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Sustainable Desalination Process Selection: Decision Support Framework under Hybrid Information

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Abstract: Desalination technology has been recognized as a promising solution for mitigating the pressure caused by water shortage. In order to help the decision-makers to select the most sustainable desalination process/technology, a multi-criteria decision analysis method under hybrid information was proposed for sustainability ranking of alternative desalination processes. The interval AHP (Analytic Hierarchy Process) method was employed to determine the weights of the evaluation, and the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) under hybrid information was employed to determine the sustainability ranking of the alternative desalination processes. Comparing with the previous studies about desalination process selection, the proposed method can achieve desalination selection based on the decision-making matrix composed by multiple types of data (i.e. crisp numbers, interval numbers and fuzzy numbers). Accordingly, the challenges of uncertainties and the quantification on the soft criteria can be successfully solved. The results based on the developed model can facilitate the decision-makers to select the most sustainability desalination technology with the considerations of economic, environmental. Technological and social pillars simultaneously. Four alternative desalination processes including multi-stage flash system (MSF), low temperature multi-effect distillation (LT-MED), reverse osmosis (RO), and vapor compression distillation (VCD) were studied by the proposed method in this study, and The closeness degree (CD) of LT-MED which represents its integrated sustainability performance is 0.6984, followed by the CDs of MSF (0.5602), VCD (0.5381) and RO (0.4116), respectively. Thus, the sustainability ranking from the best to the worst is LT-MED, MSF, VCD and RO. The results were validated by the sum weighted method, and sensitivity analysis was also carried out. The results reveal that the selection of LT-MED as the most sustainable is robust.

Keywords: Desalination technology selection; sustainability assessment; multi-criteria decision making; interval analytic hierarchy process; TOPSIS

1. Introduction

With the growth of the population, the development of industrialization and the improvement of human's quality of life, large amount of water will be required in future, but around 97% of the water on the earth is salty and cannot be used by human directly, and only less than 1% of the fresh water can be reached by human (Eltawil et al., 2009). In order to solve this challenge, various measures and actions have been taken such as developing water-saving technologies and developing desalination process for fresh water generation. Desalination has been recognized as a promising alternative for solving the problem of water shortage in many arid or water-stressed countries/regions, because it has great potential to provide unlimited desalinated water for industrial, domestic, agricultural and tourism use (Ghaffour *et al*., 2013). There are usually a variety of technologies/processes can be selected for desalination, including membrane-based processes (i.e., reverse osmosis and forward osmosis), thermal-based technologies (i.e., humidificatione-dehumidification, adsorption desalination and pervaporation, etc.), and alternative technologies (i.e., microbial desalination cell, capacitive deionization technologies, ion concentration polarization and clathrate hydrates, etc.) (Subramani and Jacangelo, 2015). And it is usually a great challenge for the users to select the best desalination technology when they face many different choices, because the users usually have to consider various aspects in the process of selecting desalination technologies, i.e., the production cost, water utilization efficiency, the environmental impacts, water purity, the energy consumption, and the technology reliability, etc. Therefore, the selection process is a compromise decision-making problem, and it is also a typical multi-criteria decision analysis (MCDA) process.

