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Evaluation of e-commerce websites: An integrated approach under a single-valued trapezoidal neutrosophic environment

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ABSTRACT

E-commerce website evaluation is recognized as a complex multi-criteria decision-making (MCDM) problem involving vast amounts of imprecise and inconsistent evaluation data. Single-valued trapezoidal neutrosophic numbers (SVTNNs), which are elements in single-valued trapezoidal neutrosophic sets (SVTNSs), have a strong capacity to model such complex evaluation information. However, only few studies simultaneously consider the imprecise and inconsistent information inherent in the evaluation data. Moreover, much literature overlooks the different priority levels and interrelationships among criteria. To bridge this gap, this paper outlines a novel integrated decision system consisting of the following three modules: (1) information acquisition; (2) the single-valued trapezoidal neutrosophic decision making trial and evaluation laboratory (SVTN-DEMATEL) module; and (3) the integration module. In this study, we used the information acquisition module to gather the SVTNN information provided by experts, applied the SVTN-DEMATEL module to analyze the causal relationships among criteria, and proposed the integration module for information fusion with consideration of interdependencies and different priority levels of criteria. Furthermore, we conducted a case study to illustrate the effectiveness and feasibility of the proposal along with the sensitivity and comparison analyses to verify its stability and superiority. Finally, conclusions and future research directions were drawn.

1. Introduction

The *China Statistical Report on Internet Development* indicated that, in December 2016, the number of Chinese Internet users and the scale of electronic commerce (e-commerce) websites reached 731 million and 4.82 million, respectively, which fully reflects that e-commerce websites are becoming increasingly widespread and significant in the new era [1]. Unlike physical stores, e-commerce incurs less taxes and rents, thereby significantly reducing the costs of business transactions and making businesses substantially practical and efficient [2], which has revolutionized the way of the traditional business model [3,4]. According to the nature of transactions, the five major types of e-commerce are business-to-business, business-to-consumer (B2C), consumer-to-consumer, consumer-to-business and business-to- government [2]. Among these types, the B2C paradigm is the initial business model wherein consumers directly purchase products and services. This paradigm has gained extensive development [5,6] and has been regarded as an essential, as well as influential, retailing channel for ordinary consumers [4].

However, the flourishing development of B2C e-commerce has raised several core issues with respect to the customers' selecting, continued satisfaction with, and trust for websites [7]. Firstly, it may be tedious and time-consuming for customers or companies to locate satisfactory products or services amongst the vast B2C e-commerce websites which provide comparable functionalities and a plethora of information sources [8]. Secondly, given the absence of personal contact and different company reputations, online customers may encounter fraud risk in e-commerce transactions. Thirdly, considering e-commerce businesses' different strategies with respect to personalization and privacy management, online customers may also face risks associated with information misuse [8]. Thus, conducting in-depth evaluation of B2C e-commerce websites is considerably essential for e-commerce businesses to understand the prioritized factors that influence online customer satisfaction as well as crucial for online customers to select the satisfactory website amongst the multiple options. Nevertheless, the currently proposed approaches for e-commerce evaluation have not yet yielded satisfactory results, especially regarding the way how to quantify evaluation information, and gave little thought to the effect of interdependencies and interactions among the hierarchically structured criteria. Aiming at these challenges, this study proposes an integrated fuzzy-based multi-criteria

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decision-making (MCDM) approach for B2C e-commerce evaluation to better its performance to meet customer needs and e-commerce businesses goals.

1.1. Literature review for evaluating e-commerce websites

The evaluation of B2C e-commerce websites is a complex MCDM process aimed at prioritizing the evaluation criteria and selecting the most suitable alternative. This evaluation process mainly includes defining the problem, identifying the evaluation criteria and alternatives, acquiring decision information, aggregating information by a certain approach, and ranking or selecting alternatives. Given the huge complexity in external environments and the inherent fuzziness in human judgments, evaluators in practical e-commerce settings usually have difficulties in expressing their judgments by crisp numbers, which determines that the evaluation of B2C e-commerce websites may rely heavily on the fuzzy-based MCDM techniques (more details please refer to Mardani et al. [9]).

In the past decades, literatures have extended and proposed several well-known fuzzy-based MCDM approaches, which are highly useful for decision-making applications, such as fuzzy TOPSIS (the Technique for Order Preference by Similarity to Ideal Solution) [10], fuzzy TODIM (an acronym in Portuguese of Interactive and Multicriteria Decision Making) [11], fuzzy AHP (fuzzy analytic hierarchy process) [12], fuzzy VIKOR (VIsekriterijumska optimizacija i KOm-promisno Resenje) [13], and fuzzy DEMATEL (Decision Making Trial and Evaluation Laboratory) [14,15]. Combining these fuzzy-based MCDM approaches, excellent studies have investigated the methodology and application of evaluation in various application domains, including new product development evaluation [16], recommendation systems [17–19], and automated essay evaluation [20].

In recent years, researchers have also established some fuzzy-based MCDM approaches for evaluating e-commerce websites from different perspectives [4,21]. For example, Zhu et al. [8] introduced a utility model of privacy in personalization services in e-commerce based on the multi-attribute utility theory. Acampora et al. [5] developed an interval type-2 fuzzy logic based framework for reputation management in peer-to-peer e-commerce websites. In some other studies, Kang et al. [22] presented a fuzzy hierarchical TOPSIS approach to handle evaluation problems for B2C e-commerce websites, wherein linguistic variables were transformed into triangular fuzzy numbers for ease of computation. Their work captured the hierarchy structure among criteria in B2C e-commerce, but failed to analyze the causal relationships among them. To explore causal dependencies among criteria, some researchers applied the fuzzy AHP and fuzzy DEMATEL approaches to e-commerce contexts. For instance, Chiu et al. [23] proposed a new hybrid MCDM model by combing the DEMATEL, DEMATEL-based Analytic Network Process, and VIKOR methods for evaluation of e-store business. Furthermore, to allow for the incorporation of indeterminate and inconsistent information, Aggarwal and Bishnoi [24] integrated the neutrosophic logic [25] in data collection module for trust evaluation of B2C e-commerce websites. The advantage of this approach over other fuzzy-based approaches was that it captured the respondent's agreement, disagreement, and indecisiveness for certain aspects [24]. Nevertheless, the data collection module may be controversial since it was based on the premise that a user could only select one of three options (true, false, or can't say). This premise could not fit human thinking well because respondents' judgments may contain active, neutral and passive information all at once [26]. In other words, these respondents may choose two or more options among the three ones (truth, false, and can't say) concurrently, which may be more in line with the nature of neutrosophic logic and can retain respondents' original judgments as many as possible. Additionally, researches [22,24] assigned the weightings of the involved criteria entirely according to the opinions of evaluators, which may be somewhat subjective and may run counter to the actual decision situations.

The evaluation of B2C e-commerce websites is a strategic decision that usually occurs in complex and uncertain environments. However, our review of previous studies suggests a scarcity of existing literature and three main challenges associated with e-commerce website evaluation: 1) indeterminate and inconsistent evaluation data; 2) multiple criteria in a hierachical structure; and 3) various interdependencies and interactions among criteria.

1.2. Motivations

Aiming at the aforementioned challenges in extant researches, the main motivations of this study are discussed below.

(1) E-commerce evaluation context requires addressing hierarchical criteria containing uncertainties with indeterminate and inconsistent information. For example, an e-commerce website evaluated by an expert may be rated as "good" in protecting customers' privacy information, with truth, falsity, and uncertainty probabilities of 80%, 20%, and 30%, respectively. In the extant studies, the involvement of fuzzy concepts, including interval numbers [8], triangular fuzzy numbers [22], type-2 fuzzy logic [5], and neutrosophic logic [24], greatly enhanced the preciseness in evaluating e-commerce websites. However, the scope of the adopted fuzzy set techniques commonly excludes the description of all the initial evaluation information, especially the inconsistent and incomplete types. Therefore, a challenge here is how to quantify assessments involving indeterminate and inconsistent types.

(2) There exist causal relationships among criteria in B2C e-commerce [22]. However, the fuzziness of the interdependencies among these criteria and their influences on B2C e-commerce performance still remain unknown. The single-valued trapezoidal neutrosophic set (SVTNS) is a generalized extension of the traditional fuzzy set (FS) [27] and intuitionistic fuzzy set (IFS) [28]. Single-valued trapezoidal neutrosophic numbers (SVTNNs), which act as elements of the SVTNS, possess a good capability for depicting indeterminate and inconsistent information [29,30]. Moreover, the DEMATEL technique, first conducted by Battelle Memorial Institute through its Geneva research center [14,15], possesses notable advantages in capturing the causal relationships between complex factors. However, despite its applications [31–34] based on crisp numbers, interval numbers, IFSs, or type-2 fuzzy sets in other theoretical and practical domains, it is still a new exploration to integrate the SVTNNs with DEMATEL technique for B2C e-commerce website evaluation with a multi-level hierarchy of criteria.

(3) Aggregation of information by a certain approach is one of the most important modules in MCDM [35]. Various interdependencies and different priority levels among criteria concurrently exist in B2C e-commerce. Specifically, the prioritized average (PA) operator is a powerful technique to solve problems in which the criteria are in different priority levels [36]. Meanwhile, the Bonferroni mean (BM) [37] is prominently characterized by its capacity to capture the interrelationships among input arguments. However, there is no research that considers all these factors at once, so an effective and comprehensive aggregation tool is necessary for B2C e-commerce evaluation.

1.3. Contributions

Motivated by the aforementioned limitations, this research developed a novel fuzzy-based MCDM approach for the evaluation of B2C e-commerce websites. Initially, we introduced the SVTNNs to quantify evaluation information on criteria and alternatives. Second, we combined the SVTNNs with DEMATEL technique to analyze the causal relationships among criteria. Subsequently, this study proposed the single-valued trapezoidal neutrosophic normalized prioritized weighted Bonferroni mean (SVTN-normalized prioritized weighted Bonferroni mean) operator to aggregate criteria by considering their interactions and different priority levels. Finally, this integrated approach created a ranked list of satisfactory B2C e-commerce websites.

The contributions of this work are as follows.

(1) In this study, a novel fuzzy-based MCDM framework for the evaluation of B2C e-commerce websites is designed and established. This framework is developed for addressing MCDM problems with multi-level hierarchy of criteria with indeterminate and inconsistent evaluation data. At the same time, it can quantitatively manage uncertainties to identify interrelationships and prioritized orders among criteria via the combination of SVTNNs and DEMATEL technique.

(2) This work initially combined the PA operator with the normalized weighted BM operator and proposed the SVTN-normalized prioritized weighted Bonferroni mean operator for information fusion, where the merits of both operators can be attained. Moreover, the identified prioritized orders among criteria were incorporated into the integration module by the SVTN-normalized prioritized weighted Bonferroni mean operator. As such, the criteria weightings can be extracted objectively, and the subjectivity in decision-making can be maximally reduced, thereby ensuring a reliable evaluation result.

