Criteria		Description
Competitive marketing advantages (C_1)	Marketing timing (C_{11})	Matches desired entry timing needed ny target segments
	Price superiority (C_{12})	Offers value for money to target segments
	Marketing competencies (C_{13})	Conforms to our salesforce, channels of distribution and logistical strengths
	Marketing attractiveness (C_{14})	Permits the company to enter into a growing, high-potential market
Superiority (C_2)	Functional competency (C_{21})	Has unique or special functions to meet and attract target segments
	Featured differentia (C_{22})	Has unique or special features to attract target segments
Technological suitability (C_3)	Design quality (C_{31})	Is design for the quality needed by target segments
	Material specialization (C_{32})	Uses materials of high quality and low rejection
	Manufacturing compatibility (C_{33})	Can be produced by our best manufacturing technology and flexibility
	Supply benefit (C_{34})	Allows the company to use very best suppliers
Risk (C_4)	Market competitiveness (C_{41})	Allows many competitive products in the market
	Technological uncertainty (C_{42})	Uses new technological skills that cannot be addressed by research
	Monetary risk (C_{43})	Products total dollar risk profile of product

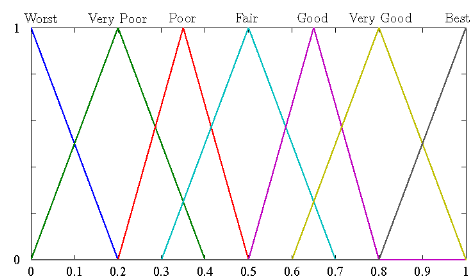

Fig. 2. Linguistic effect rating values and their fuzzy number semantics.

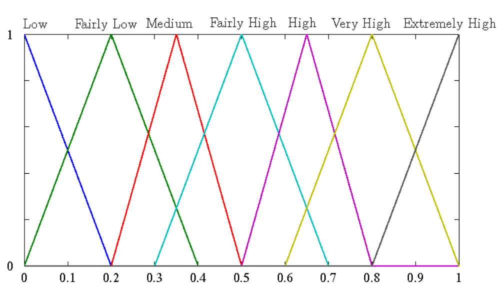

Fig. 3. Linguistic risk possibility rating values and their fuzzy number semantics.

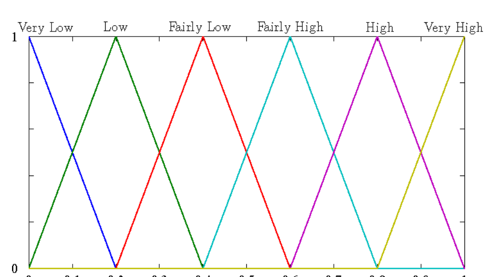

Fig. 4. Linguistic weights and their fuzzy number semantics.

3) The third term set and associated fuzzy set semantics (see Fig. 4) for linguistically evaluating the relative importance of different criteria

$$\mathcal{S}_3 = \{s_0^3(\text{Very Low}), s_1^3(\text{Low}), s_2^3(\text{Fairly Low}), s_3^3(\text{Fairly High}), s_4^3(\text{High}), s_5^3(\text{Very High})\} \quad (3)$$

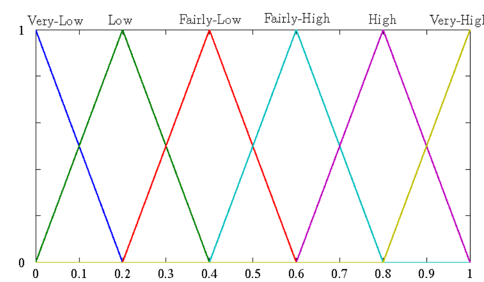

Fig. 5. Linguistic success levels and their fuzzy number semantics.

4) The fourth term set $\mathcal{S}_4$ consists of linguistic success levels associated with their fuzzy set semantics (see Fig. 5) for approximating the so-called *FPSR* of an NPD project that results from the computational procedure of the screening evaluation

$$\mathcal{S}_4 = \{s_0^4(\text{Very Low}), s_1^4(\text{Low}), s_2^4(\text{Fairly Low}), s_3^4(\text{Fairly High}), s_4^4(\text{High}), s_5^4(\text{Very High})\}. \quad (4)$$

Note that Lin and Chen [6], [7] exactly used the same term set $\mathcal{S}_4$ for representing linguistic success levels, however, with two different fuzzy set representations of linguistic terms (one as depicted in Fig. 5 [6] and the other as shown in Fig. 8 [7]). This consequently influences the final result when matching the FPSR of an NPD project with fuzzy sets representing linguistic success levels, as discussed in the Section V.

C. Gathering Data and Developing Computational Model for Evaluation

Once the criteria for evaluation as well as measurement scales serving for linguistic assessments have been carefully selected and designed, a finite set of evaluators (i.e., experts), denoted by $P = \{E_1, \ldots, E_m\}$, is called to assess the new product project under consideration in terms of selected criteria, making use of linguistic assessments. In addition, the experts would be also asked to provide their opinions on the relative important of the different criteria. Formally, the linguistic data obtained by this way can be described, as in Table II, where x_{ij} $(i = 1, \ldots, m; j = 1, \ldots, k)$ is the linguistic rating of expert E_i regarding criterion c_j, and w_{ij} $(i = 1, \ldots, m; j = 1, \ldots, k)$ is the linguistic weight, which expert E_i assigns to criterion c_j.

TABLE II
LINGUISTIC ASSESSMENTS AND RATINGS OF CRITERIA BY A GROUP OF EXPERTS

Experts	Criteria							
	Favorable Criteria				Unfavorable Criteria			
	F_1	F_2	$\cdots$	F_{k_1}	F_{k_1+1}	F_{k_1+2}	$\cdots$	F_k
E_1	$[x_{11}, w_{11}]$	$[x_{12}, w_{12}]$	$\cdots$	$[x_{1k_1}, w_{1k_1}]$	$[x_{1k_1+1}, w_{1k_1+1}]$	$[x_{1k_1+2}, w_{1k_1+2}]$	$\cdots$	$[x_{1k}, w_{1k}]$
E_2	$[x_{21}, w_{21}]$	$[x_{22}, w_{22}]$	$\cdots$	$[x_{2k_1}, w_{2k_1}]$	$[x_{2k_1+1}, w_{2k_1+1}]$	$[x_{2k_1+2}, w_{2k_1+2}]$	$\cdots$	$[x_{2k}, w_{2k}]$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
E_m	$[x_{m1}, w_{m1}]$	$[x_{m2}, w_{m2}]$	$\cdots$	$[x_{mk_1}, w_{mk_1}]$	$[x_{mk_1+1}, w_{mk_1+1}]$	$[x_{mk_1+2}, w_{mk_1+2}]$	$\cdots$	$[x_{mk}, w_{mk}]$

From the linguistic evaluation data collected, we then aim at developing a suitable computing method that allows for aggregation of linguistic information to ultimately derive an overall merit or attractiveness value supporting for the screening decision of an NPD project. Lin and Chen [6], [7] have developed a fuzzy-logic-based screening model, making use of a fuzzy-set-based computational method and linguistic approximation. In the subsequent, we shall propose a novel linguistic screening model based on the 2-tuple linguistic representation of linguistic information [10] and preference-preserving 2-tuple transformations. Before doing so, however, it is necessary to briefly summarize main features of Lin and Chen's fuzzy-set-based evaluation model.

