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A fuzzy analytic hierarchy process-enhanced fuzzy geometric mean-fuzzy technique for order preference by similarity to ideal solution approach for suitable hotel recommendation amid the COVID-19 pandemic

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Abstract

Cities around the world have reopened from the lockdown caused by the COVID-19 pandemic, and more and more people are planning regional travel. Therefore, it is a practical problem to recommend suitable hotels to travelers amid the COVID-19 pandemic. However, it is also a challenging task since the critical factors that affect hotel selection amid the COVID-19 pandemic may be different from those usually considered. From this perspective, the fuzzy analytic hierarchy process-enhanced fuzzy geometric mean-fuzzy technique for order preference by similarity to ideal solution approach is proposed in this study for hotel recommendation. The proposed methodology not only considers the critical factors affecting hotel selection amid the COVID-19 pandemic, but also establishes a systematic mechanism, that is, enhanced fuzzy geometric mean, to simultaneously improve the accuracy and efficiency of the recommendation process. The fuzzy analytic hierarchy process-enhanced fuzzy geometric mean-fuzzy technique for order preference by similarity to ideal solution approach has been successfully applied to recommend suitable hotels to 10 travelers for regional trips amid the COVID-19 pandemic.

Keywords

Hotel recommendation, fuzzy analytic hierarchy process, fuzzy geometric mean, fuzzy technique for order preference by similarity to ideal solution

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Introduction

The outbreak of COVID-19 was identified in Wuhan, China. Since then, the COVID-19 pandemic has severely affected the tourism industry. Taking the cruise industry as an example. Most cruise companies have suspended their operations to mitigate the spread of the pandemic.[1] Hotels are an important part of the tourism industry and have also been affected. For example, according to the statistics by Bloomberg, the global hotel occupancy rate dropped sharply from 1 February to 23 February. In China, Hong Kong, Singapore, South Korea, and Thailand, the rates fell by 85.3%, 73.6%, 48.7%, 33.5%, and 31.4%, respectively.[2] Later, as the pandemic gradually eased, in some countries and regions, people began to resume regional tourism,[3] accompanied by the demand for hotel accommodation. When the pandemic is not completely over, how to recommend suitable hotels to travelers is a topic worth discussing.

In the literature, a number of methods for recommending hotels have been proposed, for example, weighted average

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(WA) or fuzzy-WA (FWA),[4–8] analytic hierarchy process (AHP) or fuzzy AHP,[9,10] adaptive neuro-fuzzy inference systems (ANFISs),[11] RankBoost algorithms,[12] text mining,[13] collaborative filtering,[9,14–16] etc. There are also websites (e.g. TripAdvisor, Google Maps, and Yelp) and apps (such as TripAdvisor, Trivago, and HotelsCombined) that recommend suitable hotels to travelers.[17] However, during the COVID-19 pandemic, the following gaps existed between these existing methods and practices:

- Existing hotel recommendation methods cannot distinguish between situations with and without pandemic outbreaks. In particular, the factors to be considered during the COVID-19 pandemic are very different from those usually considered.[18–20] For example, before the outbreak of COVID-19, travel intent (or the purpose of accommodation) was a key factor. During the COVID-19 pandemic, the demand for accommodation for holiday, leisure, and recreation has almost diminished.[21] Therefore, travel intent is no longer a factor that should be considered. In contrast, the number of confirmed cases in the region where the hotel is located becomes an important factor during the COVID-19 pandemic. In addition, the availability of restaurants becomes less important because it is safer to request a room service than to go to a restaurant. Travelers will also avoid using leisure facilities. Further, many hotels have lowered room rates to attract travelers. As a result, room rate discounts, rather than room rates, have become a critical factor. Table 1 compares factors that are critical to hotel recommendation (or selection) before and amid the COVID-19 pandemic.
- Most existing methods approximate, rather than derive the values of priorities of critical factors affecting the selection of a suitable hotel using methods such as fuzzy geometric mean (FGM) and fuzzy extent analysis.[22–24] However, such approximation may lead to incorrect decisions.

Table 1. Comparison of factors critical to hotel recommendation (or selection) before and amid the COVID-19 pandemic.

	Before the COVID-19 outbreak	Amid the COVID-19 pandemic
Factors	• Room rate • Hotel reviews • Room size • WiFi accessibility and rate • Leisure facilities • Privacy • Restaurant availability; meal prices • Service quality • Environmental cleanliness • Nearby facilities and attractions • Safety	• Room rate • Room rate discount • Hotel reviews • Room size • Number of confirmed cases in the region • Availability of rooms with openable windows • Independent air conditioning • Room size • Anti-pandemic measures • WiFi accessibility and rate • Privacy • Service quality • Environmental cleanliness • Nearby facilities and attractions • Safety

The motivation of this study is to fill these gaps. To this end, a fuzzy AHP (FAHP)-enhanced FGM (EFGM)-fuzzy technique for order preference by similarity to ideal solution (FTOPSIS) approach is proposed in this study for hotel recommendation amid the COVID-19 pandemic. The novelties of the FAHP-EFGM-FTOPSIS approach include

1. Factors critical to the selection of a suitable hotel amid the COVID-19 pandemic are discussed and used as inputs to the FAHP-EFGM-FTOPSIS approach.
2. To enhance the precision of deriving the fuzzy priorities of critical factors, Chen et al.[25] proposed the approximating alpha-cut operations (xACO) method. However, Chen et al.'s method was based on alpha-cut operations (ACO) that are still time-consuming for a large-scale problem. To overcome this difficulty, the EFGM approach is proposed in this study. The EFGM approach derives the near-exact values of fuzzy priorities efficiently by fitting their membership functions.
3. Based on the derived fuzzy priorities, FTOPSIS[26,27] is applied to evaluate the overall performance of a hotel. FTOPSIS is more sensitive than FWA to the change in the overall performance.[28,29] The combination of FAHP and FTOPSIS is expected to achieve a better decision-making performance.

The remainder of this paper is organized as follows. Section "Literature review" is dedicated to the literature review. Section "The proposed methodology" is an introduction of the FAHP-EFGM-FTOPSIS approach proposed in this study. Section "Experiment" details the application of the FAHP-EFGM-FTOPSIS approach to recommending suitable hotels to 10 travelers for regional trips amid the COVID-19 pandemic. Several existing methods were also applied for comparison. Finally, section "Conclusions" provides the conclusions of this study as well as some possible topics for future investigation.

Literature review

Lin et al.[13] designed an app that can record the browsing behavior of travelers using smartphones to read hotel reviews. Then, text mining techniques were applied to analyze the results to determine the interests of travelers. Based on this analysis, suitable hotels were recommended to travelers. Boo and Busser[30] also adopted a similar methodology. Silamai et al.[5] established an on-site hotel recommendation system that takes into account a traveler's location, distance from each nearby hotel, attraction preferences and time budget, and the popularity of nearly attractions. The recommendation mechanism was similar to the WA method. Chen[4] proposed a FWA and backpropagation-network (BPN) approach for hotel recommendation, in which FWA was applied to evaluate the overall performance of a hotel and a BPN was constructed to defuzzify the overall performance. The recommendation results and travelers' choices were adopted to train the BPN defuzzifier. Yadegaridehkordi et al.[11] proposed a hybrid structural equation modeling-ANFIS approach to identify the critical factors that affect the success of a hotel. Chen and Chuang[6] proposed a fuzzy nonlinear programming approach to derive the values of weights in an FWA mechanism for explaining most travelers' choices. Wang et al.[31] mapped travelers' hotel reviews to interval neutrosophic linguistic numbers. Then, the interval neutrosophic linguistic number power average method was applied to evaluate the overall performance of a hotel, so as to recommend the top-performing hotel.

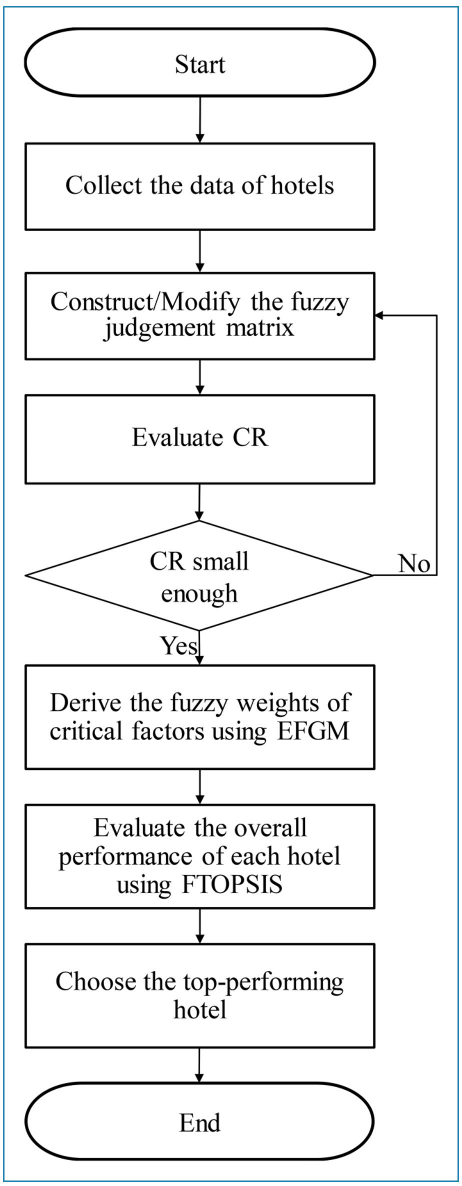

Figure 1. Steps of the FAHP-EFGM-FTOPSIS approach.
FAHP: fuzzy analytic hierarchy process; EFGM: enhanced fuzzy geometric mean; FTOPSIS: fuzzy technique for order preference by similarity to ideal solution.

The prevalence of social networks has promoted the effectiveness of hotel recommendation. Hotel recommendation systems based on social networks can better understand travelers' preferences by analyzing the information that travelers share on social networks (such as reviews, ratings, profiles, and social connections).[32] Liu and Li[32] divided hotel recommendation systems based on social networks into two categories: hotel recommendation systems using explicit feedbacks and hotel recommendation systems using implicit feedbacks. Hotel recommendation systems using explicit feedbacks apply content-based filtering methods and collaborative filtering methods; hotel recommendation systems using implicit feedbacks apply relative preference-based filtering methods and text-based filtering methods.[32] Collaborative filtering-based methods are still the mainstream of research in this field.[9,14,15] However, there are privacy issues with this type of method because travelers may not understand how their browsing history and messages on social networks are analyzed.[33]

The outbreak of COVID-19 and the ensuing city lockdowns have severely affected hotels around the world. For example, as the occupation rate dropped to single digits, many hotels in the United States were forced to close.[34] To make matters worse, as the COVID-19 pandemic continues, it is still unknown when hotels will reopen.[34] Over time, the pressure to pursue economic recovery forced cities to lift the blockade.[35] With the reopening of cities, people will travel more. However, staying in a hotel will definitely increase the exposure to COVID-19.[21] In the view of O'Neill,[21] the following issues are crucial when choosing a hotel to stay amid the COVID-19 pandemic:

1. In order to avoid the spread of COVID-19, does the hotel take measures such as social distancing and wearing masks?
2. Does hotels use new tools, such as electrostatic sprayers with hospital-grade disinfectants and ultraviolet light technology to disinfect room keys, guest rooms, lobbies, gyms, and other public areas?