1.4. The organization of this paper

The rest of the paper is organized as follows. Section 2 reviews several influential factors in evaluating e-commerce websites and revisits some fundamental concepts used in the proposed approach. Section 3 defines the problem. Section 4 constructs the integrated approach that seeks to provide a significantly practical evaluation approach for the said websites. Section 5 utilizes a case study to verify the effectiveness and practicality of our proposed approach and conducts sensitivity and comparison analyses. Finally, Section 6 presents the main conclusions of this research and further research directions.

2. Preliminaries

Prior to describing the integrated approach, we first present brief reviews on the following: impact factors in the evaluation of e-commerce websites, SVTNNs, and related aggregation operators.

2.1. Impact factors in e-commerce website evaluation

Evaluation of e-commerce websites can generally be approached from the perspective of service quality [22]. With the increasingly fierce competition and complexity in the e-commerce context, B2C e-commerce businesses have to consider more than one dimension or criterion and satisfy customer needs as much as possible to enhance their core competitiveness. Therefore, the impact factors of evaluating e-commerce websites have been discussed extensively in the past decades. For example, the well-established multiple-item instrument to evaluate a company's service quality, SERVQUAL, involved the required dimensions of reliability, responsiveness, assurance, empathy, and tangibles [38]. Nevertheless, the SERVQUAL method is suitable only for measuring the quality of all *non-Internet-based* customer interactions and experiences with companies [39]. Consequently, utilizing only the evaluation dimensions in SERVQUAL is insufficient. To measure the service quality in the e-commerce context, Barnes and Vidgen [40] developed a new version of WebQual (called WebQual 4.0) to evaluate internet bookstores; dimensions included in their work were usage of website usability, information quality, and service interaction. However, this scale focused merely on the quality of the website itself while ignoring the quality of the service provided. To offer a comprehensive assessment method for e-commerce websites, Parasuraman [39] developed an e-core service quality scale (E-S-QUAL) method for the evaluation of electronic service quality, consisting of 22 items on four dimensions, designated as efficiency, system availability, fulfillment, and privacy.

The E-S-QUAL method can serve as an appropriate framework for multi-criteria evaluation problems. In addition, the E-S-QUAL method received attention from practitioners and researchers, who contended that such a method remains reliable and useful for academics despite the fact that the e-commerce has evolved dramatically [41]. Hence, we also apply the E-S-QUAL method for our study. Table 1 presents the details on the evaluation system and its sources within each dimension.

As shown in Fig. 1, the evaluation system of e-commerce websites forms a hierarchy. The top level contains the aim of this research; the second level reveals the dimensions, which act as a summary of relevant sub-criteria; and the third level includes the sub-criteria, on which evaluation information is provided.

2.2. Single-valued trapezoidal neutrosophic numbers

Definition 1 [42]**.** Let $T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}} \in [0, 1]$; a SVTNN $\tilde{a} = \langle [a_1, a_2, a_3, a_4], (T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}})\rangle$ is a special neutrosophic set on the real number set R, whose truth-membership function $\mu_{\tilde{a}}$, indeterminacy-membership function $\nu_{\tilde{a}}$, and falsity-membership function $\lambda_{\tilde{a}}$ are given as follows:

$$\mu_{\tilde{a}}(x) = \begin{cases} (x - a_1)T_{\tilde{a}}/(a_2 - a_1) & a_1 \le x \le a_2, \\ T_{\tilde{a}} & a_2 \le x \le a_3, \\ (a_4 - x)T_{\tilde{a}}/(a_4 - a_3) & a_3 \le x \le a_4, \\ 0 & otherwise. \end{cases}$$

$$\nu_{\tilde{a}}(x) = \begin{cases} (a_2 - x + I_{\tilde{a}}(x - a_1))/(a_2 - a_1) & a_1 \le x \le a_2, \\ I_{\tilde{a}} & a_2 \le x \le a_3, \\ (x - a_3 + I_{\tilde{a}}(a_4 - x))/(a_4 - a_3) & a_3 \le x \le a_4, \\ 1 & otherwise. \end{cases}$$

$$\lambda_{\tilde{a}}(x) = \begin{cases} (a_2 - x + F_{\tilde{a}}(x - a_1))/(a_2 - a_1) & a_1 \le x \le a_2, \\ F_{\tilde{a}} & a_2 \le x \le a_3, \\ (x - a_3 + F_{\tilde{a}}(a_4 - x))/(a_4 - a_3) & a_3 \le x \le a_4, \\ 1 & otherwise. \end{cases}$$

The SVTNN $\tilde{a} = \langle [a_1, a_2, a_3, a_4], (T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}})\rangle$, which is an extension of traditional neutrosophic set [25], is composed of two correlative parts: the trapezoidal fuzzy number (TFN) $[a_1, a_2, a_3, a_4]$ and the neutrosophic part $(T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}})$ of $\tilde{a}$. By adding the neutrosophic part to a TFN, the SVTNN extends the discrete set to a continuous one. More specifically, the truth-membership, indeterminacy-membership, and falsity-membership degrees denote the extent to which the decision makers think that the element belongs to, not sure, and does not belong to a TFN $[a_1, a_2, a_3, a_4]$, respectively. As such, it makes the neutrosophic part of $\tilde{a}$ no longer relative to a fuzzy concept "good" or "poor", but relative to the continuous TFN, so the assessments of decision makers

Table 1
Description of the four dimensions of E-S-QUAL [22,39].

Dimension	*Description (number of sub-criteria)*
Efficiency	Ease and speed of accessing and using the site (8)
Fulfillment	Extent to which the promises of the site regarding order delivery and item availability are fulfilled (4)
System availability	Proper technical functioning of the site (7)
Privacy	Degree to which the site is safe and protects customer information (3)

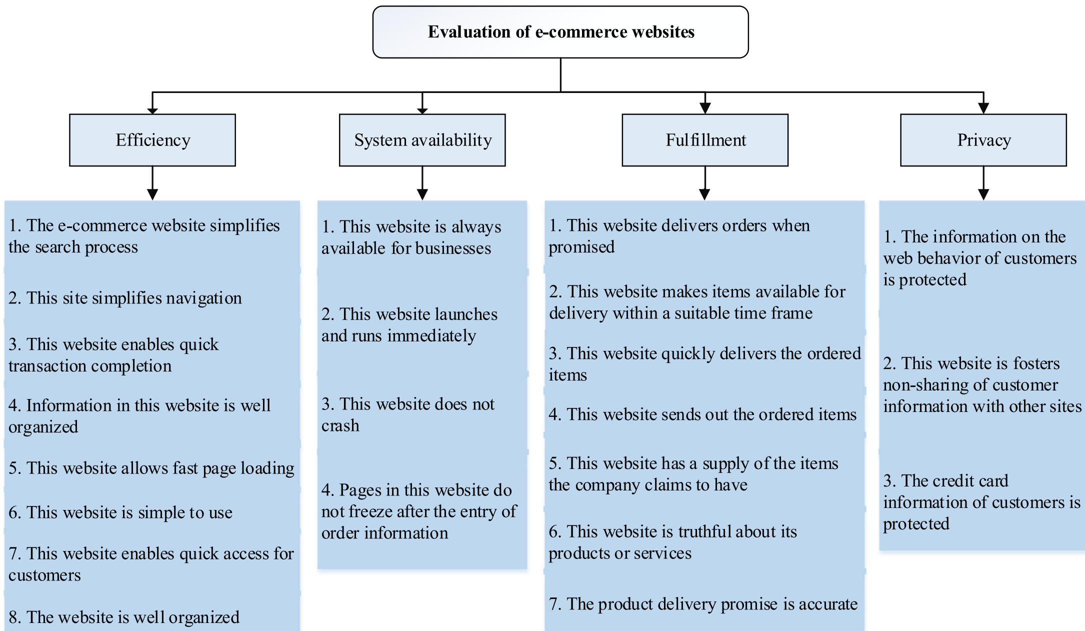

Fig. 1. Evaluation dimensions and sub-criteria of e-commerce websites [22,39].

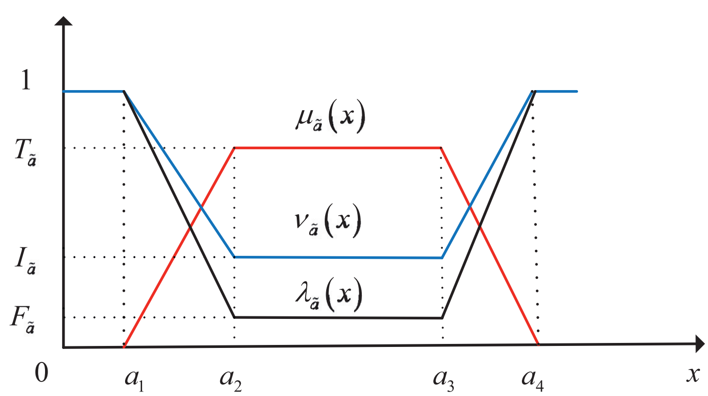

Fig. 2. Truth, indeterminacy, and falsity membership functions of SVTNNs.

can be captured and expressed in diverse dimensions [29]. In addition, the truth, indeterminacy, and falsity membership degrees of SVTNNs can be generated automatically in the following way:

As depicted in Fig. 2, $\mu_{\tilde{a}}(x)$ is a continuous monotone increasing function when $a_1 \le x \le a_2$, and is a continuous monotone decreasing function when $a_3 \le x \le a_4$. Conversely, $\nu_{\tilde{a}}(x)$ and $\lambda_{\tilde{a}}(x)$ are continuous monotone decreasing functions when $a_1 \le x \le a_2$, and are continuous monotone increasing functions when $a_3 \le x \le a_4$. Therefore, the values of $T_{\tilde{a}}$, $I_{\tilde{a}}$, and $F_{\tilde{a}}$ are the maximum degree of truth-membership function and the minimum degrees of indeterminacy-membership and falsity-membership functions, respectively, and they are independent one another. Finally, all the membership functions in Definition 1 can be calculated according to the piecewise linear equations in Fig. 2.

When $a_1 > 0$, $\tilde{a} = \langle [a_1, a_2, a_3, a_4], (T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}}) \rangle$is described as a positive SVTNN, denoted by $\tilde{a} > 0$; conversely, when $a_4 \le 0$, $\tilde{a} = \langle [a_1, a_2, a_3, a_4], (T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}}) \rangle$ becomes a negative SVTNN, denoted by $\tilde{a} < 0$; and when $0 \le a_1 \le a_2 \le a_3 \le a_4 \le 1$ and $T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}} \in [0, 1]$, $\tilde{a}$ is identified as a normalized positive SVTNN. The SVTNNs discussed in the subsequent sections are all normalized positive SVTNNs.