III. LIN AND CHEN'S EVALUATION MODEL: A FUZZY COMPUTATION-BASED APPROACH

Lin and Chen [6] have recently proposed a fuzzy-set-based computational model to aggregate the different decision makers' opinions for deriving the *FPSR* of a new product project. Essentially, this computational model is based on Zadeh's *extension principle* [27]–[29] in computation with fuzzy numbers and a linguistic approximation method. In addition, their fuzzy-logic-based screening model has been then illustrated in detail with an application to go/no-go decision making for a new machining center development at Taiwan Victory (TV) Company [7].

Formally, assume that linguistic assessments gathered for a screening evaluation is formally described in Table II, where:

1) each x_{ij}, for $i = 1, \ldots, m$, and $j = 1, \ldots, k_1$ (i.e., for favorable criteria or attractive factors), is a linguistic effect rating value semantically represented as a fuzzy number R_{ij} taken from the linguistic term set $\mathcal{S}_1$;
2) each x_{ij}, for $i = 1, \ldots, m$, and $j = k_1 + 1, \ldots, k$ (i.e., for unfavorable criteria or risk factors), is a linguistic risk possibility rating value semantically represented as a fuzzy number R'_{ij} taken from the linguistic term set $\mathcal{S}_2$;
3) each w_{ij}, for $i = 1, \ldots, m$, and $j = 1, \ldots, k$, is a linguistic weight semantically represented as a fuzzy number W_{ij} taken from the linguistic term set $\mathcal{S}_3$.

Then, Lin and Chen's procedure for deriving an overall merit value can be briefly summarized as follows.

1) *Experts' Opinion Aggregation.* For each $j = 1, \ldots, k$, the average effect rating R_j, the average risk possibility rating R'_j, and the average important weight W_j are computed as

$$R_j = \frac{1}{m} \otimes (R_{1j} \oplus R_{2j} \oplus \cdots \oplus R_{mj}), \quad j = 1, \ldots, k_1 \tag{5a}$$

$$R'_j = \frac{1}{m} \otimes (R'_{1j} \oplus R'_{2j} \oplus \cdots \oplus R'_{mj}), \quad j = k_1 + 1, \ldots, k \tag{5b}$$

$$W_j = \frac{1}{m} \otimes (W_{1j} \oplus W_{2j} \oplus \cdots \oplus W_{mj}), \quad j = 1, \ldots, k \tag{6}$$

where $\otimes$ and $\oplus$ stand for the extended multiplication and the extended addition over fuzzy numbers.
2) *Criteria Aggregation.* Weighted aggregation of criteria by means of fuzzy weighted averaging operator to obtain a FPSR $\mathcal{F}$:

$$\mathcal{F} = \frac{\sum_{j=1}^{k_1} R_j \otimes W_j \oplus \sum_{j=k_1+1}^{k} (1 \ominus R'_j) \otimes W_j}{\sum_{j=1}^{k} W_j} \tag{7}$$

where $\ominus$ stands for the extended subtraction over fuzzy numbers. Computing the expression (7) for the FPSR $\mathcal{F}$ is carried out using the fractional programming approach developed by Kao and Liu [18], [19].
3) *Linguistic Approximation.* Once the FPSR $\mathcal{F}$ for new product has been obtained, a linguistic approximation method based on Euclidean distance is used to match $\mathcal{F}$ with linguistic success levels from $\mathcal{S}_4$ with its associated fuzzy numbers semantics. The linguistic success level which matches best the FPSR $\mathcal{F}$ will be chosen as a guidance to the decision maker.

IV. NEW EVALUATION MODEL BASED ON 2-TUPLE LINGUISTIC PRESENTATION

A. Computational Model Based on Linguistic 2-Tuples

The 2-tuple linguistic representation model was proposed in [10] as a tool for computing with words that aims at overcoming the limitation of the loss of information caused by the process of linguistic approximation in fuzzy-set-based approaches. This model has been applied to group decision making [12]–[14], distributed intelligent agent systems [8], information filtering [15], information retrieval [20], and recently engineering management [26].

1) 2-Tuple Representation of Linguistic Information: Let $\mathcal{S} = \{s_0, \ldots, s_g\}$ be a linguistic term set on which a total order is defined as: $s_i \le s_j \Leftrightarrow i \le j$. In addition, a negation operator Neg can be defined by: $\mathrm{Neg}(s_i) = s_j$ such that $j = g - i$, where $g + 1$ is the cardinality of $\mathcal{S}$. In general, applying a symbolic method [16] for aggregating linguistic information often yields a value $\beta \in [0, g]$, and $\beta \notin \{0, \ldots, g\}$, then a symbolic approximation must be used to get the result expressed in $\mathcal{S}$.

To avoid any approximation process which causes a loss of information in the processes of computing with words, alternatively the 2-tuple linguistic representation model takes $\mathcal{S} \times [-0.5, 0.5)$ as the underlying space for representing information. In this representation space, if a value $\beta \in [0, g]$ representing the result of a linguistic aggregation operation, the 2-tuple (s_i, α) that expresses the equivalent information to β is obtained by means of the following transformation:

$$\begin{aligned}\Delta : [0, g] &\longrightarrow \mathcal{S} \times [-0.5, 0.5) \\ \beta &\longmapsto (s_i, \alpha)\end{aligned}$$

with $i = \mathrm{round}(\beta)$ and $\alpha = \beta - i$. Then, α is called a *symbolic translation*, which supports the "difference of information" between a counting of information $\beta \in [0, g]$ obtained after a symbolic aggregation operation and the closest value in $\{0, \ldots, g\}$ indicating the index of the best matched term in $\mathcal{S}$.