3. In order to prevent cross-infection, does the hotel allocate different rooms for different travelers?
4. Large hotel chains are safer due to the transparency of their cleaning procedures.

The proposed methodology

The proposed FAHP-EFGM-FTOPSIS approach comprises the following steps:

Step 1. Collect the data of hotels around the traveler's destination.
Step 2. Construct a fuzzy judgment matrix, or modify the current fuzzy judgment matrix, by performing a pairwise comparison of the relative priorities of factors critical to the selection of a suitable hotel.
Step 3. Evaluate the fuzzy consistency ratio ($\widetilde{CR}$) of the fuzzy judgment matrix.
Step 4. If $\widetilde{CR}$ is not small enough, return to Step 2; otherwise, proceed to Step 5.
Step 5. Derive the fuzzy priorities of critical factors using EFGM.
Step 6. Feed the derived fuzzy priorities into FTOPSIS to evaluate the overall performance of each hotel.
Step 7. Rank the overall performances of hotels to choose the top-performing hotel.

A flowchart is presented in Figure 1 to illustrate these steps.

Table 2. Linguistic terms for expressing relative priorities.

Symbol	Linguistic term	Triangular fuzzy number (TFN)
L1	As equal as	(1, 1, 3)
L2	As equal as or weakly more important than	(1, 2, 4)
L3	Weakly more important than	(1, 3, 5)
L4	Weakly or strongly more important than	(2, 4, 6)
L5	Strongly more important than	(3, 5, 7)
L6	Strongly or very strongly more important than	(4, 6, 8)
L7	Very strongly more important than	(5, 7, 9)
L8	Very or absolutely strongly more important than	(6, 8, 9)
L9	Absolutely more important than	(7, 9, 9)

Fuzzy analytic hierarchy process

In FAHP, a decision-maker compares the relative priority of a critical factor over that of another using linguistic terms[36] such as "as equal as," "weakly more important than," "strongly more important than," "very strongly more important than," and "absolutely more important than." These linguistic terms are usually mapped to triangular fuzzy numbers (TFNs) within [1, 9] (see Table 2). Some arithmetic operations on TFNs are described as follows:

- Fuzzy addition:

$$\tilde{Y}(+)\tilde{Z} = (Y_1 + Z_1, Y_2 + Z_2, Y_3 + Z_3) \tag{1}$$

- Fuzzy subtraction:

$$\tilde{Y}(-)\tilde{Z} = (Y_1 - Z_3, Y_2 - Z_2, Y_3 - Z_1) \tag{2}$$

- Fuzzy multiplication:

$$\tilde{Y}(\times)\tilde{Z} \cong (Y_1Z_1, Y_2Z_2, Y_3Z_3) \mathit{if}\ Y_1, Z_1 \geq 0 \tag{3}$$

- Fuzzy division:

$$\tilde{Y}(/)\tilde{Z} \cong (Y_1/Z_3, Y_2/Z_2, Y_3/Z_1) \text{ if } Y_1 \geq 0; Z_1 \geq 0 \tag{4}$$

For example, if critical factor i is weakly more important than critical factor j, then $\tilde{a}_{ij} = (1, 3, 5)$, meaning that the relative importance of critical factor i is about three times that of critical factor j.

Based on pairwise comparison results, the fuzzy judgment matrix $\tilde{\boldsymbol{A}}_{n\times n} = [\tilde{a}_{ij}]$ is constructed as

$$\begin{aligned}\tilde{a}_{ji} &= (a_{ji1}, a_{ji2}, a_{ji3}) \\ &= \frac{1}{\tilde{a}_{ij}} \\ &\cong (1/a_{ij3}, 1/a_{ij2}, 1/a_{ij1})\end{aligned} \tag{5}$$

$$\tilde{a}_{ii} = 1 \tag{6}$$

The left and right α cuts of $\tilde{a}_{ij}$ are indicated with $a_{ij}^L(\alpha)$ and $a_{ij}^R(\alpha)$, respectively; $\alpha = 0$–1. The fuzzy eigenvalue and eigenvector of $\tilde{\boldsymbol{A}}$, indicated with $\tilde{\lambda}$ and $\tilde{\boldsymbol{x}}$ respectively, satisfy

$$\det(\tilde{\boldsymbol{A}}(-)\tilde{\lambda}\boldsymbol{I}) = 0 \tag{7}$$

And

$$(\tilde{\boldsymbol{A}}(-)\tilde{\lambda}\boldsymbol{I})(\times)\tilde{\boldsymbol{x}} = 0 \tag{8}$$

where (−) and (×) denote fuzzy subtraction and multiplication, respectively. Equations (7) and (8) involve numerous fuzzy multiplications. However, the multiplication of

TFNs does not yield a TFN.[37] Therefore, $\widetilde{\lambda}$ and $\tilde{\boldsymbol{x}}$ are not TFNs, as illustrated in Figure 2. Approximating them with TFNs may lead to incorrect decisions. Letting the left and right α cuts of $\widetilde{\lambda}$ be indicated with $\lambda^L(\alpha)$ and $\lambda^R(\alpha)$, respectively. Similarly, the left and right α cuts of $\tilde{\boldsymbol{x}}_i$ are denoted by $x_i^L(\alpha)$ and $x_i^R(\alpha)$, respectively.

Enhanced fuzzy geometric mean

Let the left and right α cuts of fuzzy variable $\widetilde{Y}$ be indicated with $Y^L(\alpha)$ and $Y^R(\alpha)$, respectively. Some arithmetic operations on fuzzy numbers based on their α cuts are described as follows:

- Fuzzy addition:

$$(\widetilde{Y}(+)\widetilde{Z})(\alpha) = [Y^L(\alpha) + Z^L(\alpha),\ Y^R(\alpha) + Z^R(\alpha)] \quad (9)$$

- Fuzzy subtraction:

$$(\tilde{Y}(-)\tilde{Z})(\alpha) = [Y^L(\alpha) - Z^R(\alpha),\ Y^R(\alpha) - Z^L(\alpha)] \quad (10)$$

- Fuzzy multiplication:

$$(\tilde{Y}(\times)\tilde{Z})(\alpha) = [Y^L(\alpha)Z^L(\alpha),\ Y^R(\alpha)Z^R(\alpha)]\ if\ \tilde{Y}, \tilde{Z} \geq 0 \quad (11)$$

- Fuzzy division:

$$(\tilde{Y}(/)\tilde{Z})(\alpha) = [Y^L(\alpha)/Z^R(\alpha),\ Y^R(\alpha)/Z^L(\alpha)]\ if\ \tilde{Y} \geq 0, \tilde{Z} \geq 0 \quad (12)$$

The traditional FGM method can be applied to approximate the fuzzy priority of a critical factor ($\tilde{w}_i$) as

$$\tilde{w}_i \cong \frac{\sqrt[n]{\prod_{j=1}^{n} \tilde{a}_{ij}}}{\sum_{k=1}^{n} \sqrt[n]{\prod_{j=1}^{n} \tilde{a}_{ij}}} \quad (13)$$

The left and right α cuts of $\tilde{w}_i$ are indicated with $w_i^L(\alpha)$ and $w_i^R(\alpha)$, respectively.

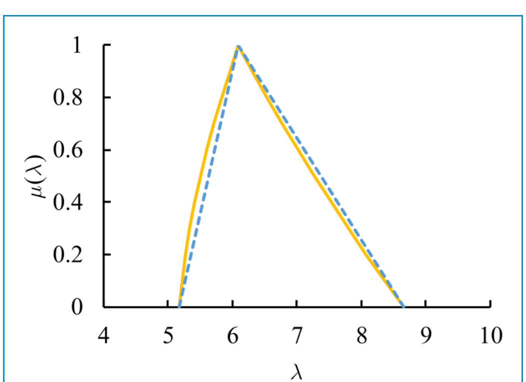

Figure 2. The non-triangular fuzzy number (TFN) nature of a fuzzy eigenvalue.

Table 3. Random consistency index.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Theorem 1.[38]

$$w_i^L(\alpha) \cong \frac{1}{1 + \sum_{k \neq i} \left(\sqrt[n]{\sum_{j=1}^{n} a_{kj}^R(\alpha)} / \sqrt[n]{\sum_{j=1}^{n} a_{ij}^L(\alpha)} \right)} \quad (14)$$

$$w_i^R(\alpha) \cong \frac{1}{1 + \sum_{k \neq i} \left(\sqrt[n]{\sum_{j=1}^{n} a_{kj}^L(\alpha)} / \sqrt[n]{\sum_{j=1}^{n} a_{ij}^R(\alpha)} \right)} \quad (15)$$

Other ways to derive the fuzzy priorities of factors, such as fuzzy decision making and trial evaluation laboratory, are also applicable.[39]

In addition, the fuzzy maximal eigenvalue $\tilde{\lambda}_{\max}$ can be estimated as

$$\tilde{\lambda}_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{\sum_{j=1}^{n} (\tilde{a}_{ij}(\times)\tilde{w}_{ij})}{\tilde{w}_i} \quad (16)$$

Theorem 2.[38]

$$\lambda_{\max}^L(\alpha) \cong 1 + \frac{1}{n} \sum_{i=1}^{n} \sum_{j \neq i} \frac{a_{ij}^L(\alpha) w_j^L(\alpha)}{w_i^R(\alpha)} \quad (17)$$

$$\lambda_{\max}^R(\alpha) \cong 1 + \frac{1}{n} \sum_{i=1}^{n} \sum_{j \neq i} \frac{a_{ij}^R(\alpha) w_j^R(\alpha)}{w_i^L(\alpha)} \quad (18)$$

Then, the consistency among pairwise comparison results can be evaluated in terms of fuzzy consistency ratio:

$$\widetilde{CR} = \frac{(\tilde{\lambda}_{\max} - n)/(n-1)}{RI} \quad (19)$$

where RI is random consistency index[40] (see Table 3). Obviously, $\widetilde{CR}$ is not a TFN. $\widetilde{CR}$ should be <0.1 for a small FAHP problem.[40] When the size of a judgment matrix is large, the requirement for $\widetilde{CR}$ can be relaxed to being <0.3.[41,42] The minimum of $\widetilde{CR}$ will be much smaller than the consistency ratio of a crisp judgment matrix, because the most consistent combination is considered. In contrast, the maximum of $\widetilde{CR}$ may be very high. As a result, defuzzifying $\widetilde{CR}$ using the center-of-gravity (COG) method may not provide valuable information regarding consistency. Instead, it is recommended that the minimum of $\widetilde{CR}$ should be <0.1, while the core of $\widetilde{CR}$ needs to be <0.3 for a fuzzy judgment matrix to be consistent. Based on equations (18) and (19), the minimum and core of $\widetilde{CR}$ can be estimated as

$$\min(\widetilde{CR}) = \max\left(\frac{[\lambda_{\max}^L(0) - n]/(n-1)}{RI}, 0\right) \quad (20)$$

$$\text{core}(\widetilde{CR}) = \frac{[\lambda_{\max}^*(1) - n]/(n-1)}{RI} \quad (21)$$

The traditional FGM method approximates $\tilde{w}_i$ and $\tilde{\lambda}_{\max}$ with TFNs, which is not precise. In the xACO method proposed by Chen et al.,[25] the membership functions of $\tilde{w}_i$ and $\widetilde{\lambda}_{\max}$ are approximated with logarithmic functions instead:

$$\mu_{\tilde{\lambda}_{\max}}(x) \cong \begin{cases} \xi_1 \ln x + \zeta_1 & \text{if} \quad \lambda_{\max}^L(0) \le x \le \lambda_{\max}^*(1) \\ \xi_2 \ln x + \zeta_2 & \text{if} \quad \lambda_{\max}^*(1) \le x \le \lambda_{\max}^R(0) \\ 0 & \text{otherwise} \end{cases} \quad (22)$$

$$\mu_{\tilde{w}_i}(x) \cong \begin{cases} \phi_{i1} \ln x + \varphi_{i1} & \text{if} \quad w_i^L(0) \le x \le w_i^*(1) \\ \phi_{i2} \ln x + \varphi_{i2} & \text{if} \quad w_i^*(1) \le x \le w_i^R(0); \\ 0 & \text{otherwise} \end{cases}$$
$$i = 1 \sim n \quad (23)$$

The xACO method[25] fits these logarithmic functions by enumerating only some α cuts of a fuzzy judgment matrix to enhance computational efficiency. However, the xACO method is still time-consuming for a large-scale FAHP problem. To solve this problem, the EFGM method fits the logarithmic functions by connecting α cuts for $\alpha = 0$, 0.5, and 1, as illustrated in Figure 3. In addition, these α cuts are derived using FGM, rather than xACO, to further save time.