MCDA method can help the decision-makers to select the best alternative from multiple choices based on a variety of criteria/indicators, and it has been used on various fields. For instance, supplier selection (Fei *et al*., 2018; Kellner *et al*., 2019), material selection (Yang *et al*., 2018; Mousavi-Nasab and Sotoudeh-Anvari, 2018), process selection (An *et al*., 2018; Ren, 2018a; Xu *et al*., 2018), and energy system selection (Ren 2018b; Arce *et al*., 2015), etc. There are also various methods developed in the previous studies for the selection of desalination technologies. Some of these studies focused on employing the MCDA method for desalination related decision-making such as desalination location selection, prioritization of seawater desalination plants and the selection of the best energy supply configuration for reverse osmosis desalination. For instance, the Dweiri *et al.* (2018) employed the analytic hierarchy process (AHP) as the multi-criteria decision-making method for ranking the criteria influencing the location selection of desalination plant. Heck *et al*. (2017) employed AHP as the multi-criteria analysis method to determine the priorities of the seawater desalination plants. Georgiou *et al*. (2015) combined AHP and PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations) to select the best energy supply configuration for reverse osmosis desalination. In addition, there are also various studies specially focused on desalination process selection. For instance, Afify (2010) employed the sum weighted method as the multi-criteria decision analysis tool to rank the desalination strategies. Vivekh *et al*. (2016) used TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) and PROMETHEE-2 as the multi-criteria evaluation tools to achieve desalination technology selection, and a total of eleven criteria were used in the multi-criteria evaluation process. Hajeeh (2010) employed the fuzzy AHP to compare different desalination technologies with the considerations of six evaluation criteria. Ghassemi and Danesh (2013) combined fuzzy AHP and TOPSIS to prioritize the alternative desalination technologies, and fuzzy AHP was used to determine the weights of the criteria as well as that of the sub-criteria, and TOPSIS was employed to determine the final priority sequence of the alternative desalination technologies. Rújula and Dia (2010) used the multi-criteria analysis method to select the most suitable desalination process among the desalination systems based on different energy sources, and five criteria including potential, economic cost, O& M cost, CO_2 emissions and adequacy were used. It is worth pointing out that there are some studies focusing on quantitative sustainability ranking of desalination processes as a special kind of multi-criteria decision analysis. For instance, Ibrahim *et al*. (2018) developed an integrated framework for sustainability assessment of desalination technologies by integrating the AHP method, swing and weighted sum method, and the criteria in the techno-economic, environmental and social dimensions were incorporated in the decision-making process. Lior (2017) and Lior and Kim (2018) developed a composite sustainability based on quantitative analysis approach for representing the integrated sustainability performances by integrating economic, environmental and social impacts, and the users can identify the most sustainable desalination process among multiple choices. All these studies are valuable for the decision-makers to select the best or the most sustainable desalination technology among multiple choices, but there are still two knowledge gaps:

(1) It lacks the method to address uncertainties or the decision-making matrix with hybrid information (Gap A): all these methods developed in the previously published studies can only rank the alternative desalination technologies when all

the data in the decision-making matrix are all crisp numbers. Sometime the value of one desalination process with respect to a criterion may vary within an interval rather than a crisp number. Moreover, sometime the decision-makers can only use the linguistic terms (corresponding to fuzzy numbers) to evaluate the desalination processes with respect to some soft criteria. Therefore, developing a MCDA method which can address the decision-making matrix which consists of multiple types of data (e.g., crisp numbers, interval numbers and fuzzy numbers) is of vital importance.

(2) It lack the method to determine the weights of the evaluation criteria in a more accurate way because of hesitations and ambiguity existing in human's judgments (Gap B): almost all these methods relying on using AHP , fuzzy AHP or some weighting methods derived from AHP to determine the weights of the evaluation criteria in the decision-making process, all these methods used a single number or a single linguistic term to represent the judgments of the users on the relative importance/priority of one criterion over another. However, the single number or single linguistic term approach cannot describe the preferences of the users accurately because there are usually various kinds of vagueness, ambiguity and uncertainties in the preferences of the decision-makers.

In order to solve the above-mentioned two challenges, a multi-criteria decision making method under hybrid information was proposed for sustainability ranking of alternative desalination processes, the interval AHP method was employed to calculate the weights of the criteria for sustainability assessment of desalination technologies, and the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) which can address the decision-making matrix composed by multiple types of data was developed for ranking the alternative desalination technologies. The TOPSIS method under hybrid information can address gap A, and the interval AHP method which allows the interval numbers rather than the crisp numbers to represents the relative preference of one criterion over another can address gap B, thus, the TOPSIS under hybrid information was integrated with interval AHP for prioritizing the alternative desalination processes in this study. Accordingly, the sustainability rankings of these desalination technologies can be determined under hybrid information and address the hesitations and ambiguity existing in human's judgments when determining the weights of the evaluation criteria for sustainability assessment of desalination technologies.