Inversely, a 2-tuple $(s_i, \alpha) \in \mathcal{S} \times [-0.5, 0.5)$ can be also equivalently represented by a numerical value in $[0, g]$ by means of the following transformation:

$$\begin{aligned}\Delta^{-1} : \mathcal{S} \times [-0.5, 0.5) &\longrightarrow [0, g] \\ (s_i, \alpha) &\longmapsto \Delta^{-1}(s_i, \alpha) = i + \alpha.\end{aligned}$$

2) Comparison of Linguistic 2-Tuples and Negation: The comparison of linguistic information represented by 2-tuples is defined as follows. Let (s_i, α_1) and (s_j, α_2) be two 2-tuples, then $(s_i, \alpha_1) > (s_j, \alpha_2)$ if either $i > j$ or $[i = j$ and $\alpha_1 > \alpha_2]$. Using two 2-tuple transformations defined earlier, the negation operator over 2-tuples is defined by

$$\mathrm{Neg}((s_i, \alpha)) = \Delta(g - (\Delta^{-1}(s_i, \alpha))) \tag{8}$$

3) Aggregation of Linguistic 2-Tuples: Making use of 2-tuple transformations Δ and Δ^{-1}, linguistic information represented by 2-tuples can be transformed into numerical information and *vice versa* without loss of information. Therefore, many aggregation operators proposed in the literature for dealing with numerical information can be easily extended to work out with linguistic 2-tuples [8], [10], [15].

Let $\mathbf{x} = [(r_1, \alpha_1), \ldots, (r_n, \alpha_n)]$ be a vector of linguistic 2-tuples, the 2-tuple arithmetic mean $\overline{\mathbf{x}}^e$ is computed as

$$\overline{\mathbf{x}}^e((r_1, \alpha_1), \ldots, (r_n, \alpha_n)) = \Delta\left(\sum_{i=1}^{n} \frac{1}{n} \Delta^{-1}(r_i, \alpha_i)\right). \tag{9}$$

Allowing different 2-tuples $\mathbf{x}_i = (r_i, \alpha_i)$ have different numerical weights indicating their relative importance in the aggregation, the weighted average operator over 2-tuples is then defined similarly. In addition, the weighted average operator can be also extended for dealing with the cases where weights are expressed by means of linguistic values [16]. This extension results in the linguistic weighted average operator defined as follows [8], [15].

Let $\mathbf{x} = [(r_1, \alpha_1), \ldots, (r_n, \alpha_n)]$ be a vector of linguistic 2-tuples and $\mathbf{w} = [(w_1, \alpha'_1), \ldots, (w_n, \alpha'_n)]$ be its associated vector of 2-tuple linguistic weights. Then, the 2-tuple linguistic weighted average $\overline{\mathbf{x}}_l^w$ is

$$\begin{aligned}&\overline{\mathbf{x}}_l^w([(r_1, \alpha_1), \ldots, (r_n, \alpha_n)], [(w_1, \alpha'_1), \ldots, (w_n, \alpha'_n)]) \\ &\quad = \Delta\left(\frac{\sum_{i=1}^{n} \Delta^{-1}(r_i, \alpha_i).\Delta^{-1}(w_i, \alpha'_i)}{\sum_{i=1}^{n} \Delta^{-1}(w_i, \alpha'_i)}\right).\end{aligned} \tag{10}$$

B. Preference-Preserving 2-Tuple Transformation

In a numerical context of multicriteria aggregation, information are often needed to be unified before performing any aggregation process by means of normalization methods. This is basically due to inhomogeneous nature of different measurement scales/units used for different criteria in the evaluation process. Such an unification operation is usually needed in the linguistic setting of multicriteria aggregation as well. It should be emphasized here that a process of unifying linguistic information has been implicitly used in [6], [7] by embedding membership functions of all linguistic terms from different term sets into the space of fuzzy numbers on $[0, 1]$. Therefore, in order to make the 2-tuple linguistic representation model applicable to the problem of multiexpert/multicriteria linguistic evaluation for go/no-go decision in NPD, it is necessary to find out a mechanism for unifying linguistic information represented by means of 2-tuples from different term sets.

To this end, we first define the following notion of preference-preserving 2-tuple transformation between two term sets. Let $\mathcal{S} = \{s_0, \ldots, s_g\}$ and $\mathcal{S}' = \{s'_0, \ldots, s'_{g'}\}$ be two linguistic term sets. Note that the total order on $\mathcal{S}$ (and $\mathcal{S}'$ as well), denoted by $\le_{\mathcal{S}}$, is either "in agreement with" or "reverse to" the preference order, denoted by $\preceq_{\mathcal{S}}$, imposed on the criterion assessed by means of linguistic values in $\mathcal{S}$, i.e., for the case of "in agreement with," the greater a linguistic value, the higher preference; and by contrast, the greater a linguistic value, the lower preference for the case of "reverse to." For example, the order relation on $\mathcal{S}_1$ defined earlier is in agreement with the preference order imposed on factors of the product-marketing competitive advantages, product superiority, and technological suitability, while the order relation on $\mathcal{S}_2$ is reverse to the preference order imposed on risky factors as market competitive, technological uncertainty and monetary risk. Now, without loss of generality, assuming that $\le_{\mathcal{S}}$ is in agreement with $\preceq_{\mathcal{S}}$. Having these considerations in mind, we are ready to define the preference-preserving 2-tuple transformation between $\mathcal{S}$ and $\mathcal{S}'$ as follows:

$$\begin{aligned}\Lambda :\ \mathcal{S} \times [-0.5, 0.5) &\longrightarrow \mathcal{S}' \times [-0.5, 0.5) \\ (s_i, \alpha) &\longmapsto \Lambda((s_i, \alpha)) = (s'_j, \alpha')\end{aligned} \tag{11}$$

such that

$$\begin{cases} j = \text{round}\left(\frac{g'}{g}(i+\alpha)\right) \\ \alpha' = \frac{g'}{g}(i+\alpha) - j \end{cases} \tag{12}$$

if $\leq_{\mathcal{S}'}$ is in agreement with $\preceq_{\mathcal{S}'}$, i.e., $\preceq_{\mathcal{S}'} \equiv \leq_{\mathcal{S}'}$, and

$$\begin{cases} j = \text{round}\left(g' - \frac{g'}{g}(i+\alpha)\right) \\ \alpha' = g' - \frac{g'}{g}(i+\alpha) - j \end{cases} \tag{13}$$

otherwise, i.e., $\preceq_{\mathcal{S}'} \equiv \leq_{\mathcal{S}'}^{-1}$ – the inversion of $\leq_{\mathcal{S}'}$. It is easily seen that

$$\Lambda = \begin{cases} \Delta \circ \tau \circ \Delta^{-1}, & \text{if } \preceq_{\mathcal{S}'} \equiv \leq_{\mathcal{S}'} \\ \text{Neg} \circ \Delta \circ \tau \circ \Delta^{-1}, & \text{if } \preceq_{\mathcal{S}'} \equiv \leq_{\mathcal{S}'}^{-1} \end{cases}$$

where $\circ$ is the composition, and $\tau : [0, g] \to [0, g']$ such that $\tau(x) = \frac{g'}{g}x$.