Theorem 3.

$$\xi_1 = \frac{6 \ln \lambda_{\max}^L(0.5) + 12 \ln \lambda_{\max}^*(1) - 3\beta_1}{6\beta_2 - \beta_1^2} \quad (24)$$

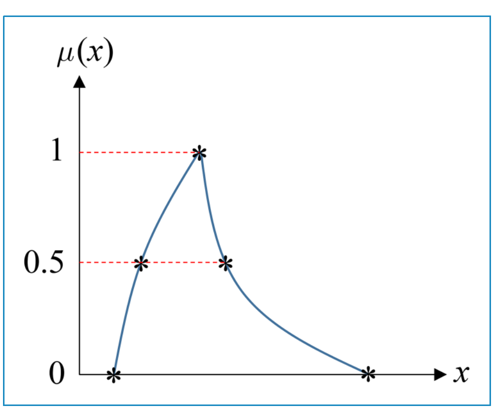

Figure 3. Fitting the membership functions with logarithmic functions in enhanced fuzzy geometric mean (EFGM).

$$\zeta_1 = \frac{18\beta_2 - 6 \ln \lambda_{\max}^L(0.5)\beta_1 - 12 \ln \lambda_{\max}^*(1)\beta_1}{36\beta_2 - 6\beta_1^2} \quad (25)$$

where

$$\beta_1 = 2 \ln \lambda_{\max}^L(0) + 2 \ln \lambda_{\max}^L(0.5) + 2 \ln \lambda_{\max}^*(1) \quad (26)$$

$$\beta_2 = 2 \ln \lambda_{\max}^L(0)^2 + 2 \ln \lambda_{\max}^L(0.5)^2 + 2 \ln \lambda_{\max}^*(1)^2 \quad (27)$$

Proof.

The membership function of $\widetilde{\lambda}_{\max}$ on the left-hand side satisfies

$$0 = \ln \lambda_{\max}^L(0)\xi_1 + \zeta_1 \quad (28)$$

$$0.5 = \ln \lambda_{\max}^L(0.5)\xi_1 + \zeta_1 \quad (29)$$

$$1 = \ln \lambda_{\max}^*(1)\xi_1 + \zeta_1 \quad (30)$$

The sum of squared deviations is to be minimized

$$\min^{Z} = (\ln \lambda_{\max}^L(0)\xi_1 + \zeta_1 - 0)^2 + (\ln \lambda_{\max}^L(0.5)\xi_1 + \zeta_1 - 0.5)^2 + (\ln \lambda_{\max}^*(1)\xi_1 + \zeta_1 - 1)^2 \quad (31)$$

Taking the derivative of (31) with respect to ξ_1 and setting the result to zero gives

$$\frac{\partial Z}{\partial \xi_1} = 2(\ln \lambda_{\max}^L(0)\xi_1 + \zeta_1) \ln \lambda_{\max}^L(0) + 2(\ln \lambda_{\max}^L(0.5)\xi_1 + \zeta_1 - 0.5) \ln \lambda_{\max}^L(0.5) + 2(\ln \lambda_{\max}^*(1)\xi_1 + \zeta_1 - 1) \ln \lambda_{\max}^*(1) = (2 \ln \lambda_{\max}^L(0)^2 + 2 \ln \lambda_{\max}^L(0.5)^2 + 2 \ln \lambda_{\max}^*(1)^2)\xi_1 + (2 \ln \lambda_{\max}^L(0) + 2 \ln \lambda_{\max}^L(0.5) + 2 \ln \lambda_{\max}^*(1))\zeta_1 - \ln \lambda_{\max}^L(0.5) - 2 \ln \lambda_{\max}^*(1) = \beta_2\xi_1 + \beta_1\zeta_1 - \ln \lambda_{\max}^L(0.5) - 2 \ln \lambda_{\max}^*(1) = 0 \quad (32)$$

where

$$\beta_1 = 2 \ln \lambda_{\max}^L(0) + 2 \ln \lambda_{\max}^L(0.5) + 2 \ln \lambda_{\max}^*(1) \quad (33)$$

$$\beta_2 = 2 \ln \lambda_{\max}^L(0)^2 + 2 \ln \lambda_{\max}^L(0.5)^2 + 2 \ln \lambda_{\max}^*(1)^2 \quad (34)$$

Similarly, taking the derivative of (31) with respect to ζ_1 and setting the result to zero gives

$$\frac{\partial Z}{\partial \zeta_1} = 2(\ln \lambda_{\max}^L(0)\xi_1 + \zeta_1) + 2(\ln \lambda_{\max}^L(0.5)\xi_1 + \zeta_1 - 0.5) + 2(\ln \lambda_{\max}^*(1)\xi_1 + \zeta_1 - 1) = (2 \ln \lambda_{\max}^L(0) + 2 \ln \lambda_{\max}^L(0.5) + 2 \ln \lambda_{\max}^*(1))\xi_1 + 6\zeta_1 - 3 = \beta_1\xi_1 + 6\zeta_1 - 3 = 0 \quad (35)$$

After merging equations (32) and (35)

$$\xi_1 = \frac{6 \ln \lambda_{\max}^L(0.5) + 12 \ln \lambda_{\max}^*(1) - 3\beta_1}{6\beta_2 - \beta_1^2} \quad (36)$$

$$\zeta_1 = \frac{18\beta_2 - 6\ln\lambda^L_{\max}(0.5)\beta_1 - 12\ln\lambda^*_{\max}(1)\beta_1}{36\beta_2 - 6\beta_1^2} \quad (37)$$

Theorem 3 is proved.
Theorem 4.

$$\xi_2 = \frac{6\ln\lambda^R_{\max}(0.5) + 12\ln\lambda^*_{\max}(1) - 3\beta_3}{6\beta_4 - \beta_3^2} \quad (38)$$

$$\zeta_2 = \frac{18\beta_4 - 6\ln\lambda^R_{\max}(0.5)\beta_3 - 12\ln\lambda^*_{\max}(1)\beta_3}{36\beta_4 - 6\beta_3^2} \quad (39)$$

where

$$\beta_3 = 2\ln\lambda^R_{\max}(0) + 2\ln\lambda^R_{\max}(0.5) + 2\ln\lambda^*_{\max}(1) \quad (40)$$

$$\beta_4 = 2\ln\lambda^R_{\max}(0)^2 + 2\ln\lambda^R_{\max}(0.5)^2 + 2\ln\lambda^*_{\max}(1)^2 \quad (41)$$

Proof.
The required proof is similar to that of Theorem 3.
Theorem 5.

$$\phi_{i1} = \frac{6\ln w^L_i(0.5) + 12\ln w^*_i(1) - \gamma_{i1}}{6\gamma_{i2} - \gamma_{i1}^2} \quad (42)$$

$$\varphi_{i1} = \frac{18\gamma_{i2} - 6\ln w^L_i(0.5)\gamma_{i1} - 12\ln w^*_i(1)\gamma_{i1}}{36\gamma_{i2} - 6\gamma_{i1}^2} \quad (43)$$

where

$$\gamma_{i1} = 2\ln w^L_i(0) + 2\ln w^L_i(0.5) + 2\ln w^*_i(1) \quad (44)$$

$$\gamma_{i2} = 2\ln w^L_i(0)^2 + 2\ln w^L_i(0.5)^2 + 2\ln w^*_i(1)^2 \quad (45)$$

Proof.
The required proof is similar to that of Theorem 3.
Theorem 6.

$$\phi_{i2} = \frac{6\ln w^R_i(0.5) + 12\ln w^*_i(1) - \gamma_{i3}}{6\gamma_{i4} - \gamma_{i3}^2} \quad (46)$$

$$\varphi_{i2} = \frac{18\gamma_{i4} - 6\ln w^R_i(0.5)\gamma_{i3} - 12\ln w^*_i(1)\gamma_{i3}}{36\gamma_{i4} - 6\gamma_{i3}^2} \quad (47)$$

where

$$\gamma_{i3} = 2\ln w^R_i(0) + 2\ln w^R_i(0.5) + 2\ln w^*_i(1) \quad (48)$$

$$\gamma_{i4} = 2\ln w^R_i(0)^2 + 2\ln w^R_i(0.5)^2 + 2\ln w^*_i(1)^2 \quad (49)$$

Proof.
The required proof is similar to that of Theorem 3.