Besides these, the remainder parts of this study were organized as follows: the multi-criteria decision analysis method under hybrid information was presented in section 2; a typical case about sustainable desalination selection was studied in section 3; the results were further discussed by validation and sensitivity analysis in section 4; and finally, this study was concluded in section 5.

2. Methods

This section consists of two sub-sections: the interval Analytic Hierarchy Process method was firstly proposed in section 2.1; and then, the multi-criteria decision making method under hybrid information was presented in section 2.2. The preliminary of interval numbers and fuzzy numbers were presented in the Appendix.

The proposed multi-criteria decision-making method was proposed by combining the interval AHP method and the TOPSIS method under hybrid information. The framework of the proposed method was presented in Figure 1. The interval AHP method was used in this study to determine the weights of the evaluation criteria, and the TOPSIS which can handle the decision-making matrix with hybrid information was employed to determine the sustainability rankings of the alternative desalination processes, and sensitivity analysis will be carried out by studying the influences of the weights of the criteria on the closeness degrees of the alternative desalination processes which represent their integrated sustainability performances.

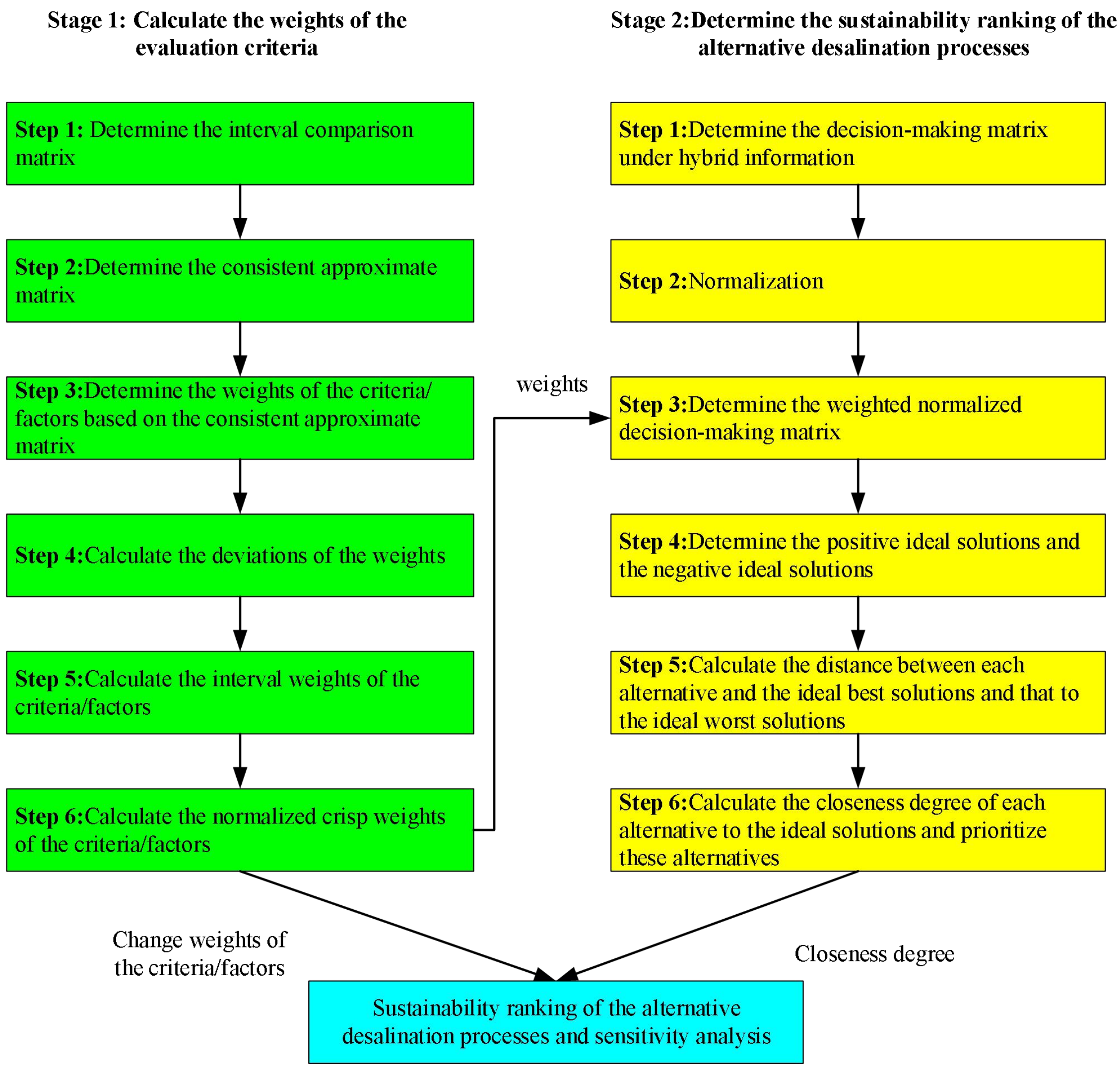

Figure 2: The framework of the proposed method

2.1 Interval AHP

The interval AHP used in this study was developed by Xu and Yang (1998), and this method allows the users to use interval numbers to compare the relative importance of one criterion/factor over another. After determining the interval comparison matrix, a consistent approximate comparison matrix will be firstly deduced as the approximate comparison matrix of the interval matrix; subsequently, the weights of the criteria/factors determined by the consistent approximate comparison matrix will be determined; then, the two deviation matrices representing the deviations of the consistent approximate comparison matrix to the interval comparison matrix as well as the deviations of the weights will be calculated; and finally, the interval weights based on the interval comparison matrix will be determined. The interval AHP method was presented in the following five steps based on the work of Xu and Yang (1998):