Due to the order-preserving property of Δ and Δ^{-1} as well as the definitions of τ and Neg, it then straightforwardly follows that Λ is preference-preserving, i.e.,

$$\text{if } (s_i, \alpha_1) \preceq_{\mathcal{S}} (s_j, \alpha_2), \text{then } \Lambda((s_i, \alpha_1)) \preceq_{\mathcal{S}'} \Lambda((s_j, \alpha_2)).$$

As such, the transformation Λ allows us to transform inhomogeneous linguistic information into the 2-tuple representation of a specific linguistic term set preserving the preference of all the criteria. In addition, in decision-making problems involving multiple experts, different experts may have different granularities of uncertainty regarding linguistic variables used for representing their assessments of criteria, depending on their own knowledge and/or their psychological characteristics. In such cases, we can also use the transformation Λ to unify multiple experts' information for the aggregation.

C. 2-Tuple Linguistic Evaluation Model

Let us return to the screening evaluation problem with linguistic information as described in Table II. For the sake of simplicity but without loss of generality, we assume that the same linguistic term set $\mathcal{S}_1$ is used for rating favorable criteria F_j ($j = 1, \ldots, k_1$), and the same linguistic term set $\mathcal{S}_2$ is used for rating unfavorable criteria F_j ($j = k_1 + 1, \ldots, k_1 + k_2$). Also, the term set $\mathcal{S}_3$ is used for representing the relative important weights of criteria.

With all the preparations made previously, the screening evaluation procedure based on 2-tuple linguistic representation is described as following.

1) 2-Tuple Linguistic Transformation and Unification: This step aims at transforming original linguistic information of an NPD project assessed by experts against a set of criteria into an unified representation by means of 2-tuples. It is composed of the following steps.

1) Convert original linguistic assessments and weights, as shown in Table II, into corresponding linguistic 2-tuples by adding a symbolic translation value of 0: $x_{ij} \Rightarrow (x_{ij}, 0)$ and $w_{ij} \Rightarrow (w_{ij}, 0)$.
2) Choose a specific linguistic term set used for information unification. In the context of screening evaluation problems, a term set of linguistic preferences $\mathcal{S}_p$ could be chosen. For example, a seven-term set of linguistic preferences is shown in (17).
3) Transform 2-tuple linguistic assessments $(x_{ij}, 0)$ into 2-tuples represented in $\mathcal{S}_p \times [-0.5, 0.5)$, making use of the following preference-preserving 2-tuple transformations:

$$\Lambda_1 : \mathcal{S}_1 \times [-0.5, 0.5) \to \mathcal{S}_p \times [-0.5, 0.5)$$
$$\Lambda_2 : \mathcal{S}_2 \times [-0.5, 0.5) \to \mathcal{S}_p \times [-0.5, 0.5)$$

where Λ_1 and Λ_2 are defined by (12) and (13), respectively. Let us denote

$$(y_{ij}, \alpha_{ij}) = \begin{cases} \Lambda_1((x_{ij}, 0)), & \text{for } j = 1, \ldots, k_1 \\ \Lambda_2((x_{ij}, 0)), & \text{for } j = k_1 + 1, \ldots, k. \end{cases}$$

2) 2-Tuple Linguistic Computation and Aggregation:

1) Multiexpert aggregation for computing 2-tuples of the average important weights and the average preferences of criteria via (9) as

$$(w_j, \alpha_j^w) = \Delta\left(\sum_{i=1}^{m} \frac{1}{m} \Delta^{-1}(w_{ij}, 0)\right) \tag{14}$$

$$(r_j, \alpha_j) = \Delta\left(\sum_{i=1}^{m} \frac{1}{m} \Delta^{-1}(y_{ij}, \alpha_{ij})\right) \tag{15}$$

for $j = 1, \ldots, k$.
2) Computing an overall figure of merit which typically expresses the preference regarding the NPD project under consideration via (10) as

$$(r, \alpha) = \Delta\left(\frac{\sum_{j=1}^{k} \Delta^{-1}(r_j, \alpha_j)\Delta^{-1}(w_j, \alpha_j^w)}{\sum_{j=1}^{k} \Delta^{-1}(w_j, \alpha_j^w)}\right) \tag{16}$$

3) 2-Tuple Linguistic Conversion: Convert the overall value of preference for the NPD project represented by 2-tuple (r, α) in $\mathcal{S}_p \times [-0.5, 0.5)$ into the corresponding 2-tuple of linguistic success levels in $\mathcal{S}_4 \times [-0.5, 0.5)$, i.e., $\Lambda((r, \alpha))$,which will be provided to the decision maker as a guidance for his/her screening decision.

Integrating this 2-tuple-based evaluation model into the new product screening evaluation framework, instead of fuzzy-set-based evaluation model developed by Lin and Chen [6], suggests a 2-tuple-based screening evaluation framework, as shown in Fig. 6.

V. Illustrative Application Example

In this section, we will show how the 2-tuple linguistic evaluation model developed previously works in practice by considering a case study taken from [6] and [7].

The studied application is the development of a new machining center at the TV Company, an internationally renowned machine-tool company with its products including conventional lathes, high-precision tools, and machining centers. To increase

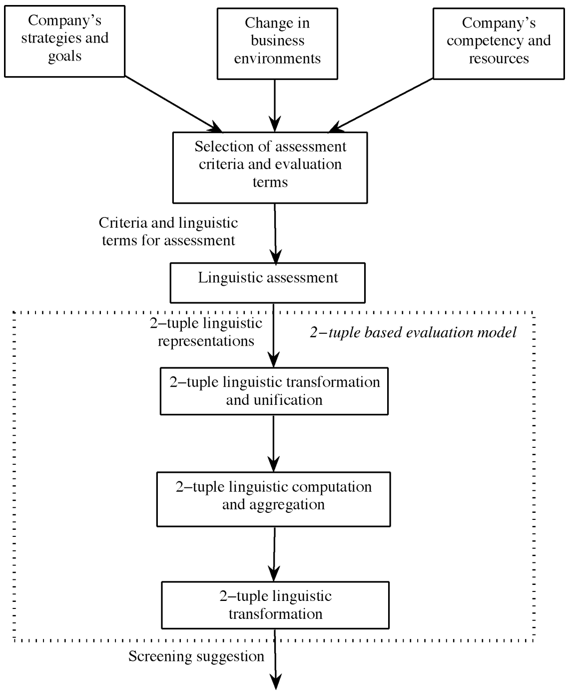

Fig. 6. 2-Tuple-based screening evaluation framework.

competitiveness of the company as well as to capture a potentially global market in the 21st century, TV decided to expand its product line to include large-size horizontal machining centers to supply the world market. Then, the new product so-called TVcenter-HX was proposed and its launching decision was reached making use of the fuzzy-logic-based evaluation approach. For detail discussions regarding the technical and business aspects of this NPD project, see [7].