FTOPSIS for evaluating the overall performance of a hotel

Subsequently, the prevalent FTOPSIS method is applied to assess the overall performance of a hotel. First, the performance of a hotel in optimizing each critical factor is normalized using fuzzy distributive normalization:

$$\tilde{\rho}_{qi} = \frac{\tilde{\rho}_{qi}}{\sqrt{\sum_{\phi=1}^{Q}\tilde{\rho}^2_{\phi i}}} = \frac{1}{\sqrt{1+\sum_{\phi\neq q}(\tilde{p}_{\phi i}\,/\,\tilde{p}_{qi})^2}} \quad (50)$$

where $\tilde{p}_{qi}$ is the performance of the qth hotel in optimizing the ith critical factor; $\tilde{p}_{qi}$ is the normalized performance. Obviously,

$$\rho^L_{qi}(\alpha) = \frac{1}{\sqrt{1+\sum_{j\neq i}(p^R_{qj}(\alpha)\,/\,\tilde{p}^L_{qi}(\alpha))^2}}\%. \quad (51)$$

$$\rho^R_{qi}(\alpha) = \frac{1}{\sqrt{1+\sum_{j\neq i}(p^L_{qj}(\alpha)\,/\,\tilde{p}^R_{qi}(\alpha))^2}}\% \quad (52)$$

Subsequently, fuzzy prioritized scores are calculated based on the fuzzy priorities derived using the EFGM approach:

$$\tilde{s}_{qi} = \tilde{w}_i(\times)\tilde{\rho}_{qi} \quad (53)$$

Equivalently,

$$s^L_{qi} = w^L_i(\alpha)\rho^L_{qi}(\alpha) \quad (54)$$

$$s^R_{qi} = w^R_i(\alpha)\rho^R_{qi}(\alpha) \quad (55)$$

Fuzzy ideal (zenith) point and fuzzy anti-ideal (nadir) point are specified, respectively, as

$$\tilde{\Lambda}^+ = \{\tilde{\Lambda}^+_i\} = \{max_q\,\tilde{s}_{qi}\} \quad (56)$$

$$\tilde{\Lambda}^- = \{\tilde{\Lambda}^-_i\} = \{\min_q \tilde{s}_{qi}\} \quad (57)$$

with the following α cuts:

$$[\Lambda^{+L}(\alpha),\ \Lambda^{+R}(\alpha)] = \{[\Lambda^{+L}_i(\alpha),\ \Lambda^{+R}_i(\alpha)]\}, = \{[\max_q s^L_{qi}(\alpha),\ \max_q s^R_{qi}(\alpha)]\} \quad (58)$$

$$[\Lambda^{-L}(\alpha),\ \Lambda^{-R}(\alpha)] = \{[\Lambda^{-L}_i(\alpha),\ \Lambda^{-R}_i(\alpha)]\}, = \{[\min_q s^L_{qi}(\alpha),\ \min_q s^R_{qi}(\alpha)]\} \quad (59)$$

The fuzzy distances from each hotel to the two reference points are calculated, respectively, as

$$\tilde{d}^+_q = \sqrt{\sum_{i=1}^{n}(\tilde{\Lambda}^+_i(-)\tilde{s}_{qi})^2} \quad (60)$$

$$\tilde{d}_q^- = \sqrt{\sum_{i=1}^{n} (\tilde{\Lambda}_i^- (-) \tilde{s}_{qi})^2} \tag{61}$$

Equivalently,

$$d_q^{+L}(\alpha) = \sqrt{\sum_{i=1}^{n} (\max(\Lambda_i^{+L}(\alpha) - s_{qi}^R(\alpha),\ 0))^2} \tag{62}$$

$$d_q^{+R}(\alpha) = \sqrt{\sum_{i=1}^{n} (\Lambda_i^{+R}(\alpha) - s_{qi}^L(\alpha))^2} \tag{63}$$

$$d_q^{-L}(\alpha) = \sqrt{\sum_{i=1}^{n} (\min(\Lambda_i^{-R}(\alpha) - s_{qi}^L(\alpha),\ 0))^2} \tag{64}$$

$$d_q^{-R}(\alpha) = \sqrt{\sum_{i=1}^{n} (\Lambda_i^{-L}(\alpha) - s_{qi}^R(\alpha))^2} \tag{65}$$

Finally, the fuzzy closeness of each hotel is obtained as

$$\tilde{C}_q = \frac{\tilde{d}_q^-}{\tilde{d}_q^+ (+) \tilde{d}_q^-} \tag{66}$$

Therefore,

$$C_q^L(\alpha) = \min\left(\frac{d_q^{-R}(\alpha)}{d_q^{+R}(\alpha) + d_q^{-R}(\alpha)},\ \frac{d_q^{-L}(\alpha)}{d_q^{+R}(\alpha) + d_q^{-L}(\alpha)}\right) \tag{67}$$

$$C_q^R(\alpha) = \max\left(\frac{d_q^{-R}(\alpha)}{d_q^{+L}(\alpha) + d_q^{-R}(\alpha)},\ \frac{d_q^{-L}(\alpha)}{d_q^{+L}(\alpha) + d_q^{-L}(\alpha)}\right) \tag{68}$$

A hotel is more suitable if its fuzzy closeness is higher. To get an absolute ranking, the fuzzy closeness can be defuzzified using the COG method:

$$\text{COG}(\tilde{C}_q) = \frac{\int_0^1 \alpha([C_q^L(\alpha) + C_q^R(\alpha)]/2)\text{d}\alpha}{\int_0^1 \alpha \text{d}\alpha} \tag{69}$$

There are other methods for evaluating and comparing the overall performances of hotels, such as fuzzy Vise Kriterijumska Optimizacija I Kompromisno Resenje.[43]

Experiment

To validate the effectiveness of the proposed methodology, a standalone hotel recommendation system has been developed using Microsoft Access 2019 on a PC with an i7-7700 CPU 272 3.6 GHz and 16 GB RAM and installed in a travel agency in Taichung City, Taiwan. The main product of the travel agency was a detailed Hualien itinerary for 3 to 4 days. All visitors to the travel agency were invited to use the system. During February 2021, a total of 10 travelers (or traveler groups) have used this system to seek recommendations for suitable hotels to stay in Hualien County, Taiwan.

Several characteristics of Hualien County made it particularly suitable for traveling amid the COVID-19 pandemic: the lowest population in the country, a rural nature, and especially, no confirmed case of COVID-19. In contrast, if these travelers were traveling in a metropolis, the risk of contracting COVID-19 would be higher. If these travelers traveled abroad, they will be quarantined in hotels for a few days after arriving at their destinations.

According to the discussion made in the previous sections, the following factors were considered critical to the selection of a suitable hotel amid the COVID-19 pandemic:

- room rate,
- room rate discount,
- pandemic prevention measures,
- number of stars, and
- hotel rating.

Among the five critical factors, room rate discount was not as important as before, and pandemic prevention measures have become very important amid the COVID-19 pandemic. The FAHP problem is illustrated in Figure 4.

Taking the first traveler as an example. The traveler first compared the relative priorities of these critical factors in linguistic terms. The results are summarized in Table 4.

Based on Table 4, the following fuzzy judgment matrix was constructed:

$$\tilde{\boldsymbol{A}} = \begin{bmatrix} 1 & 1/(1,\ 3,\ 5) & 1/(3,\ 5,\ 7) & (1,\ 3,\ 5) & 1/(1,\ 3,\ 5) \\ (1,\ 3,\ 5) & 1 & 1/(1,\ 3,\ 5) & (1,\ 3,\ 5) & 1/(1,\ 1,\ 3) \\ (3,\ 5,\ 7) & (1,\ 3,\ 5) & 1 & (3,\ 5,\ 7) & (2,\ 4,\ 6) \\ 1/(1,\ 3,\ 5) & 1/(1,\ 3,\ 5) & 1/(3,\ 5,\ 7) & 1 & (1,\ 1,\ 3) \\ (1,\ 3,\ 5) & (1,\ 1,\ 3) & 1/(2,\ 4,\ 6) & 1/(1,\ 1,\ 3) & 1 \end{bmatrix}$$

The fuzzy priorities of critical factors were derived from the fuzzy judgment matrix. The results, in terms of their α cuts for $\alpha = 0$, 0.5, and 1, are presented in Table 5. Subsequently, the membership functions of fuzzy priorities were fitted with logarithmic functions using the proposed EFGM approach. The results are shown in Figure 5.

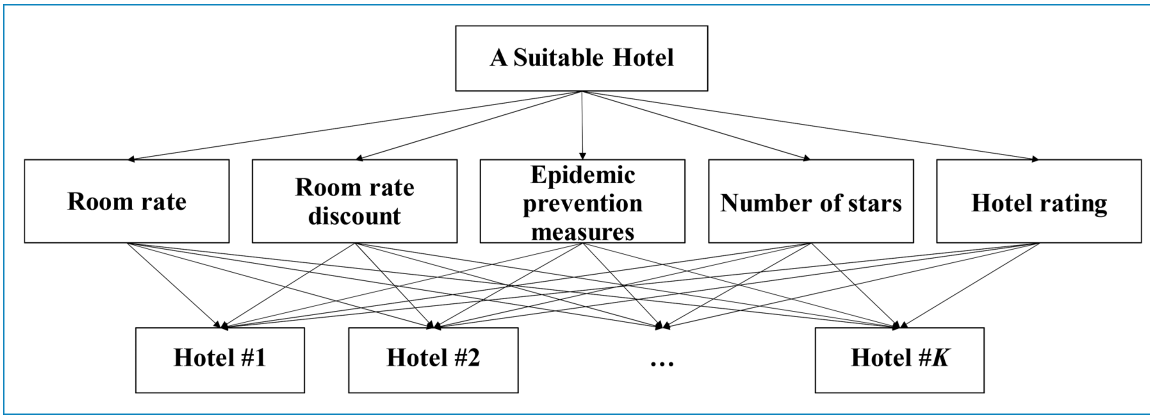

Figure 4. The fuzzy analytic hierarchy process (FAHP) problem.

Table 4. Results of pairwise comparisons.

Critical factor #1	Critical factor #2	Relative priority of critical factor #1 over critical factor #2
Room rate discount	Room rate	Strongly or very strongly more important than
Pandemic prevention measures	Room rate	Strongly more important than
Room rate	Number of stars	Weakly more important than
Hotel rating	Room rate	Weakly or strongly more important than
Pandemic prevention measures	Room rate discount	Weakly or strongly more important than
Room rate discount	Number of stars	Weakly more important than
Hotel rating	Room rate discount	As equal as
Pandemic prevention measures	Number of stars	Weakly or strongly more important than
Pandemic prevention measures	Hotel rating	Weakly or strongly more important than
Number of stars	Hotel rating	Weakly more important than

The fuzzy consistency ratio of $\widetilde{A}$ was evaluated according to equations (10) to (13). In particular,

$$\min(\widetilde{CR}) = 0 < 0.1$$

$$\mathrm{core}(\widetilde{CR}) = 0.23 < 0.3$$

Therefore, $\widetilde{A}$ was consistent. The most important critical factor was "pandemic prevention measures." followed by "room rate discount" and "hotel rating".