When $I_{\tilde{a}} = 1 - T_{\tilde{a}} - F_{\tilde{a}}$, the SVTNN $\tilde{a} = \langle [a_1, a_2, a_3, a_4], (T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}}) \rangle$ is reduced to a trapezoidal intuitionistic fuzzy number; when $a_2 = a_3$, $\tilde{a}$ is revealed to be a single-valued triangular neutrosophic number; and when $I_{\tilde{a}} = 0$ and $F_{\tilde{a}} = 0$, $\tilde{a}$ is reduced to a generalized TFN, described as $\tilde{a} = \langle [a_1, a_2, a_3, a_4], T_{\tilde{a}} \rangle$. Therefore, the SVTNS, acting as a collection of multiple SVTNNs, is an extended form of classical set theory that can cover considerable uncertainties in practical issues.

For the modified operations of SVTNNs, readers can refer to Liang et al. [29]. Furthermore, Liang et al. [29] defined a new score function to compare any two SVTNNs after examining deficiencies in previous studies.

Definition 2 [29]. Let $\tilde{a} = \langle [a_1, a_2, a_3, a_4], (T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}}) \rangle$ be a SVTNN. The score, accuracy, and certainty functions *sc*, *l*, and *c* of SVTNN $\tilde{a}$ are defined, respectively, as follows:

$$sc(\tilde{a}) = (a_1 + 2a_2 + 2a_3 + a_4)(2 + T_{\tilde{a}} - I_{\tilde{a}} - F_{\tilde{a}})/18, \quad (1)$$

$$l(\tilde{a}) = (a_1 + 2a_2 + 2a_3 + a_4)(T_{\tilde{a}} - F_{\tilde{a}})/6, \quad (2)$$

$$c(\tilde{a}) = (a_1 + 2a_2 + 2a_3 + a_4)T_{\tilde{a}}/6. \quad (3)$$

Let $\succ$ and $\sim$ be two binary relations on SVTNNs, denoted as $\tilde{a} \succ \tilde{b}$, if $\tilde{a}$ is preferred over $\tilde{b}$ and as $\tilde{a} \sim \tilde{b}$ if $\tilde{a}$ is equal to $\tilde{b}$. Assume that $\tilde{a}$ and $\tilde{b}$ are two SVTNNs, then, they can be compared using the following rules.

Definition 3 [29]. Let $\tilde{a} = \langle [a_1, a_2, a_3, a_4], (T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}}) \rangle$ and $\tilde{b} = \langle [b_1, b_2, b_3, b_4], (T_{\tilde{b}}, I_{\tilde{b}}, F_{\tilde{b}}) \rangle$ be two SVTNNs. The comparison method for $\tilde{a}$ and $\tilde{b}$ can be defined as follows.

(1) When $sc(\tilde{a}) > sc(\tilde{b})$, $\tilde{a} \succ \tilde{b}$, indicating that $\tilde{a}$ is superior to $\tilde{b}$.
(2) When $sc(\tilde{a}) = sc(\tilde{b})$ and $l(\tilde{a}) > l(\tilde{b})$, $\tilde{a} \succ \tilde{b}$, meaning $\tilde{a}$ is superior to $\tilde{b}$.
(3) When $sc(\tilde{a}) = sc(\tilde{b})$ and $l(\tilde{a}) < l(\tilde{b})$, $\tilde{b} \succ \tilde{a}$, suggesting that $\tilde{b}$ is superior to $\tilde{a}$.
(4) When $sc(\tilde{a}) = sc(\tilde{b})$, $l(\tilde{a}) = l(\tilde{b})$, and $c(\tilde{a}) > c(\tilde{b})$, $\tilde{a} \succ \tilde{b}$, signifying that $\tilde{a}$ is superior to $\tilde{b}$. Moreover, $\tilde{b} \succ \tilde{a}$ when $c(\tilde{a}) < c(\tilde{b})$, denoting that $\tilde{b}$ is superior to $\tilde{a}$. Finally, $\tilde{a} \sim \tilde{b}$ when $c(\tilde{a}) = c(\tilde{b})$, indicating that $\tilde{a}$ is equal to $\tilde{b}$.

2.3. The normalized weighted Bonferroni mean and prioritized average operator

Definition 4 [43]. Let $p,\ q \geq 0$; and $a_i (i = 1, 2, \ldots, n)$ be a collection of non-negative numbers with the weight vector $w = (w_1, w_2, \ldots, w_n)^T$ such that $w_i \in [0,\ 1]$ and $\sum_{i=1}^{n} w_i = 1$. The normalized weighted BM operator is defined as follows:

$$\text{normalized weighted } BM_w^{p,q}(a_1, a_2, \ldots, a_n) = \left(\bigoplus_{\substack{i,j=1 \\ i \neq j}}^{n} w_i w_j \left(a_i^p \otimes a_j^q \right) / (1 - w_i) \right)^{\frac{1}{p+q}}. \quad (4)$$

Definition 5 [36]. Let $C = \{C_1, C_2, \ldots, C_n\}$ be a collection of criteria, and let there be a prioritization among the criteria such that C_p has a higher priority than C_q if $p < q$. $C_j(x)$ is the evaluation value of any alternative x under criteria C_j and satisfies $C_j(x) \in [0,\ 1]$. The PA operator is defined as follows:

$$PA\left(C_j(x)\right) = \sum_{j=1}^{n} w_j C_j(x), \quad (5)$$

where $w_j = T_j / \sum_{j=1}^{n} T_j$, $T_1 = 1$ and $T_j = \prod_{k=1}^{j-1} C_k(x) (j = 2, 3, \ldots, n)$.

3. Problem statement

To make the B2C e-commerce evaluation process as efficient and effective as possible and ensure the evaluator validity, this study strategically selected several experts to operate the final evaluation. In general, the expert refers to people with high level of competence and expertise, who are well-trained professional in a certain field [44,45]. With this in mind, this study invited four experts from e-commerce field to assist in decision-making, involving a website designer, a software engineer, a professor, and an information technology (IT) analyst. Several factors were taken into consideration when selecting these appropriate experts, such as work experience, academic background, and familiarity with B2C e-commerce evaluation problem and so on. For example, the assigned website designer has the following advantages: 1) he/she is a graduate with at least a bachelor degree and ten years of experience in the B2C e-commerce industry, such that he/she has sufficient experience and knowledge about the B2C e-commerce evaluation problem; 2) he/she specializes in web design and creating website prototypes before the websites are deployed in the Internet; and 3) he/she is also an active user of B2C e-commerce so that he/she can give considerable feedback on B2C e-commerce websites. Likewise, the other selected experts also have these features.

After preliminary elimination, six widely used B2C e-commerce websites with similar features and providing similar services were selected as the alternatives, designated as B2C e-commerce 1–6 (A_1–A_6). Besides, the identified evaluation criteria were presented in Fig. 1, which were supported by the four experts after a careful review. Moreover, all the original evaluation information on criteria and alternatives must first be gathered by consulting the group of experts and then processed into SVTNN matrices. For more details on the information acquisition module, refer to Section 4.1.1.

To give a formal description of this problem, we assume that there is a list of m candidates of B2C e-commerce websites, denoted as $\{A_1, A_2, \ldots, A_m\}$, to be evaluated. Let MC and SC be the sets of dimensions and sub-criteria identified in the B2C e-commerce website evaluation model in Fig. 1, respectively. The dimension set MC contains a total number of n dimensions $MC = \{MC1, MC2, \ldots, MCn\}$ and the sub-criteria set SC includes a number of r sub-criteria $SC = \{SC1, SC2, \ldots SCr\}$ acting as evaluation criteria. Each dimension MCj is described by r_j $(j = 1, 2, \ldots, n)$ sub-criteria such that $r = \sum_{j=1}^{n} r_j$. For information acquisition (see Section 4.1.1), four experts were invited to provide their assessments on these B2C e-commerce websites with respect to each sub-criterion. Subsequently, the evaluation matrix $D^j = [d_{ik}^j]_{m \times r_j}$ were established with SVTNNs through two sessions among experts, and $d_{ik}^j = \langle [a_{ik1}^j, a_{ik2}^j, a_{ik3}^j, a_{ik4}^j], (T_{d_{ik}^j}, I_{d_{ik}^j}, F_{d_{ik}^j}) \rangle$ $(i = 1, 2, \ldots, m,$ $k = 1, 2, \ldots, r_j$ and $\sum_{j=1}^{n} r_j = r)$ stands for the evaluation value for alternative $A_i (i = 1, 2, \ldots, m)$ with respect to sub-criteria SC_k under dimension MCj that contains r_j $(j = 1, 2, \ldots, n)$ sub-criteria; thus, $k = 1, 2, \ldots, r_j$.

4. Research methodology

4.1. Overall framework

To make up the deficiencies existed in prior research, this study establishes a novel integrated fuzzy-based MCDM approach to evaluate B2C e-commerce websites. The motivation of this approach lies in not only handling the indeterminate and inconsistent evaluation data but also capturing the interrelationships and different priority levels of criteria in a hierarchical structure.

The evaluation results consist of two parts: one is the ranking order of alternatives obtained by aggregating assessments from bottom (sub-criteria) to top (dimensions) step by step along the multi-level hierarchy of criteria and comparing the score values of each alternative; the other is the causal relationships and prioritized orders among criteria generated by the SVTN-DEMATEL module. Based on these findings, two purposes can be realized: one is to compare different B2C e-commerce websites with similar functionalities to select the one which best suits online customer needs; the other is to guide e-commerce businesses to better al-

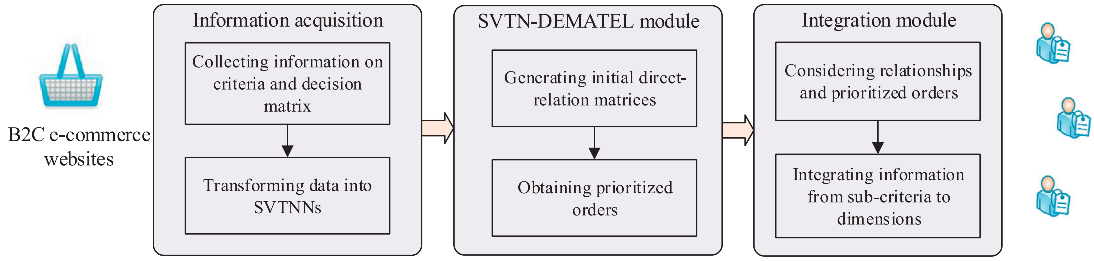

Fig. 3. Framework of the proposed approach for the evaluation of B2C e-commerce websites.

Table 2
Transformation between linguistic variables and TFNs for prioritized order of dimensions and sub-criteria.

Linguistic variables (h)	TFNs
Very high influence h_4	⟨[0.8, 0.9, 0.9, 1.0]⟩
High influence h_3	⟨[0.6, 0.7, 0.7, 0.8]⟩
Low influence h_2	⟨[0.4, 0.5, 0.5, 0.6]⟩
Very low influence h_1	⟨[0.2, 0.3, 0.3, 0.4]⟩
No influence h_0	⟨[0, 0.1, 0.1, 0.1]⟩

Table 3
Transformation between linguistic variables and TFNs for ranking alternatives.