Step 1: Establish the interval comparison matrix.

Assuming that there are a total of n criteria/factors to be evaluated and compared, and they are $\{C_1, C_2, \cdots, C_n\}$, the first step of the interval AHP is to use the interval numbers to rate the relative priority/importance between each pair of criteria/factors. The Saaty's nine-scale system (as presented in Table 1) used in the traditional AHP method was employed in this study. The use of interval numbers rather than the crisp numbers in establishing the interval comparison matrix aims to solve the ambiguity and fuzziness existed in the users' judgments, and the interval numbers such as $[1 \quad 3]$ and $[2 \quad 4]$ are used to express the opinions of the decision-makers on the relative priority/importance of one criterion/factor over another. For example, the interval number $[2 \quad 4]$ will be used to express the opinions of the decision-makers if they think that the relative importance of a criterion/factor is between "extremely less importance" which corresponds to the scale 2 and "less importance" which corresponds to the scale 4.

After comparing each pair of criteria/factors, the interval comparison matrix in which all the elements are interval numbers can be established, as presented in Eq.1.

$$\begin{array}{c|cccc} & C_1 & C_2 & \cdots & C_n \\ C_1 & 1 & a_{12}^{\pm} & \cdots & a_{1n}^{\pm} \\ C_2 & a_{21}^{\pm} & 1 & \cdots & a_{2n}^{\pm} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & a_{n1}^{\pm} & a_{n2}^{\pm} & \cdots & 1 \end{array} \tag{1}$$

$$a_{ij}^{\pm} = \left[a_{ij}^{-} \quad a_{ij}^{+} \right] \tag{2}$$

where $a_{ij}^{\pm}(i = 1, 2, \cdots, n; j = 1, 2, \cdots, n)$ which is an interval number represents the relative priority/importance of the *i*-th criterion/factor comparing with the *j*-th criterion/factor, a_{ij}^{-} and a_{ij}^{+} are the lower and upper bound of $a_{ij}^{\pm}$, respectively.