Based on the derived fuzzy priorities, six hotels, denoted by A to F, were considered by the traveler. The reason for considering these six hotels was based on the traveler's requirements: hotels should have more than 3 stars, their room rates should not exceed 4000 NTD per night, and they should be close to Hualien Port. In this way, the traveler could enjoy the most beautiful sunrise on the Pacific Ocean. The collected data of the six hotels are summarized in Table 6. The following pandemic prevention measures were taken by hotels:

Table 5. Fuzzy priorities of critical factors.

i	$\tilde{w}_i(0)$	$\tilde{w}_i(0.5)$	$\tilde{w}_i(1)$
1	[0.03, 0.17]	[0.05, 0.11]	[0.07, 0.07]
2	[0.09, 0.36]	[0.14, 0.27]	[0.21, 0.21]
3	[0.26, 0.68]	[0.38, 0.59]	[0.49, 0.49]
4	[0.04, 0.24]	[0.06, 0.14]	[0.09, 0.09]
5	[0.07, 0.32]	[0.10, 0.21]	[0.14, 0.14]

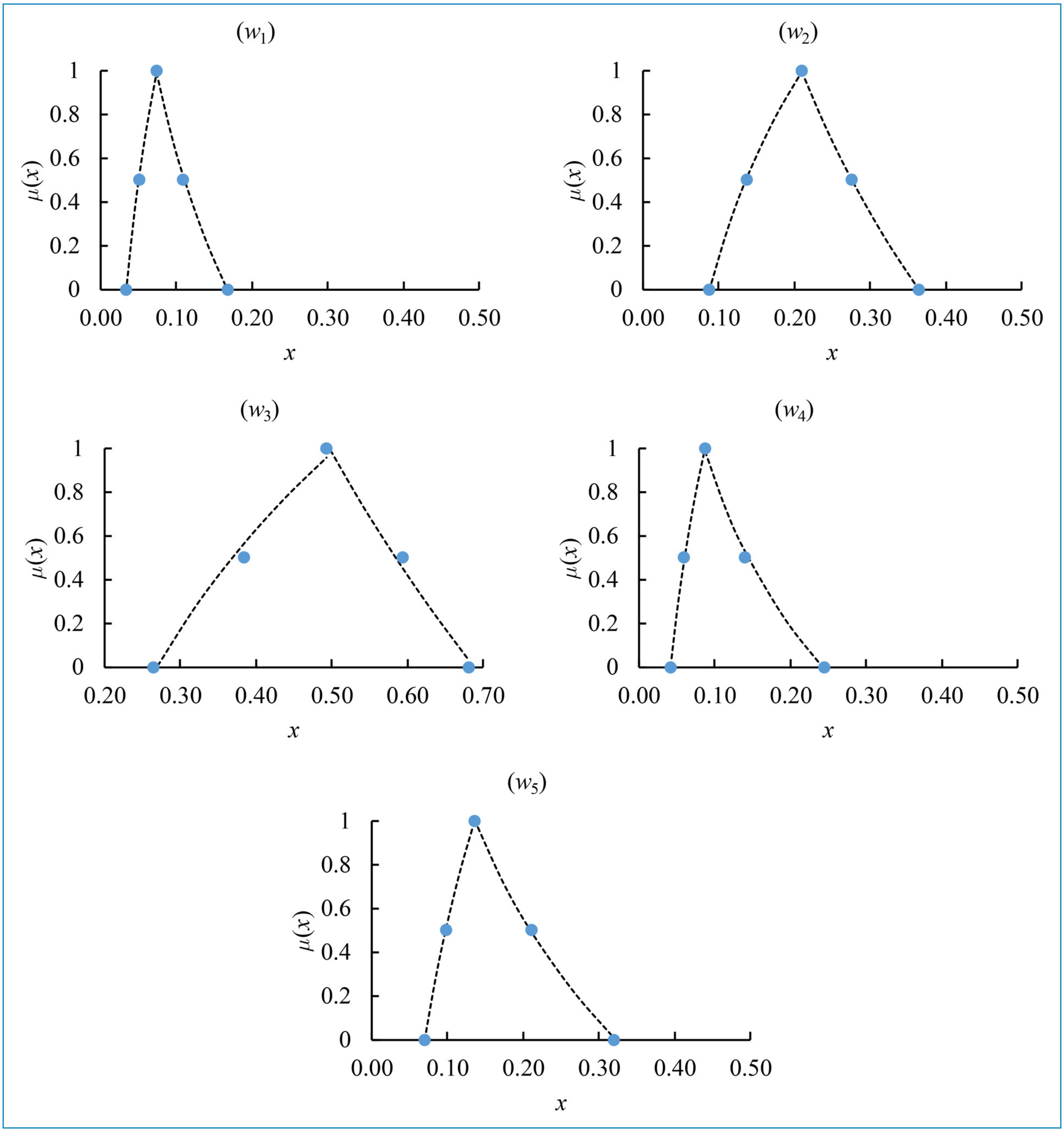

Figure 5. Fitting the membership functions of fuzzy priorities with logarithmic functions.

(i) (employees) wearing facial masks.
(ii) access control;
(iii) regular disinfection;
(iv) measuring body temperature;
(v) applications of advanced tools such as ultraviolet rays, steam sterilization, etc.
(vi) restaurant anti-pandemic measures: farther seats, barriers between seats, disposable tableware, single-use menus, reminding each customer to wear masks and reduce conversations when helping themselves, delivering food to tables instead, cashless, ordering via smartphones; and
(vii) anti-pandemic requirements for customers.

Among the five critical factors, "room rate discount," "pandemic prevention measures," "number of stars," and "hotel rating" were the-higher-the-better performances, whereas the "room rate" was the-lower-the-better performance. The performances were evaluated according to the rules depicted in Table 7. Whether the difference in the

Table 6. The collected data of the six hotels.

Hotel	Room rate (NTD/night)	Room rate discount (%)	Pandemic prevention measures	Number of Stars	Hotel rating (in Google Maps)
A	2207	69%	i, ii, iii, iv, v, vii	4	4.2
B	1954	75%	i, ii, iii, iv, vii	3	4.2
C	2341	76%	i, ii, iii, iv, v, vi, vii	4	4.3
D	2922	56%	i, ii, iii, iv, vii	4	4.4
E	1967	63%	vii	3	3.9
F	3319	60%	unknown	5	4.5

performances of two hotels is significant is an extremely subjective question. Therefore, in these rules, fuzzy numbers are used to evaluate the performance of a hotel to apply to more users. In addition, the performances of a hotel in different aspects belong to different scales, and are converted to the same scale of [0, 5] through these rules. Therefore, these rules also have the function of data normalization.

Table 8 presents the evaluation results. There was no perfect hotel that dominated the others.

FTOPSIS was applied to assess the overall performance of each hotel. First, the performance of a hotel in optimizing each criterion was normalized using fuzzy distributive normalization. The results are summarized in Table A1 of Appendix 1.

Subsequently, the fuzzy weighted scores of all hotels, in terms of α cuts, were calculated based on the derived fuzzy priorities. The results are summarized in Table A2 of Appendix 1.

Based on the fuzzy weighted scores, fuzzy ideal point and fuzzy anti-ideal point were defined, as shown in Table A3 of Appendix 1. Subsequently, the distances from each hotel to the two reference points were measured, respectively. The results are summarized in Table A4 of Appendix 1.

Finally, the fuzzy closeness of each hotel was derived. The results are also shown in Table A4 of Appendix 1.

Subsequently, COG was applied to defuzzify the fuzzy closeness of each hotel. The results are summarized in Table 9.

According to the experimental results,

1. The differences between the overall performances of hotels were significant.
2. Among the six hotels, hotel C achieved the highest overall performance, which was obviously due to its high room rate discount and many pandemic prevention measures.
3. In contrast, hotel E was considered the least suitable, owing to its low hotel rating and few pandemic prevention measures.
4. For comparison, four existing methods, FGM-FWA, FGM-FTOPSIS, xACO-FTOPSIS, and ACO-FTOPSIS, were also applied to compare these hotels. In FGM-FWA, the fuzzy priorities of criteria were approximated using FGM. Then, FWA was applied to assess the overall performance of each hotel. FGM-FTOPSIS was similar to FGM-FWA, with the exception that FTOPSIS, instead of FWA, was applied to derive the overall performance of a hotel. ACO-FTOPSIS and xACO-FTOPSIS derived the exact or near-exact membership functions of fuzzy priorities, and then compared the overall performances of hotels using FTOPSIS. The ranking results obtained using various methods are compared in Figure 6. Although the most suitable hotels recommended using these methods were the same, the ranking results were somewhat different. FGM-FWA and FGM-FTOPSIS estimated, rather than derived, the fuzzy priorities of critical factors, which led to such a difference. In contrast, the same ranking results were obtained using ACO-FTOPSIS, xACO-FTOPSIS, and the proposed methodology. Among the three methods, the proposed methodology was the most efficient.
5. To assess the effectiveness of the EFGM approach, FGM, xACO, and ACO were also applied to derive the membership functions of fuzzy priorities for comparison. The membership functions fitted using ACO represented the exact membership functions. The membership functions derived using xACO and EFGM resembled the exact membership functions, as illustrated in Figure 7. In contrast, the membership functions derived using FGM was very imprecise. In addition, both FGM and EFGM took less than 1 s, while xACO and ACO took 3 and 11 s, respectively, on the same platform to approximate or derive the membership functions.

Table 7. Rules for evaluating the performances.

Critical factor	Rule
Room rate	$\tilde{p}_{q1}(x_q) = \begin{cases} (0,\ 0,\ 1) & \text{if} \quad 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \leq x_q \text{ or data not available} \\ (0,\ 1,\ 2) & \text{if} \quad 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \leq x_q < 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \\ (1.5,\ 2.5,\ 3.5) & \text{if} \quad 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \leq x_q < 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \\ (3,\ 4,\ 5) & \text{if} \quad 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \leq x_q < 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \\ (4,\ 5,\ 5) & \text{if} \quad x_q < 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \end{cases}$ where x_q is the room rate.
Room rate discount	$\tilde{p}_{q2}(x_q) = \begin{cases} (0,\ 0,\ 1) & \text{if} \quad x_q < 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \text{ or data not available} \\ (0,\ 1,\ 2) & \text{if} \quad 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \leq x_q < 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \\ (1.5,\ 2.5,\ 3.5) & \text{if} \quad 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \leq x_q < 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \\ (3,\ 4,\ 5) & \text{if} \quad 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \leq x_q < 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \\ (4,\ 5,\ 5) & \text{if} \quad 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \leq x_q \end{cases}$ where x_q is the room rate discount.
Pandemic prevention measures	$\tilde{p}_{q3}(x_q) = \begin{cases} (0,\ 0,\ 1) & \text{if} \quad x_q < 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \text{ or data not available} \\ (0,\ 1,\ 2) & \text{if} \quad 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \leq x_q < 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \\ (1.5,\ 2.5,\ 3.5) & \text{if} \quad 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \leq x_q < 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \\ (3,\ 4,\ 5) & \text{if} \quad 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \leq x_q < 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \\ (4,\ 5,\ 5) & \text{if} \quad 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \leq x_q \end{cases}$ where x_q is the number of pandemic prevention measures.
Number of stars	$\tilde{p}_{q4}(x_q) = \begin{cases} (0,\ 0,\ 1) & \text{if} \quad x_q < 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \text{ or data not available} \\ (0,\ 1,\ 2) & \text{if} \quad 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \leq x_q < 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \\ (1.5,\ 2.5,\ 3.5) & \text{if} \quad 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \leq x_q < 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \\ (3,\ 4,\ 5) & \text{if} \quad 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \leq x_q < 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \\ (4,\ 5,\ 5) & \text{if} \quad 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \leq x_q \end{cases}$ where x_q is the number of stars.
Hotel rating	$\tilde{p}_{q5}(x_q) = \begin{cases} (0,\ 0,\ 1) & \text{if} \quad x_q < 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \text{ or data not available} \\ (0,\ 1,\ 2) & \text{if} \quad 0.9 \cdot \min_r x_r + 0.1 \cdot \max_r x_r \leq x_q < 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \\ (1.5,\ 2.5,\ 3.5) & \text{if} \quad 0.65 \cdot \min_r x_r + 0.35 \cdot \max_r x_r \leq x_q < 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \\ (3,\ 4,\ 5) & \text{if} \quad 0.35 \cdot \min_r x_r + 0.65 \cdot \max_r x_r \leq x_q < 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \\ (4,\ 5,\ 5) & \text{if} \quad 0.1 \cdot \min_r x_r + 0.9 \cdot \max_r x_r \leq x_q \end{cases}$ where x_q is the hotel rating.