Analysis and evaluation of the TVcenter-HX project were conducted by a screening committee consisting of four experts from marketing, technology, operations, and finance departments. Thirteen criteria were selected for the evaluation and categorized into four groups, as shown in Table I. The favorable criteria belonging to factors of competitive marketing advantages of the new product, its superiority, and technological suitability were assessed by experts using linguistic terms from $\mathcal{S}_1$ [refer to (1)], while the unfavorable criteria regarding company's risk profile were assessed by means of linguistic terms in $\mathcal{S}_2$ [refer to (2)]. Moreover, experts also assessed relative important of criteria using linguistic weights taken from $\mathcal{S}_3$ [refer to (3)]. Table III shows the result of linguistic assessments and linguistic weights of criteria judged by experts, denoted by E_i ($i = 1, 2, 3, 4$), regarding the TVcenter-HX project.

A. *Result of 2-Tuple Linguistic Evaluation*

Let us apply the 2-tuple linguistic evaluation model developed earlier to the TVcenter-HX project with linguistic information shown in Table III.

First, original linguistic assessments and weights are equivalently represented by means of 2-tuples by adding a symbolic translation value of 0 and the seven-term set $\mathcal{S}_p$ of linguistic preferences shown in (17), as shown at the bottom of this page, is selected for unifying information. The selection of $\mathcal{S}_p$ is based on psychological observation found in [25] and also consistent with the normalization scheme implicitly considered in [6]. However, this does not exclude the possibility of using any other term set of linguistic preferences having different granularity of uncertainty depending on the requirement of a particular situation and/or the psychological character of users. Further, it is interesting to note that the final result does not depend on the granularity, i.e., the cardinality, of $\mathcal{S}_p$.

Second, applying the preference-preserving 2-tuple transformation to unify linguistic assessments of criteria into 2-tuples represented in $\mathcal{S}_p \times [-0.5, 0.5)$ and then computing average important weights and the average preferences of criteria by (14) and (15), we obtain the results as shown in Tables IV and V, respectively.

After obtaining 2-tuple vectors of the average important weights and the average preferences of criteria as shown at the last columns of Tables IV and V, respectively, applying (16) yields the overall value of preference which reflects an overall figure of merit regarding the NPD project as

$$(s_4 = \text{Much Preference}, -0.016)$$

which is then converted into the corresponding 2-tuple of linguistic success levels in $\mathcal{S}_4 \times [-0.5, 0.5)$ by the 2-tuple transformation Λ, and we obtain

$$\Lambda((s_4, -0.016)) = (s_3^4 = \text{Fairly High}, 0.32) \qquad (18)$$

This 2-tuple $(\text{Fairly High}, 0.32)$ indicates that the possible success level of the TVcenter-HX project is a little more than fairly high, and the value of 0.32 then could positively support the decision maker in his/her decision of lunching the project if a success level of fairly high is acceptable.

Interestingly, at this juncture, we can see that the 2-tuple-based evaluation model not only yields the screening evaluation, which is consistent with that provided by the fuzzy-set-based evaluation model by Lin and Chen [6], but also supplies an additional information indicating how much difference exists between the actual evaluation and linguistic one serving as a guidance for the screening decision making. This second index of the 2-tuple result would be helpful in supporting manager's decision using the guidance of the linguistic recommendation value. In other words, the proposed evaluation model also maintains the flexibility for managers in making their decisions as in the fuzzy-computing-based approach.

B. *Comparative Study*

In the preceding part, we have applied the 2-tuple-based screening evaluation model to a case study of the TVcenter-HX

$$\begin{aligned}\mathcal{S}_p = \{&s_0 = \text{Nonpreference}, s_1 = \text{Very Little Preference}, s_2 = \text{Little Preference}, s_3 = \text{Moderate Preference},\\ &s_4 = \text{Much Preference}, s_5 = \text{Very Much Preference}, s_6 = \text{Most Preference}\}\end{aligned} \qquad (17)$$

TABLE III
LINGUISTIC ASSESSMENTS AND WEIGHTS OF CRITERIA REGARDING THE TVCENTER-HX PROJECT

Experts	Criteria												
	Favorable Criteria										Unfavorable Criteria		
	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}	C_{34}	C_{41}	C_{42}	C_{43}
E_1	$[s_4^1, s_5^3]$	$[s_3^1, s_2^3]$	$[s_3^1, s_5^3]$	$[s_5^1, s_4^3]$	$[s_6^1, s_5^3]$	$[s_5^1, s_3^3]$	$[s_5^1, s_4^3]$	$[s_4^1, s_4^3]$	$[s_6^1, s_4^3]$	$[s_3^1, s_3^3]$	$[s_4^2, s_5^3]$	$[s_4^2, s_4^3]$	$[s_2^2, s_3^3]$
E_2	$[s_6^1, s_4^3]$	$[s_4^1, s_4^3]$	$[s_2^1, s_5^3]$	$[s_5^1, s_5^3]$	$[s_6^1, s_4^3]$	$[s_5^1, s_2^3]$	$[s_5^1, s_4^3]$	$[s_5^1, s_3^3]$	$[s_5^1, s_3^3]$	$[s_4^1, s_4^3]$	$[s_5^2, s_4^3]$	$[s_5^2, s_4^3]$	$[s_4^2, s_4^3]$
E_3	$[s_6^1, s_5^3]$	$[s_2^1, s_4^3]$	$[s_2^1, s_4^3]$	$[s_6^1, s_5^3]$	$[s_5^1, s_5^3]$	$[s_6^1, s_3^3]$	$[s_5^1, s_5^3]$	$[s_4^1, s_3^3]$	$[s_5^1, s_2^3]$	$[s_3^1, s_3^3]$	$[s_4^2, s_5^3]$	$[s_4^2, s_5^3]$	$[s_3^2, s_3^3]$
E_4	$[s_5^1, s_5^3]$	$[s_3^1, s_3^3]$	$[s_3^1, s_4^3]$	$[s_6^1, s_5^3]$	$[s_6^1, s_4^3]$	$[s_5^1, s_3^3]$	$[s_6^1, s_5^3]$	$[s_5^1, s_2^3]$	$[s_4^1, s_3^3]$	$[s_4^1, s_3^3]$	$[s_5^2, s_5^3]$	$[s_4^2, s_4^3]$	$[s_2^2, s_2^3]$