Table 1: Nine-scale system for the relative importance (Saaty,1980)

Definition	Explanations	Scale
Equal importance	C_i is equally important comparing with C_j	1
Extremely less importance	C_i is extremely less important comparing with C_j	2
Strongly less importance	C_i is strongly less important comparing with C_j	3
Less importance	C_i is less important comparing with C_j	4
Moderate less importance	C_i is moderately less important comparing with C_j	5
Moderate importance	C_i is moderately important comparing with C_j	6
Strong importance	C_i is strongly important comparing with C_j	7
Very Strong importance	C_i is very strongly important comparing with C_j	8
Extreme importance	C_i is extremely important comparing with C_j	9

Step 2: Determine the consistent approximate matrix.

The interval comparison matrix presented in Eq.1 can be used to determine the consistent approximate matrix according to Eq.3 and Eq.4.

$$m_{ij} = \left(\prod_{k=1}^{n} \frac{a_{ik}^{-} a_{ik}^{+}}{a_{jk}^{-} a_{jk}^{+}} \right)^{\frac{1}{2n}} \tag{3}$$

$$M = \begin{array}{c|cccc} & C_1 & C_2 & \cdots & C_n \\ C_1 & 1 & m_{12} & \cdots & m_{1n} \\ C_2 & m_{21} & 1 & \cdots & m_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & m_{n1} & m_{n2} & \cdots & 1 \end{array} \tag{4}$$

where M represents the consistent approximate matrix derived from the interval comparison matrix, and $m_{ij} (i = 1, 2, \cdots, n; j = 1, 2, \cdots, n)$ represents the relative priority/importance of the *i*-th criterion/factor comparing with the *j*-th criterion/factor.

Step 3: Determine the weights of the criteria/factors based on the consistent approximate matrix.

The crisp weights of the criteria/factors determined by the consistent approximate matrix can be determined by Eq.5.

$$\omega_j^* = \frac{1}{\sum_{i=1}^{m} m_{ij}} \tag{5}$$

where ω_j^* represents the weight of the *j*-th criterion/factor

Step 4: Calculate the deviations of the weights.

Two deviation matrices can be determined according to Eq.6 and Eq.7, respectively.

$$
\Delta M_1 = \begin{array}{c|cccc} & C_1 & C_2 & \cdots & C_n \\ C_1 & 0 & m_{12} - a_{12}^{-} & \cdots & m_{1n} - a_{1n}^{-} \\ C_2 & m_{21} - a_{21}^{-} & 0 & \cdots & m_{2n} - a_{2n}^{-} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & m_{n1} - a_{n1}^{-} & m_{n2} - a_{n1}^{-} & \cdots & 0 \end{array} \tag{6}
$$

$$
\Delta M_2 = \begin{array}{c|cccc} & C_1 & C_2 & \cdots & C_n \\ C_1 & 0 & a_{12}^{+} - m_{12} & \cdots & a_{12}^{+} - m_{1n} \\ C_2 & a_{12}^{+} - m_{21} & 0 & \cdots & a_{12}^{+} - m_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & a_{12}^{+} - m_{n1} & a_{12}^{+} - m_{n2} & \cdots & 0 \end{array} \tag{7}
$$

where ΔM_1 and ΔM_2 are the negative and positive deviations of the interval comparison matrix to the consistent approximate matrix, respectively.