Linguistic variables	TFNs
Very good (VG)	[0.8, 0.9, 0.9, 1.0]
Good (G)	[0.6, 0.7, 0.7, 0.9]
Fair (F)	[0.3, 0.5, 0.5, 0.7]
Poor (P)	[0.1, 0.3, 0.3, 0.5]
Very poor (VP)	[0, 0.1, 0.1, 0.2]

locate resources in designing websites according to the prioritized orders of evaluation criteria.

For clarity, Fig. 3 depicts the following three main modules in our study: 1) information acquisition; 2) SVTN-DEMATEL module; and 3) the integration module. Further details of this integrated approach are explained throughout the subsequent sections.

4.1.1. Information acquisition

The information acquisition module was conducted by consulting experts to gather information on both criteria and alternatives. For collecting information on criteria, evaluators were asked to establish the initial direct-relation matrices by providing their assessments on each pair of dimensions and sub-criteria. Two sessions were needed. First, experts were required to assess each pair of dimensions and sub-criteria aimed at classifying the level of strength of their interdependencies into different categories (e.g., "no influence" or "very high influence"). In this work, we adopted the five-point linguistic rating scale shown in Table 2 to indicate the causal relationships of dimensions and sub-criteria on one another. Second, experts were asked to anonymously evaluate the obtained preference degrees through voting (in favor, against, or by abstaining) on each evaluation index. Therefore, the initial direct-relation matrices characterized by simplified neutrosophic linguistic sets (SNLSs) were established (refer to Tian et al. [46–48] and Wang et al. [49]). Particularly, when the experts provided their judgments on the obtained linguistic term, they could assess the linguistic term with probabilities of truth, falsity, and indeterminacy all at once, and the three degrees of truth, falsity, and indeterminacy were independent one another. Subsequently, the gathered linguistic variables in SNLSs were translated into their corresponding TFNs, as shown in Table 2, to ensure that the preference degrees were relative to the continuous TFN. Finally, the initial direct-relation matrices on criteria were established as characterized by SVTNNs.

For collecting information on alternatives, two sessions similar to those processes on criteria were carried out. First, experts were required to assess the given evaluative objects with respect to each sub-criterion by eliciting linguistic terms to sort these candidates into different classes (e.g., "poor" or "good"). Second, experts were asked to anonymously evaluate the obtained preference degrees through voting (in favor, against, or by abstaining) on each evaluation index. Therefore, the initial decision matrices characterized by SNLSs were established. Subsequently, the gathered linguistic variables in SNLSs were translated into corresponding TFNs (see Table 3 [22]) to ensure that the preference degrees can be obtained in a continuous manner [50]. Finally, the SVTNN evaluation matrices were identified.

4.1.2. The SVTN-DEMATEL module

In the second module, the SVTN-DEMATEL approach was applied to analyze the causal relationships among dimensions and sub-criteria, aiming at obtaining the prioritized orders of both; accordingly, the direct-relation matrices obtained from the first module were defuzzified into score value matrices using Eq. (1). Subsequently, the direct-relation matrices were normalized, and the total-influence matrices were identified. Finally, we analyzed the results and obtained the prioritized orders for dimensions and sub-criteria.

4.1.3. The integration module

Due to the multi-level hierarchy of evaluation criteria, the integration module was conducted in two stages (see Fig. 4). In the first stage, since the initial decision information was collected under each sub-criterion, the overall evaluation information on dimension level was obtained by integrating initial evaluation information on sub-criterion level. Subsequently, in the second stage, the same aggregation process was performed on the dimension level to generate the overall assessment on each alternative. Finally, the ranking order of alternatives was obtained by Eq. (1).

In particular, the integration module was conducted by the SVTN-normalized prioritized weighted Bonferroni mean operator. For ease of understanding, the formula of the SVTN-normalized prioritized weighted Bonferroni mean operator was provided in Appendix A, and the procedures of the integration module were illustrated in Fig. 4.

4.2. Detailed procedure

To interpret our approach in great detail, we provide the algorithm of the proposed model in Appendix B, additionally, we present Fig. 5 to illustrate the framework of the proposed approach that includes 11 sub-steps.

The proposed approach involves the following 11 steps:

Step 1: Collect and transform data into SVTNNs.

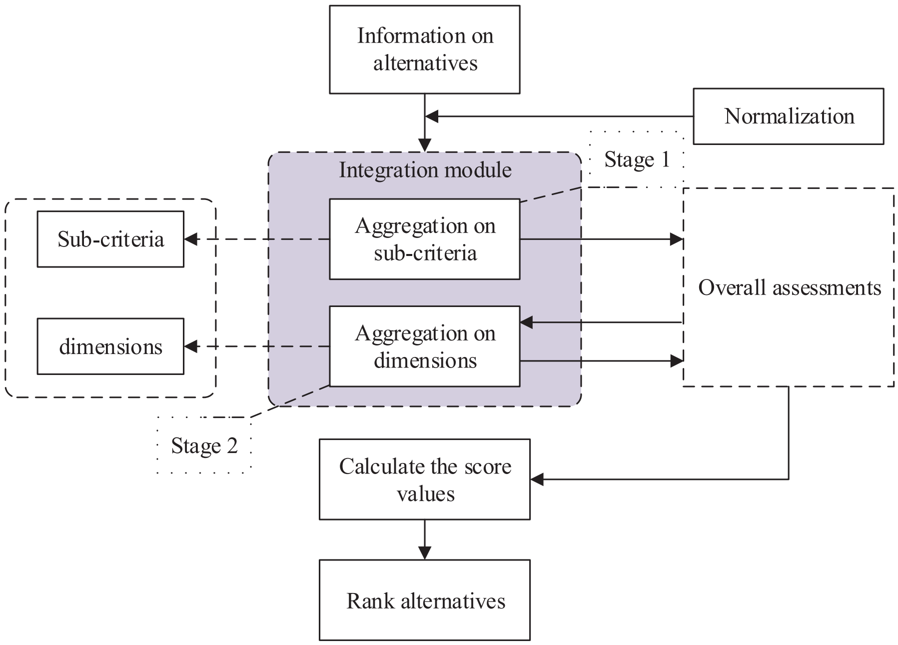

Fig. 4. The integration module for SVTNNs.

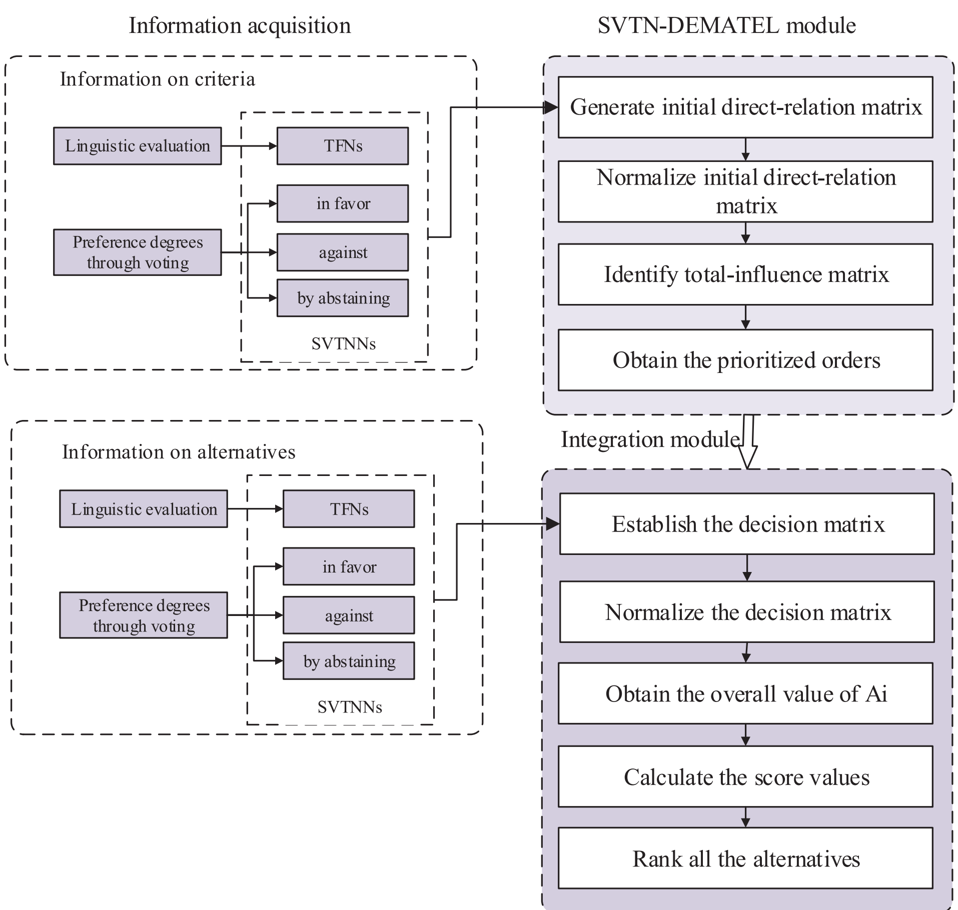

Fig. 5. The framework for evaluation of B2C e-commerce websites.

Section 4.1.1 explains that the initial direct-relation matrices among dimensions $MC = \{MC1, MC2, \ldots, MCn\}$ and sub-criteria $SC = \{SC1, SC2, \ldots SCr\}$ with SVTNN information were established as T_{MC} and T_{SC}^{j} $(j = 1, 2, \ldots, n)$, respectively. Given that the calculations between the dimensions and sub-criteria are categorically similar, we present only the calculation procedures for the dimension level for simplicity.

Step 2: Calculate the initial direct-relation matrix by score function.

Using the score function in Eq. (1), the score value matrices for dimension level S_{MC} can be calculated.

Step 3: Normalize the score value matrix S_{MC}.

The normalized matrix $\bar{S}_{MC}$ is acquired by the following equation.

$$\bar{S} = \frac{S_{MC}}{\nu}, \tag{6}$$

where $\nu = \max\{\max_{1\le i\le n}\sum_{j=1}^{n} S_{MC}^{ij}, \max_{1\le j\le n}\sum_{i=1}^{n} S_{MC}^{ij}\}, \quad i, j = 1, 2, \ldots, n,$ indicating that the score value matrix (S_{MC}) should be divided by the bigger value between the sum of each row and the sum of each column of matrix S_{MC}. The sums of each row and each column can be interpreted respectively as the total direct effects the criterion i exerts on the other criteria and the total direct effects received by criterion i from other criteria.

Step 4: Identify the total-influence matrix G.

The total-influence matrix G can be obtained using the normalized matrix $\bar{S}$ and the identity matrix I:

$$G = \bar{S}\left(I - \bar{S}\right)^{-1}. \tag{7}$$

Step 5: Analyze the results.

In this step, the causal diagram can be constructed by calculating the sums of the row and the column in the total-influence matrix G, respectively denoted as $r = [\sum_{j=1}^{n} G_{ij}]' = (r_1, r_2, \ldots, r_n)$ and $s = [\sum_{i=1}^{n} G_{ij}] = (s_1, s_2, \ldots, s_n)$. Subsequently, the horizontal axis vector $(r+s)$, designated as "Prominence", represents the degree of importance that criterion i plays in the system, and the vertical axis $(r-s)$, labeled "Relation", shows the net effect that criterion i plays in the system. Generally, the sub-criterion or dimension i belongs to the cause group when $r - s \ge 0$ and belongs to the effect group when $r - s < 0$.