Table 8. Evaluation results.

q	$\tilde{p}_{q1}$	$\tilde{p}_{q2}$	$\tilde{p}_{q3}$	$\tilde{p}_{q4}$	$\tilde{p}_{q5}$
1	(3.00, 4.00, 5.00)	(1.50, 2.50, 3.50)	(3.00, 4.00, 5.00)	(1.50, 2.50, 3.50)	(1.50, 2.50, 3.50)
2	(4.00, 5.00, 5.00)	(4.00, 5.00, 5.00)	(3.00, 4.00, 5.00)	(0.00, 0.00, 1.00)	(1.50, 2.50, 3.50)
3	(3.00, 4.00, 5.00)	(4.00, 5.00, 5.00)	(4.00, 5.00, 5.00)	(1.50, 2.50, 3.50)	(3.00, 4.00, 5.00)
4	(0.00, 1.00, 2.00)	(0.00, 0.00, 1.00)	(3.00, 4.00, 5.00)	(1.50, 2.50, 3.50)	(3.00, 4.00, 5.00)
5	(4.00, 5.00, 5.00)	(0.00, 1.00, 2.00)	(0.00, 1.00, 2.00)	(0.00, 0.00, 1.00)	(0.00, 0.00, 1.00)
6	(0.00, 0.00, 1.00)	(0.00, 1.00, 2.00)	(0.00, 0.00, 1.00)	(4.00, 5.00, 5.00)	(4.00, 5.00, 5.00)

Table 9. Defuzzification results.

Q	Defuzzified closeness
1	0.670
2	0.673
3	0.784
4	0.579
5	0.277
6	0.298

Table 10. The recommendation results to all travelers.

Traveler	Recommended hotel	Traveler's choice
1	C	C
2	B	B
3	K	K
4	C	C
5	A	A
6	L	L
7	L	L
8	C	C
9	B	A
10	B	B

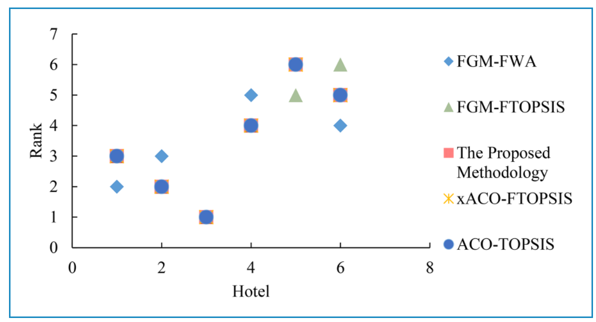

Figure 6. Comparison of the ranking results using various methods.

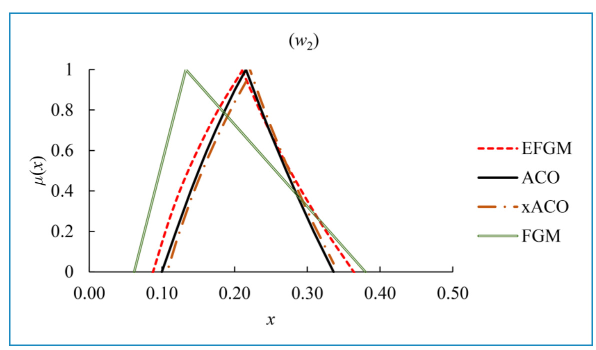

Figure 7. Comparing the membership function derived using various methods.

6. Other travelers compared the relative priorities of the five critical factors in the same way. However, due to space limitations, it is not possible to present all the pairwise comparison results here. Each traveler told the travel agency of the estimated budget, star rating, and desired attractions or facilities near the hotel. According to these conditions, the travel agency screened and listed <10 hotels for the traveler to choose from. The codes of hotels were the same for all travelers. The recommended hotels to all travelers, as well as their choices, are summarized in Table 10. Ninety percent of the travelers followed

the recommendations, which was very high because the travelers relied heavily on the information provided by the recommendation system amid the COVID-19 pandemic.
7. Compared to before the COVID-19 pandemic, most of the package trips to Hualien were 3 to 5 days. After the outbreak, similar package tours averaged only 2 to 3 days, which showed that travelers avoid staying in the same hotel for too long to increase the infection risk.
8. During the COVID-19 pandemic, travelers avoided using the facilities in hotels, which not only reduced the attractiveness of hotels with rich facilities, but also shortened the time that travelers stayed in hotels.

Managerial implications

- The number of pandemic prevention measures was one of the most important factors. Therefore, hotels should take more anti-pandemic measures and announce the anti-pandemic measures taken on the hotel website and relevant travel recommendation websites.
- It is a common practice to make decisions based on estimated fuzzy priorities. However, the results of this study clearly showed that such an approach might lead to wrong decisions.
- In the course of conducting this experiment, we found that during the COVID-19 pandemic, people's willingness to conduct regional tourism activities was much higher than we expected. This is a good opportunity for the hotel industry.

Conclusions

Although the COVID-19 pandemic continues, cities around the world cannot wait to reopen to restore the economy. People also want to travel to relax themselves. However, at the beginning of 2021, cross-border travel was still not a viable option. On the contrary, regional travel is experiencing explosive demand growth. Therefore, how to recommend suitable hotels to travelers amid the COVID-19 pandemic has become a key issue. However, this problem is obviously different from the traditional hotel recommendation problem, because the critical factors considered amid the COVID-19 pandemic may be different from those usually considered. To bridge this gap, this study proposed the FAHP-EFGM-FTOPSIS approach. Unlike existing FAHP methods, which are inaccurate or time-consuming, the proposed EFGM approach can accurately and efficiently estimate the priorities of critical factors, so that FTOPSIS can be applied for a reliable selection.

The proposed methodology has been applied to recommend suitable hotels to 10 travelers for regional trips amid the COVID-19 pandemic. Two existing methods were also applied to compare these hotels to make a comparison. After analyzing the experimental results, the following conclusions were drawn:

1. "Pandemic prevention measures" and "room rate discount" were considered as the most important critical factors, which were obviously due to the COVID-19 pandemic.
2. The most suitable hotel was usually the best hotel with many pandemic prevention measures, while the least suitable hotel was often among the hotels that took the fewest pandemic prevention measures.
3. The overall performances of hotels varied greatly, because their pandemic prevention measures were quite different, since pandemic prevention was considered the most critical issue.
4. Most of the travelers followed the recommendations, showing that they relied heavily on the information provided by the recommendation system amid the COVID-19 pandemic.

It is difficult to know for how long the COVID-19 pandemic will last. Therefore, the priorities of critical factors may change, so the same analysis needs to be conducted again to see whether the experimental results obtained in this study are still applicable.

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Appendix 1

Table A1. Normalized performances.

Q	$\tilde{p}_{q1}$	$\tilde{p}_{q2}$	$\tilde{p}_{q3}$	$\tilde{p}_{q4}$	$\tilde{p}_{q5}$
1	(0.32, 0.44, 0.62)	(0.19, 0.33, 0.53)	(0.32, 0.46, 0.65)	(0.20, 0.38, 0.61)	(0.16, 0.30, 0.50)
2	(0.42, 0.55, 0.62)	(0.51, 0.66, 0.75)	(0.32, 0.46, 0.65)	(0.00, 0.00, 0.17)	(0.16, 0.30, 0.50)
3	(0.32, 0.44, 0.62)	(0.51, 0.66, 0.75)	(0.42, 0.58, 0.65)	(0.20, 0.38, 0.61)	(0.32, 0.48, 0.72)
4	(0.00, 0.11, 0.25)	(0.00, 0.00, 0.15)	(0.32, 0.46, 0.65)	(0.20, 0.38, 0.61)	(0.32, 0.48, 0.72)
5	(0.42, 0.55, 0.62)	(0.00, 0.13, 0.30)	(0.00, 0.12, 0.26)	(0.00, 0.00, 0.17)	(0.00, 0.00, 0.14)
6	(0.00, 0.00, 0.12)	(0.00, 0.13, 0.30)	(0.00, 0.00, 0.13)	(0.55, 0.76, 0.87)	(0.42, 0.60, 0.72)

Table A2. Fuzzy weighted scores.