TABLE IV
2-TUPLE LINGUISTIC WEIGHTS OF CRITERIA ASSESSED BY EXPERTS AND THE AVERAGE 2-TUPLE WEIGHTS

Criteria	Experts				Average
	E_1	E_2	E_3	E_4	(w_j, α_j^w)
C_{11}	$(s_5^3, 0)$	$(s_4^3, 0)$	$(s_5^3, 0)$	$(s_5^3, 0)$	$(s_5^3, -0.25)$
C_{12}	$(s_2^3, 0)$	$(s_4^3, 0)$	$(s_4^3, 0)$	$(s_3^3, 0)$	$(s_3^3, 0.25)$
C_{13}	$(s_5^3, 0)$	$(s_5^3, 0)$	$(s_4^3, 0)$	$(s_4^3, 0)$	$(s_5^3, -0.5)$
C_{14}	$(s_4^3, 0)$	$(s_5^3, 0)$	$(s_5^3, 0)$	$(s_5^3, 0)$	$(s_5^3, -0.25)$
C_{21}	$(s_5^3, 0)$	$(s_4^3, 0)$	$(s_5^3, 0)$	$(s_4^3, 0)$	$(s_5^3, -0.5)$
C_{22}	$(s_3^3, 0)$	$(s_2^3, 0)$	$(s_3^3, 0)$	$(s_3^3, 0)$	$(s_3^3, -0.25)$
C_{31}	$(s_4^3, 0)$	$(s_4^3, 0)$	$(s_5^3, 0)$	$(s_5^3, 0)$	$(s_5^3, -0.5)$
C_{32}	$(s_4^3, 0)$	$(s_3^3, 0)$	$(s_3^3, 0)$	$(s_2^3, 0)$	$(s_3^3, 0)$
C_{33}	$(s_4^3, 0)$	$(s_3^3, 0)$	$(s_2^3, 0)$	$(s_3^3, 0)$	$(s_3^3, 0)$
C_{34}	$(s_3^3, 0)$	$(s_4^3, 0)$	$(s_3^3, 0)$	$(s_3^3, 0)$	$(s_3^3, 0.25)$
C_{41}	$(s_5^3, 0)$	$(s_4^3, 0)$	$(s_5^3, 0)$	$(s_5^3, 0)$	$(s_5^3, -0.25)$
C_{42}	$(s_4^3, 0)$	$(s_4^3, 0)$	$(s_5^3, 0)$	$(s_4^3, 0)$	$(s_4^3, 0.25)$
C_{43}	$(s_3^3, 0)$	$(s_4^3, 0)$	$(s_3^3, 0)$	$(s_2^3, 0)$	$(s_3^3, 0)$

TABLE V
2-TUPLE LINGUISTIC PREFERENCES OF CRITERIA REGARDING THE TVCENTER-HX PROJECT

Criteria	Experts				Average
	E_1	E_2	E_3	E_4	(r_j, α_j)
C_{11}	$(s_4, 0)$	$(s_6, 0)$	$(s_6, 0)$	$(s_5, 0)$	$(s_5, 0.25)$
C_{12}	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$	$(s_3, 0)$	$(s_3, 0)$
C_{13}	$(s_3, 0)$	$(s_2, 0)$	$(s_2, 0)$	$(s_3, 0)$	$(s_3, -0.5)$
C_{14}	$(s_5, 0)$	$(s_5, 0)$	$(s_6, 0)$	$(s_6, 0)$	$(s_6, -0.5)$
C_{21}	$(s_6, 0)$	$(s_6, 0)$	$(s_5, 0)$	$(s_6, 0)$	$(s_6, -0.25)$
C_{22}	$(s_5, 0)$	$(s_5, 0)$	$(s_6, 0)$	$(s_5, 0)$	$(s_5, 0.25)$
C_{31}	$(s_5, 0)$	$(s_5, 0)$	$(s_5, 0)$	$(s_6, 0)$	$(s_5, 0.25)$
C_{32}	$(s_4, 0)$	$(s_5, 0)$	$(s_4, 0)$	$(s_5, 0)$	$(s_5, -0.5)$
C_{33}	$(s_6, 0)$	$(s_5, 0)$	$(s_5, 0)$	$(s_4, 0)$	$(s_5, 0)$
C_{34}	$(s_3, 0)$	$(s_4, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_4, -0.5)$
C_{41}	$(s_2, 0)$	$(s_1, 0)$	$(s_2, 0)$	$(s_1, 0)$	$(s_2, -0.5)$
C_{42}	$(s_2, 0)$	$(s_1, 0)$	$(s_2, 0)$	$(s_2, 0)$	$(s_2, -0.25)$
C_{43}	$(s_4, 0)$	$(s_2, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_3, 0.25)$

project implemented by Lin and Chen [6], [7]. As for a comparative study, let us now report and analyze the results obtained by their fuzzy-set-based evaluation model in comparison to the result obtained by the 2-tuple-based method earlier.

TABLE VI
AVERAGE FUZZY NUMBERS OF CRITERIA RATINGS AND AVERAGE WEIGHTS REGARDING THE TVCENTER-HX PROJECT [6]

Criteria	Average Fuzzy Ratings	Average Weights
C_{11}	$R_1 = (0.68, 0.86, 0.95)$	$W_1 = (0.8, 1, 1)$
C_{12}	$R_2 = (0.33, 0.5, 0.68)$	$W_2 = (0.45, 0.65, 0.85)$
C_{13}	$R_3 = (0.25, 0.43, 0.6)$	$W_3 = (0.7, 0.9, 1)$
C_{14}	$R_4 = (0.7, 0.9, 1)$	$W_4 = (0.75, 0.95, 1)$
C_{21}	$R_5 = (0.75, 0.95, 1)$	$W_5 = (0.7, 0.9, 1)$
C_{22}	$R_6 = (0.65, 0.85, 1)$	$W_6 = (0.35, 0.55, 0.75)$
C_{31}	$R_7 = (0.65, 0.85, 1)$	$W_7 = (0.7, 0.9, 1)$
C_{32}	$R_8 = (0.55, 0.73, 0.9)$	$W_8 = (0.4, 0.6, 0.8)$
C_{33}	$R_9 = (0.63, 0.81, 0.95)$	$W_9 = (0.4, 0.6, 0.8)$
C_{34}	$R_{10} = (0.4, 0.58, 0.75)$	$W_{10} = (0.45, 0.65, 0.85)$
C_{41}	$R'_{11} = (0.55, 0.73, 0.9)$	$W_{11} = (0.75, 0.95, 1)$
C_{42}	$R'_{12} = (0.53, 0.69, 0.85)$	$W_{12} = (0.65, 0.85, 1)$
C_{43}	$R'_{13} = (0.3, 0.46, 0.63)$	$W_{13} = (0.4, 0.6, 0.8)$

It is worth noting here that although with the same case study and using the same computational method based on fuzzy numbers, these two papers, i.e., [6] and [7], reported two different results of final linguistic evaluation for screening decision making. This is basically due to these two paper used two different fuzzy number representations for linguistic success levels of $\mathcal{S}_4$, as mentioned previously.