According to the error transfer formula, the weight derivations of the interval comparison matrix with respect to the consistent approximate matrix can be determined by Eq.8 and Eq.9, respectively.

$$
\Delta\omega_i^{-} = \sqrt{\frac{\sum_{j=1}^{n} \left(m_{ij\_} a_{ij}^{-} \right)^2}{\left(\sum_{j=1}^{n} m_{ij} \right)^4}} \tag{8}
$$

$$
\Delta\omega_i^{+} = \sqrt{\frac{\sum_{j=1}^{n} \left(a_{ij}^{+} - m_{ij} \right)^2}{\left(\sum_{j=1}^{n} m_{ij} \right)^4}} \tag{9}
$$

where $\Delta\omega_i^-$ and $\Delta\omega_i^+$ represent the negative and positive deviations of the weight of the i-th criterion determined by the interval comparison matrix to that determined by the consistent approximate matrix.

Step 5: Calculate the interval weights of the criteria/factors.

The interval weight of the *i*-th criteria can be determined by Eq.10.

$$\omega_i^{\pm} = \left[\omega_i^* - \Delta\omega_i^- \quad \omega_i^* + \Delta\omega_i^+ \right] \tag{10}$$

where $\omega_i^{\pm}$ represents the interval weight of the *i*-th criterion/factor.

Step 6: Normalizing the interval weights of the criteria/factors to obtain the crisp weights.

The midpoint of each interval weight can be determined by Eq.11.

$$MP_i = \frac{\left(\omega_i^* - \Delta\omega_i^-\right) + \left(\omega_i^* + \Delta\omega_i^+\right)}{2} = \omega_i^* + \frac{\Delta\omega_i^+ - \Delta\omega_i^-}{2} \tag{11}$$

where MP_i represents the midpoint of the interval weight of the *i*-th criterion/factor

Then, the normalized crisp weight of each criterion/factor can be calculated by Eq.12.

$$\omega_i = \frac{\omega_i^* + \frac{\Delta\omega_i^+ - \Delta\omega_i^-}{2}}{\sum_{i=1}^{n} \left[\omega_i^* + \frac{\Delta\omega_i^+ - \Delta\omega_i^-}{2} \right]} \tag{12}$$

where ω_i represents the normalized crisp weight of the *i*-th criterion/factor

It is worth pointing out that there are usually several criteria in two or more hierarchies in the evaluation criteria system, and the users can firstly use Eqs.1-11 to determine the relative importance/weights of the four categories/dimensions as well as that of the criteria in each category/dimension. Then, the global interval weight of each criterion can be determined by using the local interval weight of the criterion to multiply the interval weight of the corresponding dimension to which the criterion belongs to. After calculating the global interval weights of all the criteria, the normalized crisp weights of the criteria can be determined by Eqs.11-12.

2.2 Multi-Criteria Decision Analysis Under Hybrid Information

The TOPSIS under hybrid information which can address the decision-making matrix composed by multiple types of data was employed to rank the alternative desalination technologies/processes. It can handle the decision-making matrix with multiple types of data, i.e., crisp numbers, interval numbers and fuzzy numbers. It is an extension of the traditional TOPSIS method: the decision-making matrix with multiple types of data will be firstly normalized; subsequently, the ideal best and the ideal worst solutions will be determined; then, the distance of each alternative to the ideal best solutions and that of each alternative to the ideal worst solutions will be determined; and finally, the closeness degree of each alternative can be determined to rank these alternatives. The TOPSIS under hybrid information was summarized in the following six steps based on the work of Xia and Wu (2004):

Step 1: Determine the decision-making matrix under hybrid information.

The decision-making matrix used in this study is different from that used in the traditional multi-criteria decision analysis methods, and it consists of crisp numbers, interval numbers and fuzzy numbers. In other words, multiple types of data including crisp, interval and fuzzy numbers will be used in this decision-making matrix, as presented in Eq.13.