After performing the above steps for the dimension level, the same calculations are conducted on the sub-criteria level. Finally, the prioritized orders for dimensions and sub-criteria can be obtained by comprehensively considering their prominence and relation vectors.

Step 6: Establish the decision matrices D^j.

Section 4.1.1 illuminates that the evaluation information with respect to all the sub-criteria $SC = \{SC1, SC2, \ldots, SCr\}$, which are assigned by SVTNNs, is gathered and transformed from the opinion of the group of experts. Consequently, a number of j decision matrices $D^j = [d_{ik}^{j}]_{m\times r_j}$ are constructed as follows:

$$D^j = \begin{bmatrix} d_{11}^{j} & d_{12}^{j} & \cdots & d_{1r_j}^{j} \\ d_{21}^{j} & d_{22}^{j} & \cdots & d_{2r_j}^{j} \\ \vdots & \vdots & \vdots & \vdots \\ d_{m1}^{j} & d_{m2}^{j} & \cdots & d_{mr_j}^{j} \end{bmatrix}_{m\times r_j}, \quad (j = 1, 2, \ldots, n), \tag{8}$$

Step 7: Determine the normalized decision matrices $\bar{D}^j$.

The following are the two types of sub-criteria present in the evaluation of B2C e-commerce websites: benefit and cost types. The sub-criteria should be made uniform in type for comparison. Therefore, no operations are required for benefit sub-criteria; as for the cost sub-criteria, all the evaluation values under these cost sub-criteria would be modified by the negative operation as follows:

$$neg(\tilde{a}) = \langle [1 - a_4, 1 - a_3, 1 - a_2, 1 - a_1], (F_{\tilde{a}}, 1 - I_{\tilde{a}}, T_{\tilde{a}})\rangle \tag{9}$$

Step 8: Obtain the aggregated decision matrix A.

In the first stage, the aggregated value of each alternative A_i with respect to each dimension is obtained by integrating the initial evaluation information on the sub-criteria level. The results are constructed asfollows:

$$A = \begin{array}{c} \begin{matrix} MC1 & MC2 & \cdots & MCn \end{matrix} \\ \begin{bmatrix} A_1^1 & A_1^2 & \cdots & A_1^n \\ A_2^1 & A_2^2 & \cdots & A_2^n \\ \vdots & \vdots & \vdots & \vdots \\ A_m^1 & A_m^2 & \cdots & A_m^n \end{bmatrix}_{m\times n} \end{array} \tag{10}$$

where $A_i^j = \langle [a_{i1}^j, a_{i2}^j, a_{i3}^j, a_{i4}^j], (T_{A_i^j}, I_{A_i^j}, F_{A_i^j})\rangle \quad (i = 1, 2, \ldots, m, j = 1, 2, \ldots, n)$ represents the aggregated evaluation value for alternative $A_i (i = 1, 2, \ldots, m)$ under dimension $MCj (j = 1, 2, \ldots, n)$.

Step 9: Calculate the overall value of A_i.

In the second stage, the overall assessment on each alternative A_i is obtained by integrating information on the dimension level.

Step 10: Identify the score value of A_i.

The score value of each alternative A_i can be obtained by Eq. (1).

Step 11: Rank all the alternatives.

Based on the score values obtained in Step 10, the ranking order for all the alternatives can be identified. The bigger the score value is, the better the option will be.

5. Case study

As illustrated in Section 3, this section aims to carry out the evaluation of six B2C e-commerce websites to verify the performance of the proposed integrated approach. Moreover, a sensitivity analysis was conducted to test its validity, and the comparison and discussion were carried out to demonstrate its advantages over comparative approaches.

5.1. Evaluation process and results

The main evaluation procedures are shown as follows.

Step 1: Collect and transform data into SVTNNs.

Section 4.1.1 explains that the experts were asked to determine the relative influence and direction of one criterion over another through pair-wise comparison. For example, the comparison result between *MC1* and *MC2* dimensions is denoted as $s_{MC}^{12} = \langle [0, 0.1, 0.1, 0.1], (0.8, 0, 1)\rangle$, this result was obtained by two sessions among experts. In the first round, the linguistic term h_0 was obtained by experts meaning that *MC1* dimension generates no influence on *MC2* dimension. Given that the linguistic term h_0 was still a kind of subjective information with uncertainty [51], different experts might hold different supporting degrees on the linguistic term h_0 and be reluctant to modify their opinions. Subsequently, the second round of consultation within the experts was held to improve the group consensus, where the experts were asked to anonymously evaluate the linguistic term h_0 by voting (in favor, against, or by abstaining); accordingly, the preference degrees of the truth, falsity, and indeterminacy degrees toward the linguistic term h_0 were obtained as 0.8, 0.1, and 0, respectively. Finally, the linguistic term h_0 was transformed into the corresponding TFN $\langle [0, 0.1, 0.1, 0.1]\rangle$ according to Table 2, and the SVTNN $s_{MC}^{12} = \langle [0, 0.1, 0.1, 0.1], (0.8, 0, 1)\rangle$ was obtained. Similarly, the pair-wise comparison results for dimensions were listed in Table 4 as below.

Step 2: Calculate the initial direct-relation matrix by score function.

Table 4
Pair-wise comparison for the dimensions.

Dimension	*MC1*	*MC2*	*MC3*	*MC4*
MC1	0	$\langle[0, 0.1, 0.1, 0.1], (0.8, 0, 0.1)\rangle$	$\langle[0.6, 0.7, 0.7, 0.8], (1, 0, 0)\rangle$	$\langle[0, 0.1, 0.1, 0.1], (0.7, 0, 0)\rangle$
MC2	$\langle[0.2, 0.3, 0.3, 0.4], (0.9, 0, 0)\rangle$	0	$\langle[0.6, 0.7, 0.7, 0.8], (1, 0, 0)\rangle$	$\langle[0.2, 0.3, 0.3, 0.4], (1, 0, 0)\rangle$
MC3	$\langle[0.8, 0.9, 0.9, 1], (1, 0, 0.2)\rangle$	$\langle[0.8, 0.9, 0.9, 1], (1, 0, 0)\rangle$	0	$\langle[0.6, 0.7, 0.7, 0.8], (1, 0, 0)\rangle$
MC4	$\langle[0.4, 0.5, 0.5, 0.6], (1, 0, 0)\rangle$	$\langle[0.2, 0.3, 0.3, 0.4], (0.9, 0, 0)\rangle$	$\langle[0.6, 0.7, 0.7, 0.8], (1, 0, 0)\rangle$	0

Table 5
Crisp values of dimensions.

Dimension	$(r+s)$	$(r-s)$
MC1	3.0623	−0.7275
MC2	3.1579	0.0406
MC3	4.7289	0.2622
MC4	3.0871	0.4272

With the employment of the score function in Eq. (1), the score value matrix can be calculated as follows:

$$T = \begin{bmatrix} 0 & 0.075 & 0.7 & 0.075 \\ 0.29 & 0 & 0.7 & 0.3 \\ 0.84 & 0.9 & 0 & 0.7 \\ 0.5 & 0.29 & 0.7 & 0 \end{bmatrix}.$$

Step 3: Normalize the score value matrix S.
Utilizing Eq. (6):

$$\bar{S} = \begin{bmatrix} 0 & 0.0307 & 0.287 & 0.0307 \\ 0.3443 & 0 & 0.3869 & 0.123 \\ 0.3443 & 0.3689 & 0 & 0.2869 \\ 0.2049 & 0.1189 & 0.2869 & 0 \end{bmatrix}.$$

Step 4: Identify the total-influence matrix G.
Using Eq. (7):

$$G = \begin{bmatrix} 0.2372 & 0.2408 & 0.4832 & 0.2062 \\ 0.4186 & 0.2664 & 0.5795 & 0.3348 \\ 0.7272 & 0.6618 & 0.5563 & 0.55 \\ 0.5119 & 0.3897 & 0.6144 & 0.2399 \end{bmatrix}.$$

Step 5: Analyze the results.
By calculating $r = [\sum_{j=1}^{n} G_{ij}] = (r_1, r_2, \dots, r_n)^T$ and $s = [\sum_{i=1}^{n} G_{ij}] = (s_1, s_2, \dots, s_n)$ in the total-influence matrix G, the crisp values and causal diagram of the dimensions are shown in Table 5 and Fig. 6, respectively.

Fig. 6 depicts that *MC1* dimension can be classified into the effect group of criteria and the others into the cause group. Considerable control and attention should be directed toward the cause group factors rather than to its counterpart because such cause group factors can generate considerable impact on the other group of factors, thereby contributing to decision-making. In other words, the cause group of criteria implies the influencing factors, whereas the effect group denotes the influenced factors [34]. More specifically, *MC3* has the highest prominence value (4.7289), suggesting that the importance degree of *MC3* should be given the greatest value. Moreover, the prominence values of *MC4* and *MC2* are 3.0871 and 3.1579, respectively, indicating a lower ranking order than *MC3*. From the perspective of relation value, only the *MC1* dimension has a negative value; hence, this dimension is the only effect element in the effect group of criteria. This outcome means that *MC1* can be easily influenced by other factors. By considering the prominence and relation vectors comprehensively, the prioritized order of dimensions was identified as $MC3 \succ MC4 \succ MC2 \succ MC1$.

Similarly, for the sub-criteria level, we can gather the pair-wise comparison information from the team of experts. Here, we took only the sub-criteria in the *MC2* dimension as an example, and the comparative results are exhibited in Table 6.

After repeating Steps 2–5, we quantitatively extracted the interrelationships among sub-criteria in the *MC2* dimension as follows.

Fig. 7 and Table 7 illustrate that *SC23* is the most important sub-criterion in the *MC2* dimension because this sub-criterion has the highest prominence value (3.5367) and the highest relation value (1.328). Therefore, *SC23* is one of the most influencing sub-criteria in *MC2*. Moreover, *SC23* can be classified into the cause group, which can generate a remarkable effect on the members of the effect group. Similarly, *SC24* also has a relatively high prominence value (3.3907). Meanwhile, the relation value of *SC24* (0.4096) is also positive, indicating that this sub-criterion is not easily influenced by the other factors. Therefore, *SC24* also belongs to the cause group. Conversely, *SC21* and *SC22* belong to the effect group because their relation values (−1.1353 and −0.6023) are both negative. This finding implies that the *SC21* and *SC22* are easily affected by the other factors in the cause group. In summary, we suggest that e-commerce businesses pay considerable attention to *SC23* followed by *SC24*, *SC21*, and *SC22*. Subsequently, the sub-criteria in the *MC2* dimension can be prioritized as $SC23 \succ SC24 \succ SC21 \succ SC22$.