Let us return to the linguistic assessments and relative important weights of different criteria regarding the TVcenter-HX project given in Table III. Here, linguistic values $s_i^1 \in \mathcal{S}_1$, $s_j^2 \in \mathcal{S}_2$, and $s_k^3 \in \mathcal{S}_3$ are semantically represented by triangular fuzzy numbers of [0, 1], as graphically shown in Figs. 1–3, respectively.

Then, by applying mean operations (5a), (5b), and (6) for aggregating the different experts' opinions expressed by the linguistic effect ratings and risk possibility ratings, as well as linguistic important weights against criteria, the aggregated fuzzy numbers of average effect ratings and risk possibility ratings, as well as average important weights are obtained, as shown in Table VI. Then, the FPSR $\mathcal{F}$ of the TVcenter-HX project is defined by (7) as the following fuzzy weighted average

$$\mathcal{F} = \frac{\sum_{j=1}^{13} R_j \otimes W_j}{\sum_{j=1}^{13} W_j} \tag{19}$$

where for $j = 11, 12, 13$, $R_j = 1 \ominus R'_j$ (see Table VI).

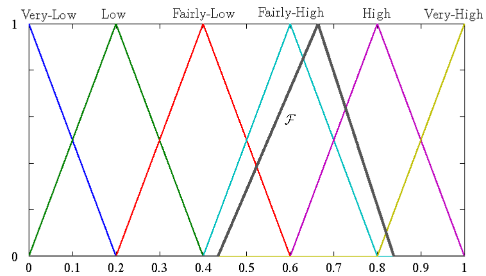

Fig. 7. Linguistic approximation for the FPSR $\mathcal{F}$ [6].

The membership function of FPSR $\mathcal{F}$ is then approximately constructed by enumerating its different α-cuts of which their lower and upper bounds, denoted by $\mathcal{F}_\alpha^L$ and $\mathcal{F}_\alpha^U$, respectively, are solutions of the following programs[1]:

$$\begin{aligned}\mathcal{F}_\alpha^L &= \min \sum_{j=1}^{13} v_j (R_j)_\alpha^L \\ \text{s.t.} \quad & t(W_j)_\alpha^L \le v_j \le t(W_j)_\alpha^U, j = 1, \ldots, 13 \\ & \sum_{j=1}^{13} v_j = 1 \\ & t \ge 0; v_j \ge 0 (j = 1, \ldots, 13)\end{aligned} \tag{20a}$$

$$\begin{aligned}\mathcal{F}_\alpha^U &= \min \sum_{j=1}^{13} v_j (R_j)_\alpha^U \\ \text{s.t.} \quad & t(W_j)_\alpha^L \le v_j \le t(W_j)_\alpha^U, j = 1, \ldots, 13 \\ & \sum_{j=1}^{13} v_j = 1 \\ & t \ge 0; v_j \ge 0 (j = 1, \ldots, 13).\end{aligned} \tag{20b}$$

Solving these linear programs at $\alpha = 0$ and $\alpha = 1$, we obtain the FPSR approximately represented as a triangular fuzzy number[2]

$$\mathcal{F} = (0.434, 0.659, 0.838). \tag{21}$$

Finally, this FPSR $\mathcal{F}$ is matched with fuzzy numbers representing linguistic terms from $\mathcal{S}_4$ (refer to (4) and Fig. 5) by using Euclidean distance as following:

$$d(\mathcal{F}, s_i^4) = \sqrt{\sum_{x \in X} (\mu_{\mathcal{F}}(x) - \mu_{s_i^4}(x))^2}, \qquad \text{for } i = 0, \ldots, 5 \tag{22}$$

where X is, for example $\{0, 0.1, \ldots, 0.9, 1\}$, a finite sample taken from [0, 1]. Then, the linguistic success level

$$s_3^4 = \text{Fairly High} = \arg\min_{s_i^4 \in S_4} \{d(\mathcal{F}, s_i^4)\} \tag{23}$$

which is best matched to $\mathcal{F}$ (see Fig. 7) is the successful possibility of the TVcenter-HX project development recommended to the decision maker for making the screening decision.

[1] See Kao and Liu [18], [19] for more details.
[2] The modal value of this fuzzy number given by Lin and Chen [6] is 0.664; however, by our computation the correct value should be 0.659 as shown.

TABLE VII
MEDIAN FUZZY NUMBERS OF CRITERIA RATINGS AND MEDIAN WEIGHTS REGARDING THE TVCENTER-HX PROJECT [7]

Criteria	Median Fuzzy Ratings	Median Weights
C_{11}	$R_1 = (0.7, 0.9, 1)$	$W_1 = (0.8, 1, 1)$
C_{12}	$R_2 = (0.3, 0.5, 0.7)$	$W_2 = (0.5, 0.7, 0.9)$
C_{13}	$R_3 = (0.25, 0.43, 0.6)$	$W_3 = (0.7, 0.9, 1)$
C_{14}	$R_4 = (0.7, 0.9, 1)$	$W_4 = (0.8, 1, 1)$
C_{21}	$R_5 = (0.8, 1, 1)$	$W_5 = (0.7, 0.9, 1)$
C_{22}	$R_6 = (0.6, 0.8, 1)$	$W_6 = (0.4, 0.6, 0.8)$
C_{31}	$R_7 = (0.6, 0.8, 1)$	$W_7 = (0.7, 0.9, 1)$
C_{32}	$R_8 = (0.55, 0.73, 0.9)$	$W_8 = (0.4, 0.6, 0.8)$
C_{33}	$R_9 = (0.6, 0.8, 1)$	$W_9 = (0.4, 0.6, 0.8)$
C_{34}	$R_{10} = (0.4, 0.58, 0.75)$	$W_{10} = (0.4, 0.6, 0.8)$
C_{41}	$R'_{11} = (0.55, 0.73, 0.9)$	$W_{11} = (0.8, 1, 1)$
C_{42}	$R'_{12} = (0.5, 0.65, 0.8)$	$W_{12} = (0.6, 0.8, 1)$
C_{43}	$R'_{13} = (0.25, 0.43, 0.6)$	$W_{13} = (0.4, 0.6, 0.8)$

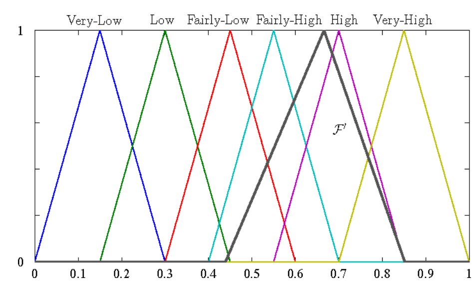

Fig. 8. Linguistic approximation for the FPSR $\mathcal{F}'$ [7].