q	$\tilde{s}_{q1}$ (α:α cut)	$\tilde{s}_{q2}$ (α:α cut)	$\tilde{s}_{q3}$ (α:α cut)	$\tilde{s}_{q4}$ (α:α cut)	$\tilde{s}_{q5}$ (α:α cut)
1	0.0: [0.01, 0.10]	0.0: [0.02, 0.19]	0.0: [0.09, 0.45]	0.0: [0.01, 0.15]	0.0: [0.01, 0.16]
	0.1: [0.01, 0.09]	0.1: [0.02, 0.17]	0.1: [0.10, 0.42]	0.1: [0.01, 0.13]	0.1: [0.01, 0.14]
	0.2: [0.01, 0.08]	0.2: [0.02, 0.16]	0.2: [0.11, 0.40]	0.2: [0.01, 0.11]	0.2: [0.01, 0.12]
	0.3: [0.02, 0.07]	0.3: [0.03, 0.14]	0.3: [0.12, 0.37]	0.3: [0.01, 0.10]	0.3: [0.02, 0.11]
	0.4: [0.02, 0.07]	0.4: [0.03, 0.13]	0.4: [0.13, 0.35]	0.4: [0.02, 0.08]	0.4: [0.02, 0.10]
	0.5: [0.02, 0.06]	0.5: [0.04, 0.12]	0.5: [0.14, 0.33]	0.5: [0.02, 0.07]	0.5: [0.02, 0.08]
	0.6: [0.02, 0.05]	0.6: [0.04, 0.11]	0.6: [0.16, 0.30]	0.6: [0.02, 0.06]	0.6: [0.03, 0.07]
	0.7: [0.02, 0.05]	0.7: [0.05, 0.10]	0.7: [0.18, 0.29]	0.7: [0.02, 0.05]	0.7: [0.03, 0.06]
	0.8: [0.03, 0.04]	0.8: [0.05, 0.09]	0.8: [0.19, 0.27]	0.8: [0.03, 0.04]	0.8: [0.03, 0.05]
	0.9: [0.03, 0.04]	0.9: [0.06, 0.08]	0.9: [0.21, 0.25]	0.9: [0.03, 0.04]	0.9: [0.04, 0.05]
	1.0: [0.03, 0.03]	1.0: [0.07, 0.07]	1.0: [0.24, 0.23]	1.0: [0.03, 0.03]	1.0: [0.04, 0.04]
2	0.0: [0.01, 0.10]	0.0: [0.04, 0.27]	0.0: [0.09, 0.45]	0.0: [0.00, 0.04]	0.0: [0.01, 0.16]
	0.1: [0.02, 0.09]	0.1: [0.05, 0.26]	0.1: [0.10, 0.42]	0.1: [0.00, 0.03]	0.1: [0.01, 0.14]
	0.2: [0.02, 0.09]	0.2: [0.06, 0.24]	0.2: [0.11, 0.40]	0.2: [0.00, 0.03]	0.2: [0.01, 0.12]
	0.3: [0.02, 0.08]	0.3: [0.06, 0.22]	0.3: [0.12, 0.37]	0.3: [0.00, 0.02]	0.3: [0.02, 0.11]
	0.4: [0.02, 0.07]	0.4: [0.07, 0.21]	0.4: [0.13, 0.35]	0.4: [0.00, 0.02]	0.4: [0.02, 0.10]
	0.5: [0.02, 0.06]	0.5: [0.08, 0.19]	0.5: [0.14, 0.33]	0.5: [0.00, 0.01]	0.5: [0.02, 0.08]
	0.6: [0.03, 0.06]	0.6: [0.09, 0.18]	0.6: [0.16, 0.30]	0.6: [0.00, 0.01]	0.6: [0.03, 0.07]
	0.7: [0.03, 0.05]	0.7: [0.10, 0.17]	0.7: [0.18, 0.29]	0.7: [0.00, 0.01]	0.7: [0.03, 0.06]
	0.8: [0.03, 0.05]	0.8: [0.11, 0.16]	0.8: [0.19, 0.27]	0.8: [0.00, 0.00]	0.8: [0.03, 0.05]
	0.9: [0.04, 0.04]	0.9: [0.12, 0.15]	0.9: [0.21, 0.25]	0.9: [0.00, 0.00]	0.9: [0.04, 0.05]
	1.0: [0.04, 0.04]	1.0: [0.14, 0.14]	1.0: [0.24, 0.23]	1.0: [0.00, 0.00]	1.0: [0.04, 0.04]
3	0.0: [0.01, 0.1]	0.0: [0.04, 0.27]	0.0: [0.11, 0.45]	0.0: [0.01, 0.15]	0.0: [0.02, 0.23]
	0.1: [0.01, 0.09]	0.1: [0.05, 0.26]	0.1: [0.13, 0.43]	0.1: [0.01, 0.13]	0.1: [0.02, 0.20]
	0.2: [0.01, 0.08]	0.2: [0.06, 0.24]	0.2: [0.14, 0.41]	0.2: [0.01, 0.11]	0.2: [0.03, 0.18]
	0.3: [0.02, 0.07]	0.3: [0.06, 0.22]	0.3: [0.15, 0.39]	0.3: [0.01, 0.10]	0.3: [0.03, 0.16]
	0.4: [0.02, 0.07]	0.4: [0.07, 0.21]	0.4: [0.17, 0.38]	0.4: [0.02, 0.08]	0.4: [0.03, 0.14]
	0.5: [0.02, 0.06]	0.5: [0.08, 0.19]	0.5: [0.19, 0.36]	0.5: [0.02, 0.07]	0.5: [0.04, 0.13]
	0.6: [0.02, 0.05]	0.6: [0.09, 0.18]	0.6: [0.20, 0.34]	0.6: [0.02, 0.06]	0.6: [0.04, 0.11]
	0.7: [0.02, 0.05]	0.7: [0.10, 0.17]	0.7: [0.22, 0.33]	0.7: [0.02, 0.05]	0.7: [0.05, 0.10]
	0.8: [0.03, 0.04]	0.8: [0.11, 0.16]	0.8: [0.25, 0.32]	0.8: [0.03, 0.04]	0.8: [0.05, 0.09]
	0.9: [0.03, 0.04]	0.9: [0.12, 0.15]	0.9: [0.27, 0.30]	0.9: [0.03, 0.04]	0.9: [0.06, 0.07]
	1.0: [0.03, 0.03]	1.0: [0.14, 0.14]	1.0: [0.29, 0.29]	1.0: [0.03, 0.03]	1.0: [0.07, 0.07]
4	0.0: [0.00, 0.04]	0.0: [0.00, 0.05]	0.0: [0.09, 0.45]	0.0: [0.01, 0.15]	0.0: [0.02, 0.23]
	0.1: [0.00, 0.04]	0.1: [0.00, 0.05]	0.1: [0.10, 0.42]	0.1: [0.01, 0.13]	0.1: [0.02, 0.20]
	0.2: [0.00, 0.03]	0.2: [0.00, 0.04]	0.2: [0.11, 0.40]	0.2: [0.01, 0.11]	0.2: [0.03, 0.18]
	0.3: [0.00, 0.03]	0.3: [0.00, 0.03]	0.3: [0.12, 0.37]	0.3: [0.01, 0.10]	0.3: [0.03, 0.16]
	0.4: [0.00, 0.02]	0.4: [0.00, 0.03]	0.4: [0.13, 0.35]	0.4: [0.02, 0.08]	0.4: [0.03, 0.14]
	0.5: [0.00, 0.02]	0.5: [0.00, 0.02]	0.5: [0.14, 0.33]	0.5: [0.02, 0.07]	0.5: [0.04, 0.13]
	0.6: [0.00, 0.02]	0.6: [0.00, 0.02]	0.6: [0.16, 0.30]	0.6: [0.02, 0.06]	0.6: [0.04, 0.11]
	0.7: [0.00, 0.01]	0.7: [0.00, 0.01]	0.7: [0.18, 0.29]	0.7: [0.02, 0.05]	0.7: [0.05, 0.10]
	0.8: [0.01, 0.01]	0.8: [0.00, 0.01]	0.8: [0.19, 0.27]	0.8: [0.03, 0.04]	0.8: [0.05, 0.09]
	0.9: [0.01, 0.01]	0.9: [0.00, 0.00]	0.9: [0.21, 0.25]	0.9: [0.03, 0.04]	0.9: [0.06, 0.07]
	1.0: [0.01, 0.01]	1.0: [0.00, 0.00]	1.0: [0.24, 0.23]	1.0: [0.03, 0.03]	1.0: [0.07, 0.07]
5	0.0: [0.01, 0.10]	0.0: [0.00, 0.11]	0.0: [0.00, 0.18]	0.0: [0.00, 0.04]	0.0: [0.00, 0.05]
	0.1: [0.02, 0.09]	0.1: [0.00, 0.10]	0.1: [0.00, 0.16]	0.1: [0.00, 0.03]	0.1: [0.00, 0.04]
	0.2: [0.02, 0.09]	0.2: [0.00, 0.09]	0.2: [0.01, 0.15]	0.2: [0.00, 0.03]	0.2: [0.00, 0.03]
	0.3: [0.02, 0.08]	0.3: [0.00, 0.08]	0.3: [0.01, 0.14]	0.3: [0.00, 0.02]	0.3: [0.00, 0.02]
	0.4: [0.02, 0.07]	0.4: [0.01, 0.07]	0.4: [0.02, 0.12]	0.4: [0.00, 0.02]	0.4: [0.00, 0.02]
	0.5: [0.02, 0.06]	0.5: [0.01, 0.06]	0.5: [0.02, 0.11]	0.5: [0.00, 0.01]	0.5: [0.00, 0.01]

(continued)

Table A2. Continued.

q	$\tilde{s}_{q1}$ (α:α cut)	$\tilde{s}_{q2}$ (α:α cut)	$\tilde{s}_{q3}$ (α:α cut)	$\tilde{s}_{q4}$ (α:α cut)	$\tilde{s}_{q5}$ (α:α cut)
	0.6: [0.03, 0.06] 0.7: [0.03, 0.05] 0.8: [0.03, 0.05] 0.9: [0.04, 0.04] 1.0: [0.04, 0.04]	0.6: [0.01, 0.05] 0.7: [0.01, 0.04] 0.8: [0.02, 0.04] 0.9: [0.02, 0.03] 1.0: [0.03, 0.03]	0.6: [0.03, 0.10] 0.7: [0.03, 0.09] 0.8: [0.04, 0.08] 0.9: [0.05, 0.07] 1.0: [0.06, 0.06]	0.6: [0.00, 0.01] 0.7: [0.00, 0.01] 0.8: [0.00, 0.00] 0.9: [0.00, 0.00] 1.0: [0.00, 0.00]	0.6: [0.00, 0.01] 0.7: [0.00, 0.01] 0.8: [0.00, 0.00] 0.9: [0.00, 0.00] 1.0: [0.00, 0.00]
6	0.0: [0.00, 0.02] 0.1: [0.00, 0.02] 0.2: [0.00, 0.01] 0.3: [0.00, 0.01] 0.4: [0.00, 0.01] 0.5: [0.00, 0.01] 0.6: [0.00, 0.01] 0.7: [0.00, 0.00] 0.8: [0.00, 0.00] 0.9: [0.00, 0.00] 1.0: [0.00, 0.00]	0.0: [0.00, 0.11] 0.1: [0.00, 0.10] 0.2: [0.00, 0.09] 0.3: [0.00, 0.08] 0.4: [0.01, 0.07] 0.5: [0.01, 0.06] 0.6: [0.01, 0.05] 0.7: [0.01, 0.04] 0.8: [0.02, 0.04] 0.9: [0.02, 0.03] 1.0: [0.03, 0.03]	0.0: [0.00, 0.09] 0.1: [0.00, 0.08] 0.2: [0.00, 0.07] 0.3: [0.00, 0.06] 0.4: [0.00, 0.05] 0.5: [0.00, 0.04] 0.6: [0.00, 0.03] 0.7: [0.00, 0.02] 0.8: [0.00, 0.01] 0.9: [0.00, 0.01] 1.0: [0.00, 0.00]	0.0: [0.02, 0.21] 0.1: [0.03, 0.19] 0.2: [0.03, 0.17] 0.3: [0.03, 0.15] 0.4: [0.04, 0.13] 0.5: [0.04, 0.12] 0.6: [0.04, 0.10] 0.7: [0.05, 0.09] 0.8: [0.05, 0.08] 0.9: [0.06, 0.07] 1.0: [0.07, 0.06]	0.0: [0.03, 0.23] 0.1: [0.03, 0.21] 0.2: [0.04, 0.19] 0.3: [0.04, 0.17] 0.4: [0.05, 0.15] 0.5: [0.05, 0.14] 0.6: [0.06, 0.12] 0.7: [0.06, 0.11] 0.8: [0.07, 0.10] 0.9: [0.07, 0.09] 1.0: [0.08, 0.08]

Table A3. Fuzzy ideal point and fuzzy anti-ideal point.