The similar calculations and analyses were performed for all the sub-criteria with respect to each dimension and the results are shown in Fig. 8.

Step 6: Establish the decision matrices D^j.

Section 4.1.3 elucidates that the evaluation information on alternatives is collected in the same way as Step 1. Thus, the details are omitted here due to space limitation.

Step 7: Determine the normalized decision matrices $\bar{D}^j$.

Given that all the sub-criteria are beneficial, normalization is not required.

Step 8: Obtain the aggregated decision matrix A.

We incorporate the prioritized orders of sub-criteria into the integration module to aggregate information on sub-criteria to obtain the overall assessment on each dimension.

Step 9: Calculate the overall value of A_i.

As the prioritized order of dimensions has been identified as $MC3 \succ MC4 \succ MC2 \succ MC1$, we incorporate it into the integration module to aggregate information on dimension to generate the overall assessment on each alternative A_i. The results are shown as follows (here we assume that $p = q = 1$).

$$A_1 = \left\langle \begin{matrix}[0.3166, 0.508, 0.508, 0.686] \\ , (0.441, 0.167, 0.149)\end{matrix} \right\rangle; \quad A_2 = \left\langle \begin{matrix}[0.419, 0.58, 0.58, 0.782] \\ , (0.544, 0.058, 0.121)\end{matrix} \right\rangle;$$
$$A_3 = \left\langle \begin{matrix}[0.489, 0.63, 0.63, 0.83] \\ , (0.579, 0.15, 0.09)\end{matrix} \right\rangle; \quad A_4 = \left\langle \begin{matrix}[0.498, 0.633, 0.633, 0.83] \\ , (0.419, 0.323, 0.169)\end{matrix} \right\rangle;$$
$$A_5 = \left\langle \begin{matrix}[0.3336, 0.521, 0.521, 0.69] \\ , (0.66, 0.09, 0.146)\end{matrix} \right\rangle; \quad \text{and} \quad A_6 = \left\langle \begin{matrix}[0.4, 0.572, 0.572, 0.77] \\ , (0.68, 0.01, 0.218)\end{matrix} \right\rangle.$$

Step 10: Identify the score value of A_i.

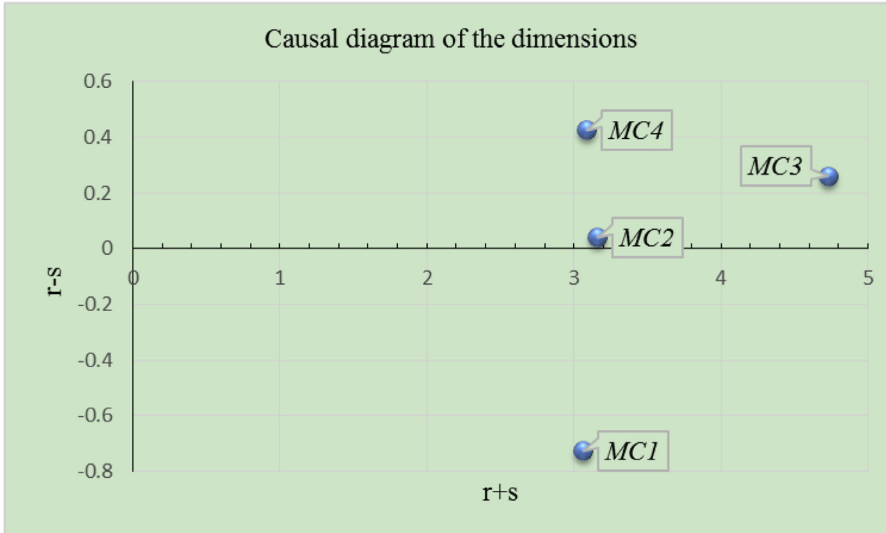

Fig. 6. Causal diagram of the dimensions.

Table 6
Pair-wise comparison for sub-criteria in the *MC2* dimension.

Sub-criterion	*SC21*	*SC22*	*SC23*	*SC24*
SC21	0	⟨[0.4, 0.5, 0.5, 0.6], (1, 0.5, 0)⟩	⟨[0.2, 0.3, 0.3, 0.4], (1, 0, 0)⟩	⟨[0.2, 0.3, 0.3, 0.4], (1, 0.2, 0)⟩
SC22	⟨[0.6, 0.7, 0.7, 0.8], (0.9, 0, 0)⟩	0	⟨[0, 0.1, 0.1, 0.1], (1, 0, 0)⟩	⟨[0.2, 0.3, 0.3, 0.4], (1, 0, 0)⟩
SC23	⟨[0.8, 0.9, 0.9, 1], (1, 0, 0)⟩	⟨[0.8, 0.9, 0.9, 1], (1, 0, 0)⟩	0	⟨[0.8, 0.9, 0.9, 1], (0.8, 0.3, 0)⟩
SC24	⟨[0.8, 0.9, 0.9, 1], (1, 0, 0)⟩	⟨[0.2, 0.3, 0.3, 0.4], (0.9, 0, 0)⟩	⟨[0.4, 0.5, 0.5, 0.6], (1, 0, 0)⟩	0

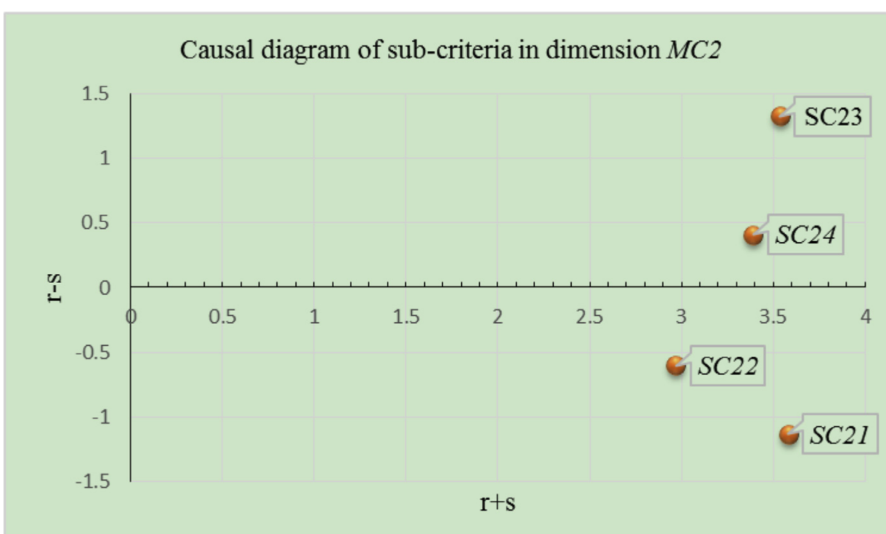

Fig. 7. Causal diagram of sub-criteria in the *MC2* dimension.

The score values of each alternative can be obtained by Eq. (1):

$sc(A_1) = 0.3583;\ \ sc(A_2) = 0.4629;\ \ sc(A_3) = 0.4982;$
$sc(A_4) = 0.4134;\ \ sc(A_5) = 0.4174;\ \ sc(A_6) = 0.4722.$

Step 11: Rank all the alternatives.

According to the score values obtained in Step 10, the ranking order for all the alternatives is $A_3 \succ A_6 \succ A_2 \succ A_5 \succ A_4 \succ A_1$; thus, the alternative A_3 is the best option.

5.2. Sensitivity analysis

For the exploration of the effects of different parameters (p and q) in the SVTN-normalized prioritized weighted Bonferroni mean operator, the ranking results are listed in Table 8 with different values of p and q. (The ranking order "$A_i \succ A_j \succ A_k \succ A_l \succ A_m \succ A_n$" is denoted by "$A_iA_jA_kA_lA_mA_n$" to save space.)

Table 8 exhibits that dissimilar ranking results were obtained when different values were assigned to the parameters p and q. B2C e-commerce A_3 had the best ranking among all the alterna-

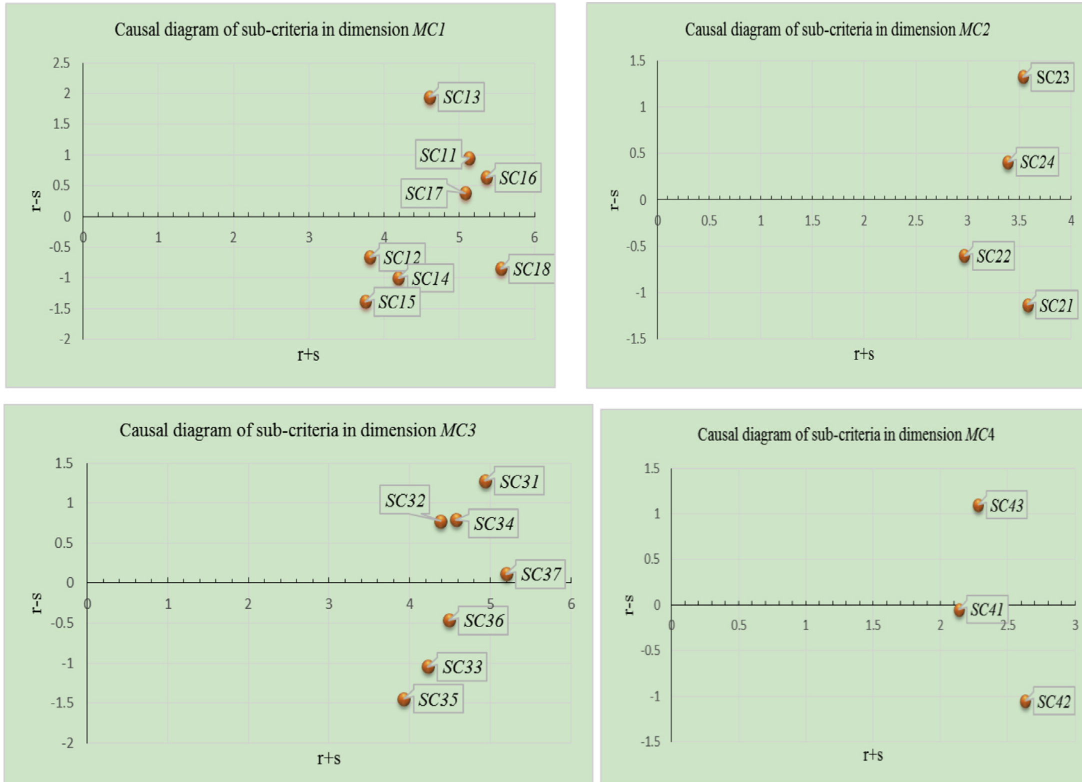

Fig. 8. Causal diagrams of sub-criteria in the *MC1-4* dimensions.

Table 7
Crisp values of sub-criteria in the *MC2* dimension.