As graphically depicted in Fig. 7, the FPSR $\mathcal{F}$ somewhat dominates the fuzzy number representing its approximated linguistic expression of s_3^4 = Fairly High. This shows that the linguistic approximation by (22) and (23) may cause a loss of information, which does not happen in the 2-tuple-based evaluation model, as shown previously.

Now, let us consider the experimental result reported by Lin and Chen [7] applied to the same case study. Regarding the evaluation method, instead of using the averaging operation, i.e., (5a), (5b), and (6), as by Lin and Chen [6], the authors have used in [7] the median as an aggregation operator for calculating R_j $(j = 1, \ldots, 10)$, R'_j $(j = 11, 12, 13)$, and W_j $(j = 1, \ldots, 13)$ to aggregate the experts's opinions, which, however, resulted in almost the same results, as shown in Table VII compared to Table VI.

Then, solving linear programs (20a) and (20b) at $\alpha = 0$ and $\alpha = 1$ yields the FPSR approximately represented as the following fuzzy number:

$$\mathcal{F}' = (0.439, 0.666, 0.852) \tag{24}$$

which is only slightly different from the result (21), which uses the averaging operation described earlier. This FPSR $\mathcal{F}'$ of (24) is then matched with fuzzy numbers representing linguistic terms from $\mathcal{S}_4$, whose membership functions are graphically depicted in Fig. 8, and differently from those shown in Fig. 7.

The result yielded by matching using Euclidean distance (22) is, however, the possible success of the TVcenter-HX project being $s_4^4 =$ High, which is different from $s_3^4 =$ Fairly High, as shown in (23) earlier.

It should be emphasized here that if we use membership functions of linguistic terms from $\mathcal{S}_4$, as shown in Fig. 7, with Euclidean distance (22) used, the FPSR $\mathcal{F}'$ is best matched to $s_3^4 =$ Fairly High but not $s_4^4 =$ High. This observation along with similar results shown in Tables VII and VI as well as nearly the same overall fuzzy number of (21) and (24) mean that, the difference in the final result expressed by linguistic success levels $s_3^4 =$ Fairly High and $s_4^4 =$ High regarding the TVcenter-HX project represented by these two papers is not due to the different use of average and median operators for aggregating experts' opinions, but mainly because of the use of different fuzzy set representations for linguistic success levels of $\mathcal{S}_4$ for the linguistic approximation process, as just described earlier.

In summary, the subjectivity in defining membership functions of linguistic terms involved in a new product screening evaluation can yield a change in the final result of the evaluation, and therefore, leading to an undesired effect, which should be strictly avoided, due to critically importance of a decision in screening product innovations.

VI. Conclusion and Discussion

In this paper, we have proposed a new linguistic screening evaluation model for NPD based on the 2-tuple representation of linguistic information. We have introduced the preference-preserving 2-tuple transformation serving for the unification of linguistic information that makes 2-tuple aggregation operators appropriately applicable in the 2-tuple linguistic screening model. It has been shown that the 2-tuple linguistic screening model not only yields the screening evaluation by means of a linguistic expression as in the fuzzy-set-based screening model, but also supplies an additional information indicating how much difference exists between the true evaluation and linguistic one serving as a guidance for the screening decision making. Further, by performing direct computation on linguistic terms via 2-tuples in the proposed approach, the burden of quantifying qualitative concepts as well as performing complicated computation on fuzzy numbers can be also eliminated.

From a practical perspective, besides the sensitivity of final evaluation result to the fuzzy set representation of linguistic values in the fuzzy-set-based screening evaluation model, its computation of a fuzzy weighted average via (20a) and (20b) is complicated and would be regarded as "a black box" by managers. Therefore, managers who seek to preserve a sense of ownership over their decision processes might prefer simpler and more transparent processes. Such processes may allow managers to gain sights into their decision problem and as such have confidence that the model's recommendation is a reliable reflection of their preferences. So, we hope the advantages of the proposed approach over the fuzzy-set-based approach in terms of simplicity and consistency in the final evaluation result would convincingly encourage those managers to buy in this new method.

In addition, it is worth emphasizing that, while fuzzy-set-based semantics of linguistic terms is often defined subjectively and context-dependently, the order-based semantics may be universally accepted and has been widely used in the literature [9]–[11], [17]. Therefore, the practical implication from this work is that it provides an additional methodology of screening evaluation that hopefully helps decision makers to have a proper utilization of evaluation models when dealing with linguistic information in NPD. More particularly, in situations of linguistic screening evaluation where evaluation criteria or features are mostly qualitative in nature, i.e., linguistic assessments seem to be unavoidable due to having no properly underlying numerical domain for any possible numerical valuation of variables, such as the case study of TVcenter-HX Project conducted by Lin and Chen [6], [7] earlier, the proposed screening evaluation model with the computation solely based on the order-based semantics of the linguistic terms would be appropriately applied. However, in situations or problems where involved linguistic assessments are just a qualitatively valuation of quantitative criteria or features typically associated with their underlying numerical domains, fuzzy-set-based approaches should be necessarily to be applied. Because in such situations, the fuzzy set representation could represent somewhat experience and knowledge of an expertise about the problem under consideration, while the 2-tuple representation does not directly take into account the underlying vagueness of quantitatively linguistic terms.

Finally, in increasingly competitive markets with rising customer expectations nowadays, many firms or companies face with decision problems regarding product innovation or quality management that are becoming more complex and usually involving with both quantitative and qualitative information affected by vagueness and uncertainty in subjective judgements. Appealingly, an interesting direction for future work could be to extend the screening evaluation model so that it would suitably integrate both fuzzy-set-based approach and 2-tuple-based approach for representing linguistic information, for making it applicable to such more complex situations in NPD.

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