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_M \end{array} \begin{array}{ccccccccc} C_1 & \cdots & C_K & C_{K+1} & \cdots & C_{K+L} & C_{K+L+1} & \cdots & C_{K+L+T} \\ x_{11} & \cdots & x_{1K} & y^{\pm}_{1(K+1)} & \cdots & y^{\pm}_{1(K+L)} & z'_{1(K+L+1)} & \cdots & z'_{1(K+L+T)} \\ x_{21} & \cdots & x_{2K} & y^{\pm}_{2(K+1)} & \cdots & y^{\pm}_{2(K+L)} & z'_{2(K+L+1)} & \cdots & z'_{2(K+L+T)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ x_{M1} & \cdots & x_{MK} & y^{\pm}_{M(K+1)} & \cdots & y^{\pm}_{3(K+L)} & z'_{M(K+L+1)} & \cdots & z'_{M(K+L+T)} \end{array} \quad (13)$$

where D is the decision-making matrix, $A_i (i=1,2,\cdots,M)$ represents the *i*-th desalination technology. $C_j\left(j=1,2,\cdots,K\right)$, $C_j\left(j=K+1,K+2,\cdots,K+L\right)$ and $C_j\left(j=K+L+1, j=K+L+2,\cdots, j=K+L+T\right)$ represents the criteria which can be described by crisp number, interval number and fuzzy numbers, respectively. $x_{ij}\left(j=1,2,\cdots,K\right)$, $y^{\pm}_{ij}=\left[y^{-}_{ij} \quad y^{+}_{ij}\right]\left(j=K+1,K+2,\cdots,K+L\right)$ and $z'_{ij}=\left(z^{l}_{ij},z^{m}_{ij},z^{u}_{ij}\right)\left(j=K+L+1,K+L+2,\cdots,K+L+T\right)$ which represent the data of the *i*-th desalination technology with respect to the *j*-th criterion are crisp numbers, interval numbers and fuzzy numbers, respectively.

Crisp numbers are used when the data of the alternative desalination technologies with respect to the hard evaluation criteria are determinate. Interval numbers are used when the data of the alternative desalination technologies with respect to the hard evaluation cannot be described by crisp numbers directly due to various uncertainties. Fuzzy numbers can be to rate the alternative desalination technologies based on their relative performances with respect to these soft criteria. Seven linguistic judgments corresponding to seven triangular fuzzy numbers were used to describe the relative performances of the alternative desalination technologies with respect to these soft criteria, as presented in Table 2.

Table 2: The linguistic terms and the corresponding fuzzy numbers (Xia and Wu, 2004)

Linguistic terms	Extremely bad	Very Bad	Bad	Moderate	Good	Very Good	Extremely Good
Abbreviation	EB	VB	B	M	G	VG	EG
Fuzzy numbers	(0,0,0.1)	(0.1,0.2,0.3)	(0.2,0.3,0.4)	(0.4,0.5,0.6)	(0.6.0.7,0.8)	(0.8,0.9,1.0)	(0.9,1.0,1.0)

Step 2: Normalization

In order to eliminate the impacts of the units on the rankings of the desalination technologies, the decision-making matrix should be normalized. There are two types of criteria: one is the benefit-type criteria, and another is the cost-type criteria. The benefit-type criteria represent a set of criteria (denotes by BC) that can benefit the alternative with the increase of the data with respect to these criteria. However, the cost-type criteria represent a set of criteria (denotes by CC) that will make the alternative worse with the increase of the data with respect to these criteria. As mentioned above, there three types of numbers in the decision-making matrix (as presented in Eq.15) including crisp numbers, interval numbers and fuzzy numbers, they can be normalized by Eqs.14-16.

As for the crisp numbers $x_{ij}\left(j=1,2,\cdots,K\right)$ (Özcan *et al.*, 2011),

$$Nx_{ij}=\begin{cases}\dfrac{x_{ij}-\min\limits_{i}^{M}\left\{x_{ij}\right\}}{\max\limits_{i}^{M}\left\{x_{ij}\right\}-\min\limits_{i}^{M}\left\{x_{ij}\right\}} & \left(i=1,2,\cdots,M;j\in BC\right)\\ \dfrac{\max\limits_{i}^{n}\left\{x_{ij}\right\}-x_{ij}}{\max\limits_{i}^{M}\left\{x_{ij}\right\}-\min\limits_{i}^{M}\left\{x_{ij}\right\}} & \left(i=1,2,\cdots,M;j\in CC\right)\end{cases} \tag{14}$$