Sub-criterion	$(r_i + s_i)$	$(r_i - s_i)$
SC21	3.5806	−1.1353
SC22	2.9668	−0.6023
SC23	3.5367	1.328
SC24	3.3907	0.4096

Table 8
Ranking orders with different values of p and q.

p and q	Ranking	p and q	Ranking
$p = 1, q = 0$	$A_6A_3A_2A_5A_4A_1$	$p = q = 4$	$A_3A_6A_4A_2A_5A_1$
$p = 0.5, q = 0.5$	$A_2A_6A_3A_5A_4A_1$	$p = q = 5$	$A_3A_6A_4A_2A_5A_1$
$p = q = 1$	$A_3A_6A_2A_4A_5A_1$	$p = q = 6$	$A_3A_6A_4A_2A_5A_1$
$p = 1, q = 2$	$A_3A_6A_2A_4A_5A_1$	$p = q = 7$	$A_3A_4A_6A_2A_5A_1$
$p = 2, q = 1$	$A_3A_6A_2A_4A_5A_1$	$p = q = 8$	$A_3A_2A_4A_6A_5A_1$
$p = q = 2$	$A_3A_6A_2A_4A_5A_1$	$p = q = 9$	$A_3A_2A_4A_6A_5A_1$
$p = q = 3$	$A_3A_6A_4A_2A_5A_1$	$p = q = 20$	$A_3A_2A_4A_6A_5A_1$

tives, except for two situations: when $p = 1, q = 0$ and $p = 0.5, q = 0.5$. Additionally, alternative A_1 was consistently identified as the worst choice regardless of how the parameters changed. The subtle differences in ranking results may be caused by two reasons. (1) The interrelationships among criteria cannot be captured when one or more parameters between p and q equal zero. (2) When the value of parameters p and q are smaller than one, the aggregated value may be amplified by the SVTN-normalized prioritized weighted Bonferroni mean operator, whereas the same effect will not occur in other occasions.

Furthermore, to visually exhibit the global effects of different attitudinal characters p and q on the integration module and conveniently determine the best promising alternative, we investigated the distribution characteristics of the score values for each alternative A_i when the values of parameters p and q varied from 0 to 20 using 0.5 increments, and we calculated a total number of 10,086 score values for all the alternatives. Fig. 9 depicts the results.

Fig. 9 illustrates that different score values for each alternative were obtained when parameters p and q had distinct values between 0 and 20. Moreover, the score value of each alternative increased with the increase in the values of parameters p and q. Using Fig. 9(a) as an example, the blue portion of the mapping surface indicates very high score values for alternative A_1 for the corresponding high values of parameters p and q. In addition, a large blue area will lead to considerably stable alternative A_1. Conversely, if one of the parameters (p or q) is fixed, then the score value of alternative A_1 continues to increase with increases in values of the other parameter. The extreme values are shown in the two purple parts of the mapping surface.

Comparing Fig. 9(a–f), we readily identify the ranking order of alternatives. For example, comparing Fig. 9(a,b), we find that the biggest blue area of the mapping surface in Fig. 9(b) represents the score value of alternative A_2 as around 0.55, whereas the corresponding area in Fig. 9(a) suggests that the score value of alternative A_1 is around 0.45. Therefore, alternative A_2 is better than A_1 when parameters p and q take values between 0 and 20. Moreover, we can find that most score values of alternatives A_4 and A_6 lie in the purple portions representing values higher than 0.5 and that their score values appear to intersect at a certain point. This outcome also explains why the orders of alternatives A_4 and A_6 exchanged as depicted in Table 8. Similarly, in Fig. 9(c), the most widely distributed blue and green areas indicate that the score values of alternative A_3 lie nearest to 0.6, which is steadily bigger than the others. Therefore, alternative A_3 can be regarded as the benchmarking B2C e-commerce website providing directions for others to improve their service quality.

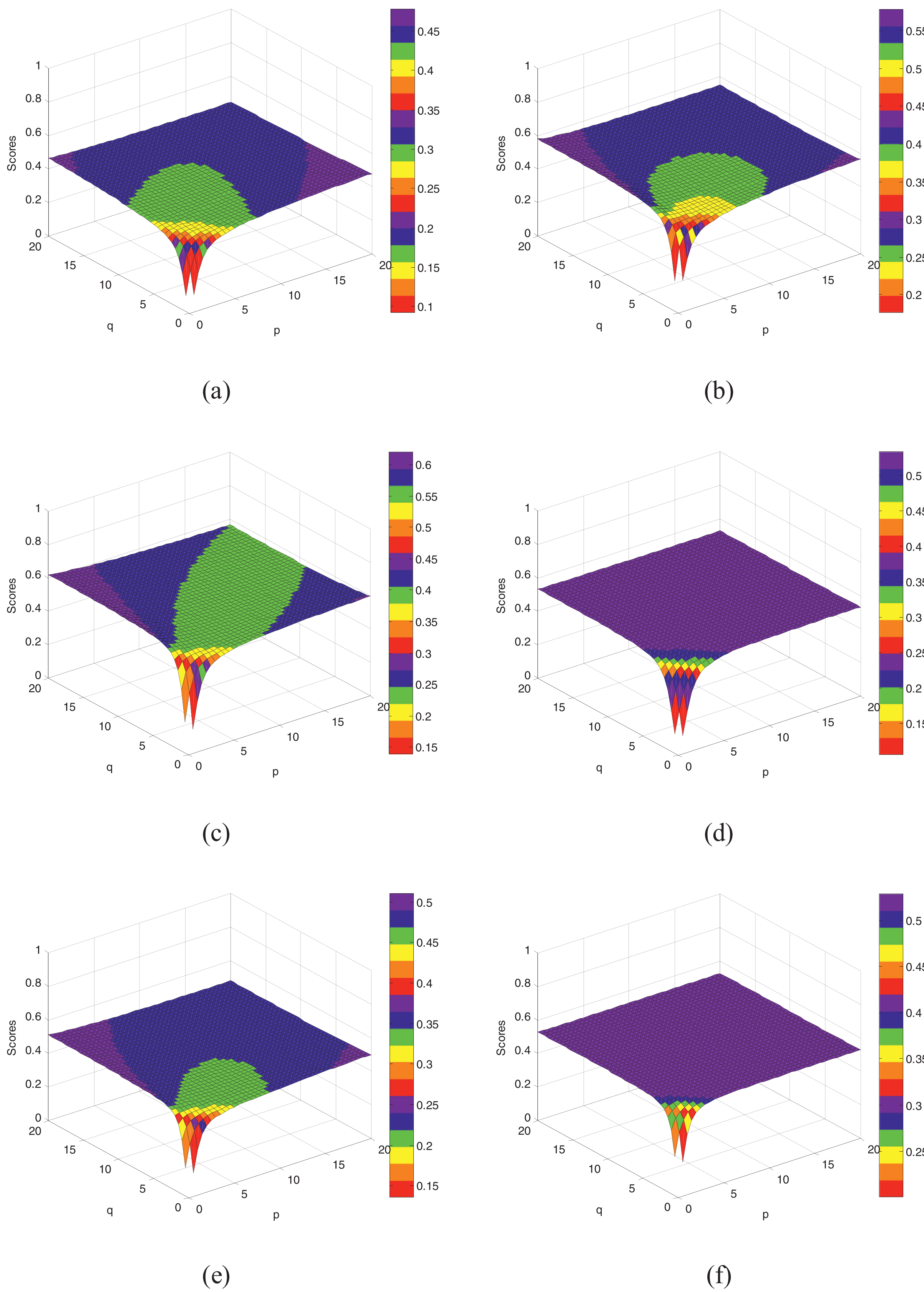

Fig. 9. Scores for alternatives $A_1 - A_6$ by the integration module. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 9
Comparison with other approaches.

Approach	Ranking order
Fuzzy TOPSIS approach [52].	$A_6 \succ A_2 \succ A_3 \succ A_5 \succ A_4 \succ A_1$
Fuzzy hierarchical TOPSIS approach [22]	$A_3 \succ A_5 \succ A_4 \succ A_6 \succ A_2 \succ A_1$
Aggregation operator-based approaches	
TNWAA operator [42]	$A_3 \succ A_2 \succ A_1 \succ A_6 \succ A_5 \succ A_4$
TNWGA operator [42]	$A_3 \succ A_6 \succ A_4 \succ A_1 \succ A_2 \succ A_5$
SVTN-normalized weighted	
Bonferroni mean operator [29] ($p = q = 1$)	$A_3 \succ A_2 \succ A_6 \succ A_1 \succ A_4 \succ A_5$
Proposed integrated approach ($p = q = 1$)	$A_3 \succ A_6 \succ A_2 \succ A_5 \succ A_4 \succ A_1$

5.3. Comparison and discussion of the results

To observe the changes of the evaluation results generated by applying different MCDM approaches, we compared this proposed model with four other approaches based on the same problem in this study and explored the reasons for differences. Accordingly, we summarized the advancements of the proposed model over the exiting studies. Below are the brief descriptions about the comparative approaches.

(1) Fuzzy TOPSIS approach [52]: A traditional fuzzy-based MCDM approach based on the idea that the evaluated alternative should have the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution.
(2) Fuzzy hierarchical TOPSIS approach [22]: An extended version of the traditional fuzzy TOPSIS approach. It improves the traditional fuzzy TOPSIS approach by taking the hierarchical structure among criteria into consideration.
(3) Aggregation operator-based approaches [29,42]: Aggregation operators including the trapezoidal neutrosophic weighted arithmetic averaging (TNWAA), trapezoidal neutrosophic weighted geometric averaging (TNWGA), and the single-valued trapezoidal neutrosophic normalized weighted Bonferroni mean (SVTN-normalized weighted Bonferroni mean) operators are proposed for information fusion, then, ranking results are obtained by the score functions of SVTNNs. More aggregation operators with SVTNNs can be tested in the future.

Given that the decision information in comparison approaches [52] and [22] are not totally consistent with this study, we performed certain modifications and applied only the basic ideas of these approaches to solve our problem. Table 9 exhibits the comparative results.

Table 9 shows that, although the detailed ranking results of alternatives differ in each comparative method, A_3 remains the highest ranked alternative, despite the condition in the fuzzy TOPSIS approach [52]. These differences may be explained by various reasons. First, the fuzzy TOPSIS approach [52] overlooked the hierarchical structure between criteria inherent in the e-commerce settings. Second, although the fuzzy hierarchical TOPSIS approach [22] considered the hierarchical structure of criteria, it ignored the causal relationships among them. In case of the aggregation operator-based approaches ([29, 42]), the TNWAA and TNWGA operators in Ref. [42] were developed respectively using the arithmetic mean and geometric mean, which determined that the former TNWAA operator emphasized a group's comprehensive evaluation, whereas the latter TNWGA operator gave more importance to individual opinions [33]. In addition, they were both based on the assumption that inputs were independent one another. Conversely, the SVTN-normalized weighted Bonferroni mean operator in Ref. [29] considered the interrelationships among input arguments, and the SVTN-normalized prioritized weighted Bonferroni mean operator in this work was proposed aiming at capturing both the interrelationships among criteria and different prioritized levels of them. The inherent characteristics of these aggregation tools are remarkably different thus yielding distinct rankings of alternatives. These differences in evaluation results also indicated the importance for evaluators to carefully select the most suitable aggregation tool based on the natures of decision-making problem and criteria [51].