Reference point	$\widetilde{\Lambda}_1^*$ (α:α cut)	$\widetilde{\Lambda}_2^*$ (α:α cut)	$\widetilde{\Lambda}_3^*$ (α:α cut)	$\widetilde{\Lambda}_4^*$ (α:α cut)	$\widetilde{\Lambda}_5^*$ (α:α cut)
Fuzzy ideal point	0.0: [0.01, 0.10] 0.1: [0.02, 0.09] 0.2: [0.02, 0.09] 0.3: [0.02, 0.08] 0.4: [0.02, 0.07] 0.5: [0.02, 0.06] 0.6: [0.03, 0.06] 0.7: [0.03, 0.05] 0.8: [0.03, 0.05] 0.9: [0.04, 0.04] 1.0: [0.04, 0.04]	0.0: [0.04, 0.27] 0.1: [0.05, 0.26] 0.2: [0.06, 0.24] 0.3: [0.06, 0.22] 0.4: [0.07, 0.21] 0.5: [0.08, 0.19] 0.6: [0.09, 0.18] 0.7: [0.10, 0.17] 0.8: [0.11, 0.16] 0.9: [0.12, 0.15] 1.0: [0.14, 0.14]	0.0: [0.11, 0.45] 0.1: [0.13, 0.43] 0.2: [0.14, 0.41] 0.3: [0.15, 0.39] 0.4: [0.17, 0.38] 0.5: [0.19, 0.36] 0.6: [0.20, 0.34] 0.7: [0.22, 0.33] 0.8: [0.25, 0.32] 0.9: [0.27, 0.30] 1.0: [0.29, 0.29]	0.0: [0.02, 0.21] 0.1: [0.03, 0.19] 0.2: [0.03, 0.17] 0.3: [0.03, 0.15] 0.4: [0.04, 0.13] 0.5: [0.04, 0.12] 0.6: [0.04, 0.10] 0.7: [0.05, 0.09] 0.8: [0.05, 0.08] 0.9: [0.06, 0.07] 1.0: [0.07, 0.06]	0.0: [0.03, 0.23] 0.1: [0.03, 0.21] 0.2: [0.04, 0.19] 0.3: [0.04, 0.17] 0.4: [0.05, 0.15] 0.5: [0.05, 0.14] 0.6: [0.06, 0.12] 0.7: [0.06, 0.11] 0.8: [0.07, 0.10] 0.9: [0.07, 0.09] 1.0: [0.08, 0.08]
Fuzzy anti-ideal point	0.0: [0.00, 0.02] 0.1: [0.00, 0.02] 0.2: [0.00, 0.01] 0.3: [0.00, 0.01] 0.4: [0.00, 0.01] 0.5: [0.00, 0.01] 0.6: [0.00, 0.01] 0.7: [0.00, 0.00] 0.8: [0.00, 0.00] 0.9: [0.00, 0.00] 1.0: [0.00, 0.00]	0.0: [0.00, 0.05] 0.1: [0.00, 0.05] 0.2: [0.00, 0.04] 0.3: [0.00, 0.03] 0.4: [0.00, 0.03] 0.5: [0.00, 0.02] 0.6: [0.00, 0.02] 0.7: [0.00, 0.01] 0.8: [0.00, 0.01] 0.9: [0.00, 0.00] 1.0: [0.00, 0.00]	0.0: [0.00, 0.09] 0.1: [0.00, 0.08] 0.2: [0.00, 0.07] 0.3: [0.00, 0.06] 0.4: [0.00, 0.05] 0.5: [0.00, 0.04] 0.6: [0.00, 0.03] 0.7: [0.00, 0.02] 0.8: [0.00, 0.01] 0.9: [0.00, 0.01] 1.0: [0.00, 0.00]	0.0: [0.00, 0.04] 0.1: [0.00, 0.03] 0.2: [0.00, 0.03] 0.3: [0.00, 0.02] 0.4: [0.00, 0.02] 0.5: [0.00, 0.01] 0.6: [0.00, 0.01] 0.7: [0.00, 0.01] 0.8: [0.00, 0.00] 0.9: [0.00, 0.00] 1.0: [0.00, 0.00]	0.0: [0.00, 0.05] 0.1: [0.00, 0.04] 0.2: [0.00, 0.03] 0.3: [0.00, 0.02] 0.4: [0.00, 0.02] 0.5: [0.00, 0.01] 0.6: [0.00, 0.01] 0.7: [0.00, 0.01] 0.8: [0.00, 0.00] 0.9: [0.00, 0.00] 1.0: [0.00, 0.00]

Table A4. Hotel distances and closenesses.

q	$\tilde{d}_q^{+}$ (α:α cut)	$\tilde{d}_q^{-}$ (α:α cut)	$\tilde{C}_q$ (α:α cut)
1	0.0: [0.00, 0.54] 0.1: [0.00, 0.49] 0.2: [0.00, 0.45] 0.3: [0.00, 0.40] 0.4: [0.00, 0.35] 0.5: [0.00, 0.31] 0.6: [0.00, 0.27] 0.7: [0.00, 0.23] 0.8: [0.03, 0.18] 0.9: [0.06, 0.14] 1.0: [0.11, 0.10]	0.0: [0.00, 0.54] 0.1: [0.02, 0.50] 0.2: [0.04, 0.46] 0.3: [0.06, 0.43] 0.4: [0.08, 0.40] 0.5: [0.11, 0.37] 0.6: [0.13, 0.34] 0.7: [0.16, 0.32] 0.8: [0.19, 0.29] 0.9: [0.22, 0.27] 1.0: [0.25, 0.25]	0.0: [0.00, 1.00] 0.1: [0.03, 1.00] 0.2: [0.08, 1.00] 0.3: [0.13, 1.00] 0.4: [0.19, 1.00] 0.5: [0.26, 1.00] 0.6: [0.33, 1.00] 0.7: [0.42, 0.99] 0.8: [0.51, 0.91] 0.9: [0.61, 0.81] 1.0: [0.71, 0.70]
2	0.0: [0.00, 0.53] 0.1: [0.00, 0.48] 0.2: [0.00, 0.43] 0.3: [0.01, 0.39] 0.4: [0.02, 0.34] 0.5: [0.03, 0.30] 0.6: [0.03, 0.25] 0.7: [0.04, 0.21] 0.8: [0.05, 0.17] 0.9: [0.07, 0.13] 1.0: [0.10, 0.09]	0.0: [0.00, 0.56] 0.1: [0.02, 0.52] 0.2: [0.04, 0.49] 0.3: [0.07, 0.45] 0.4: [0.10, 0.42] 0.5: [0.12, 0.39] 0.6: [0.15, 0.37] 0.7: [0.18, 0.34] 0.8: [0.21, 0.32] 0.9: [0.24, 0.30] 1.0: [0.28, 0.27]	0.0: [0.00, 1.00] 0.1: [0.04, 1.00] 0.2: [0.09, 1.00] 0.3: [0.15, 0.98] 0.4: [0.22, 0.96] 0.5: [0.29, 0.94] 0.6: [0.37, 0.91] 0.7: [0.46, 0.89] 0.8: [0.56, 0.86] 0.9: [0.66, 0.82] 1.0: [0.75, 0.74]
3	0.0: [0.00, 0.51] 0.1: [0.00, 0.45] 0.2: [0.00, 0.4] 0.3: [0.00, 0.35] 0.4: [0.00, 0.30] 0.5: [0.00, 0.26] 0.6: [0.00, 0.21] 0.7: [0.00, 0.16] 0.8: [0.01, 0.11] 0.9: [0.02, 0.07] 1.0: [0.04, 0.04]	0.0: [0.02, 0.60] 0.1: [0.05, 0.56] 0.2: [0.07, 0.53] 0.3: [0.10, 0.49] 0.4: [0.13, 0.46] 0.5: [0.16, 0.44] 0.6: [0.19, 0.41] 0.7: [0.23, 0.39] 0.8: [0.26, 0.37] 0.9: [0.30, 0.35] 1.0: [0.33, 0.33]	0.0: [0.05, 1.00] 0.1: [0.10, 1.00] 0.2: [0.16, 1.00] 0.3: [0.22, 1.00] 0.4: [0.30, 1.00] 0.5: [0.39, 1.00] 0.6: [0.48, 1.00] 0.7: [0.58, 1.00] 0.8: [0.69, 0.98] 0.9: [0.81, 0.94] 1.0: [0.90, 0.90]
4	0.0: [0.00, 0.55] 0.1: [0.00, 0.50] 0.2: [0.02, 0.45] 0.3: [0.03, 0.41] 0.4: [0.04, 0.37] 0.5: [0.06, 0.33] 0.6: [0.07, 0.29] 0.7: [0.09, 0.25] 0.8: [0.11, 0.22] 0.9: [0.13, 0.18] 1.0: [0.16, 0.16]	0.0: [0.00, 0.53] 0.1: [0.02, 0.49] 0.2: [0.04, 0.45] 0.3: [0.06, 0.42] 0.4: [0.08, 0.39] 0.5: [0.11, 0.36] 0.6: [0.13, 0.33] 0.7: [0.16, 0.31] 0.8: [0.19, 0.28] 0.9: [0.22, 0.26] 1.0: [0.25, 0.24]	0.0: [0.00, 1.00] 0.1: [0.03, 0.99] 0.2: [0.08, 0.96] 0.3: [0.13, 0.93] 0.4: [0.19, 0.90] 0.5: [0.25, 0.86] 0.6: [0.32, 0.82] 0.7: [0.39, 0.77] 0.8: [0.46, 0.73] 0.9: [0.54, 0.67] 1.0: [0.61, 0.61]
5	0.0: [0.00, 0.62] 0.1: [0.00, 0.57] 0.2: [0.01, 0.53] 0.3: [0.03, 0.50]	0.0: [0.00, 0.24] 0.1: [0.00, 0.22] 0.2: [0.00, 0.20] 0.3: [0.01, 0.18]	0.0: [0.00, 1.00] 0.1: [0.00, 1.00] 0.2: [0.01, 0.97] 0.3: [0.02, 0.87]

(continued)

Table A4. Continued.

q	$\widetilde{d}_q^+$ (α:α cut)	$\widetilde{d}_q^-$ (α:α cut)	$\widetilde{C}_q$ (α:α cut)
	0.4: [0.06, 0.46] 0.5: [0.09, 0.43] 0.6: [0.12, 0.40] 0.7: [0.16, 0.36] 0.8: [0.20, 0.33] 0.9: [0.24, 0.30] 1.0: [0.28, 0.28]	0.4: [0.01, 0.16] 0.5: [0.02, 0.14] 0.6: [0.02, 0.13] 0.7: [0.03, 0.11] 0.8: [0.04, 0.10] 0.9: [0.06, 0.09] 1.0: [0.08, 0.08]	0.4: [0.03, 0.74] 0.5: [0.04, 0.61] 0.6: [0.05, 0.50] 0.7: [0.08, 0.41] 0.8: [0.12, 0.33] 0.9: [0.16, 0.27] 1.0: [0.22, 0.21]
6	0.0: [0.02, 0.60] 0.1: [0.05, 0.56] 0.2: [0.07, 0.52] 0.3: [0.10, 0.49] 0.4: [0.12, 0.46] 0.5: [0.15, 0.43] 0.6: [0.18, 0.40] 0.7: [0.21, 0.37] 0.8: [0.24, 0.35] 0.9: [0.28, 0.33] 1.0: [0.32, 0.31]	0.0: [0.00, 0.34] 0.1: [0.00, 0.31] 0.2: [0.01, 0.27] 0.3: [0.02, 0.24] 0.4: [0.03, 0.22] 0.5: [0.04, 0.19] 0.6: [0.06, 0.17] 0.7: [0.07, 0.15] 0.8: [0.08, 0.14] 0.9: [0.09, 0.12] 1.0: [0.11, 0.11]	0.0: [0.00, 0.93] 0.1: [0.00, 0.86] 0.2: [0.01, 0.79] 0.3: [0.04, 0.72] 0.4: [0.06, 0.64] 0.5: [0.09, 0.56] 0.6: [0.12, 0.49] 0.7: [0.15, 0.42] 0.8: [0.19, 0.36] 0.9: [0.22, 0.30] 1.0: [0.26, 0.25]