In summary, the advancements of this proposed approach over existing works are as follows.

(1) Approaches [29,42,52] assigned weightings of criteria in advance, which may lead to subjective randomness. In this research, the DEMATEL technique was extended to the SVTNN environment, and the SVTN-DEMATEL module was proposed to determine the prioritized orders of involved criteria. Consequently, this study identified the prioritized orders of criteria in a quantitative way and incorporated them into the proposed integration module rather than assigning them totally by experts' opinions, thereby generating a substantially objective and rational ranking order of alternatives.
(2) Approach [52] failed to capture the hierarchical structure among criteria, and approach [22] considered the hierarchical criteria but overlooked their causal relationships, which commonly existed in evaluation criteria involved in B2C e-commerce. By contrast, we considered both by utilizing the SVTN-DEMATEL module.
(3) For information fusion, neither the approach in Ref. [42] nor Ref. [29] took the interrelationships and priority levels among criteria into account simultaneously. However, it has been proven that the sub-criteria and dimensions in e-commerce context were correlative one another [53]. To address this issue, this research proposed the SVTN-normalized prioritized weighted Bonferroni mean operator to take these characteristics into consideration. Overall, when evaluated against the aforementioned comparative approaches, the proposed model could yield considerably accurate and reliable ranking results.

6. Conclusions and future research

Evaluation of B2C e-commerce websites has become an interesting topic in the e-era, and such evaluation involves various correlative dimensions and sub-criteria. This research aimed at combining the SVTN-DEMATEL technique with the SVTN-normalized prioritized weighted Bonferroni mean operator for recommending an appropriate B2C e-commerce website for customers accurately and efficiently. The SVTN-DEMATEL technique captured the causal relationships among criteria and identified their prioritized orders, whereas the proposed SVTN-normalized prioritized weighted Bonferroni mean operator incorporated the identified prioritized orders and interrelationships when integrating criteria. Subsequently, the ranking order of alternatives was obtained by the score function of SVTNNs. In addition, the proposed model was tested by a B2C e-commerce website evaluation problem, and further validated by sensitivity and comparative analyses.

Summary of the novelties of our research is threefold. (1) We introduced the SVTNNs to quantify the evaluation information in the e-commerce context. (2) We proposed a novel theoretical approach for solving fuzzy-based MCDM problems by combining information acquisition, the SVTN-DEMATEL module, and the integration module, where the inputs of the latter module were entirely generated by the former module. (3) We proposed the SVTN-normalized prioritized weighted Bonferroni mean operator for information fusion, which could conform to highly practical decision-making situations.

The practical implications of our research may lie in several aspects. On the one hand, this research indicated that there were different priority levels and interrelationships among the impact factors affecting the e-commerce service quality. This finding can serve as suggestion in two directions: 1) gave the e-commerce website managers a clue for identifying and distributing the prioritized orders for impact factors; and 2) help e-commerce businesses allocate resources reasonably to increase customer satisfaction according to the identified prioritized criteria. On the other hand, this research introduced the SVTNNs to quantify evaluation information in the e-commerce context, which provided a rich and comprehensive context of how managers perceive and respond to this phenomenon. In addition, this work was a further extension and complement to our previous works, and could suggest interesting avenues for potential applications to other related or different domains, such as sustainable service design, new product development evaluation, and risk assessment and so on.

Clearly, certain limitations are extant in this work, and they can serve as suggestions for further research. First, the calculations of our model were somewhat complicated because of the complex form of SVTNNs. Explorations should be made for easy computations. Second, as an important part of online consumption, online reviews reveal, to a large degree, the service level of e-commerce websites. Moreover, some comprehensive text reviews, especially those with high-quality, could be labeled as expert reviews. Therefore, these helpful reviews could be used to supplement the experts' assessments for the future applications of evaluation. Third, the evaluation information in this study was mainly gathered by consulting evaluators, they are experts in this study, which was subjective information. Motivated by studies [16,51], the objective information collected from instruments or machines had better be combined with the subjective information for better evaluation of e-commerce websites. Fourth, for the extensions of our study, the proposed SVTN-DEMATEL module can also be combined with other fuzzy-based MCDM approaches, such as the QUALIFLEX (qualitative flexible multiple criteria) method, which is very suitable to handle MCDM problems involving numerous criteria and limited alternatives.

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Appendix A. Formula of the SVTN-normalized prioritized weighted Bonferroni mean operator

Let $p,\ q \geq 0$ and $C = \{C_1, C_2, \ldots, C_n\}$ be a collection of criteria, such that a prioritization $C_1 \succ C_2 \succ \cdots \succ C_n$ exists among these criteria. Let $\tilde{a}_i = \langle [a_{i1}, a_{i2}, a_{i3}, a_{i4}], (T_{\tilde{a}_i}, I_{\tilde{a}_i}, F_{\tilde{a}_i}) \rangle$ $(i = 1, 2, \ldots, n)$ be a set of SVTNNs representing the performance values of object $\tilde{a}$ under criterion C_i. Subsequently, the SVTN-normalized prioritized weighted Bonferroni mean operator can be defined as follows:

$$
\begin{aligned}
&\mathit{SVTN\text{–}normalized\ prioritized\ weighted\ Bonferroni\ mean}_w^{p,q}(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n) = \\
&= \Bigg\langle \Bigg[\left(\bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} T_iT_j a_{i1}^p a_{j1}^q \Big/ \sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right) \right)^{\frac{1}{p+q}}, \left(\bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} T_iT_j a_{i2}^p a_{j2}^q \Big/ \sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right) \right)^{\frac{1}{p+q}}, \left(\bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} T_iT_j a_{i3}^p a_{j3}^q \Big/ \sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right) \right)^{\frac{1}{p+q}}, \left(\bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} T_iT_j a_{i4}^p a_{j4}^q \Big/ \sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right) \right)^{\frac{1}{p+q}} \Bigg], \\
&\Bigg(\left(\frac{\bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} \frac{1}{2} \frac{T_iT_j}{\sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right)} \left[a_{i3}^p a_{j3}^q - a_{i2}^p a_{j2}^q + a_{i4}^p a_{j4}^q - a_{i1}^p a_{j1}^q \right] \left(T_{\tilde{a}_i}\right)^p \left(T_{\tilde{a}_j}\right)^q}{\bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} \frac{1}{2} \frac{T_iT_j}{\sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right)} \left[a_{i3}^p a_{j3}^q - a_{i2}^p a_{j2}^q + a_{i4}^p a_{j4}^q - a_{i1}^p a_{j1}^q \right]} \right)^{\frac{1}{p+q}}, 1 - \left(1 - \frac{\bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} \frac{1}{2} \frac{T_iT_j}{\sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right)} \left[a_{i3}^p a_{j3}^q - a_{i2}^p a_{j2}^q + a_{i4}^p a_{j4}^q - a_{i1}^p a_{j1}^q \right] \left(1 - I_{\tilde{a}_i}\right)^p \left(1 - I_{\tilde{a}_j}\right)^q}{\bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} \frac{1}{2} \frac{T_iT_j}{\sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right)} \left[a_{i3}^p a_{j3}^q - a_{i2}^p a_{j2}^q + a_{i4}^p a_{j4}^q - a_{i1}^p a_{j1}^q \right]} \right)^{\frac{1}{p+q}}, \\
&1 - \left(1 - \bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} \frac{1}{2} \frac{T_iT_j}{\sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right)} \left[a_{i3}^p a_{j3}^q - a_{i2}^p a_{j2}^q + a_{i4}^p a_{j4}^q - a_{i1}^p a_{j1}^q \right] \left(1 - F_{\tilde{a}_i}\right)^p \left(1 - F_{\tilde{a}_j}\right)^q \Big/ \bigoplus_{\substack{i,j=1\\ i\neq j}}^{n} \frac{1}{2} \frac{T_iT_j}{\sum_{i=1}^{n} T_i \left(\sum_{i=1}^{n} T_i - T_i \right)} \left[a_{i3}^p a_{j3}^q - a_{i2}^p a_{j2}^q + a_{i4}^p a_{j4}^q - a_{i1}^p a_{j1}^q \right] \right)^{\frac{1}{p+q}} \Bigg) \Bigg\rangle.
\end{aligned}
\tag{A.1}
$$

where $T_1 = 1$, $T_i = \prod_{k=1}^{i-1} sc(\tilde{a}_k)(i = 2, 3, \ldots, n)$, $T_j = \prod_{k=1}^{j-1} sc(\tilde{a}_k)(j = 2, 3, \ldots, n)$, and $sc(\tilde{a}_k)$ is the score function of SVTNN $\tilde{a}_k$ by Eq. (1). The processes proving Eq. (A.1) are omitted here (refer to Liang et al. [29] and Ji et al. [54]).

Appendix B. The algorithm of the proposed integrated approach

We present the algorithm of our proposed integrated approach based on the illustration in Section 4 to explain how the model can be implemented as follows:

Algorithm: The integrated approach for B2C e-commerce website evaluation.

Input:	The initial direct-relation matrix among dimensions T_{MC} and sub-criteria T_{SC}^{j} $(j = 1, 2, \ldots, n)$, the decision matrix under each sub-criteria D^{j} $(j = 1, 2, \ldots, n)$.
Output:	The score values of each alternative A_i
Steps:	
1.	for each group of sub-criteria in dimension l from 1 to 4
	for each SC_{li} who rated i ranging from 1 to r_l where l ranges from 1 to 4
2.	$//SC_{li}$ represents "Prominence" value, indicating the degree of importance that sub-criterion i plays in the lth dimension; the r_l represents the total number of sub-criteria in the lth dimension
3.	initialize the variable $c_{li} = 1$;
4.	for each SC_{lj} who rated j ranging from 1 to r_l where l ranges from 1 to $4//SC_{lj}$ represents "Prominence" value, indicating the degree of importance that sub-criterion j plays in the lth dimension
5.	If $SC_{li} < SC_{lj}$
6.	obtain $c_{li} \leftarrow c_{li}+1$;
7.	end
8.	end
9.	add c_{li} to matrix C_l;
10.	end
11.	end
12.	return C_l;
13.	obtain the normalized decision matrices $\bar{D}^{j}$ by Eq. (9);
14.	obtain the aggregated decision matrix A by Eq. (A.1);
15.	for each dimension MC_q who rated q ranging from 1 to $4//MC_q$ represents "Prominence" value, indicating the degree of importance that the qth dimension plays in system
16.	initialize the variable $mc_i = 1$;
17.	for each dimension MC_k who rated k ranging from 1 to $4//MC_k$ represents "Prominence" value, indicating the degree of importance that the kth dimension plays in system
18.	If $MC_q < MC_k$
19.	obtain $mc_i \leftarrow mc_i+1$;
20.	end
21.	end
22.	add mc_i to matrix M;
23.	end
24.	return M;
25.	obtain the overall value of A_i by Eq. (A.1);
26.	identify the score value $sc(A_i)$ of A_i by Eq. (1);
27.	return $sc(A_i)$;

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