where Nx_{ij} represents the normalized data of x_{ij}

As for the interval numbers $y_{ij}^{\pm}=\left[y_{ij}^{-}\quad y_{ij}^{+}\right]\left(j=K+1,K+2,\cdots,K+L\right)$ (Ren and Toniolo, 2018),

$$Ny_{ij}^{\pm}=\begin{cases}\left[\dfrac{y_{ij}^{-}-\min\limits_{i}^{M}\left\{y_{ij}^{-}\right\}}{\max\limits_{i}^{M}\left\{y_{ij}^{+}\right\}-\min\limits_{i}^{M}\left\{y_{ij}^{-}\right\}}\quad \dfrac{y_{ij}^{+}-\min\limits_{i}^{M}\left\{y_{ij}^{-}\right\}}{\max\limits_{i}^{M}\left\{y_{ij}^{+}\right\}-\min\limits_{i}^{M}\left\{y_{ij}^{-}\right\}}\right] & \left(i=1,2,\cdots,M;j\in BC\right)\\ \left[\dfrac{\max\limits_{i}^{M}\left\{y_{ij}^{+}\right\}-y_{ij}^{+}}{\max\limits_{i}^{M}\left\{y_{ij}^{+}\right\}-\min\limits_{i}^{M}\left\{y_{ij}^{-}\right\}}\quad \dfrac{\max\limits_{i}^{M}\left\{y_{ij}^{+}\right\}-y_{ij}^{-}}{\max\limits_{i}^{M}\left\{y_{ij}^{+}\right\}-\min\limits_{i}^{M}\left\{y_{ij}^{-}\right\}}\right] & \left(i=1,2,\cdots,M;j\in CC\right)\end{cases} \tag{15}$$

where $Ny_{ij}^{\pm}$ represents the normalized data of $y_{ij}^{\pm}$

As for the fuzzy numbers $z'_{ij}=\left(z_{ij}^{l},z_{ij}^{m},z_{ij}^{u}\right)\left(j=K+L+1,K+L+2,\cdots,K+L+T\right)$

$$Nz'_{ij}=\begin{cases}\left(\dfrac{z_{ij}^{l}-\min\limits_{i}^{M}\left\{z_{ij}^{l}\right\}}{\max\limits_{i}^{M}\left\{z_{ij}^{u}\right\}-\min\limits_{i}^{M}\left\{z_{ij}^{l}\right\}},\dfrac{z_{ij}^{m}-\min\limits_{i}^{M}\left\{z_{ij}^{l}\right\}}{\max\limits_{i}^{M}\left\{z_{ij}^{u}\right\}-\min\limits_{i}^{M}\left\{z_{ij}^{l}\right\}},\dfrac{z_{ij}^{u}-\min\limits_{i}^{M}\left\{z_{ij}^{l}\right\}}{\max\limits_{i}^{M}\left\{z_{ij}^{u}\right\}-\min\limits_{i}^{M}\left\{z_{ij}^{l}\right\}}\right) & \left(i=1,2,\cdots,M;\, j\in BC\right)\\ \left(\dfrac{\max\limits_{i}^{M}\left\{z_{ij}^{u}\right\}-z_{ij}^{u}}{\max\limits_{i}^{M}\left\{z_{ij}^{u}\right\}-\min\limits_{i}^{M}\left\{z_{ij}^{l}\right\}},\dfrac{\max\limits_{i}^{M}\left\{z_{ij}^{u}\right\}-z_{ij}^{m}}{\max\limits_{i}^{M}\left\{z_{ij}^{u}\right\}-\min\limits_{i}^{M}\left\{z_{ij}^{l}\right\}},\dfrac{\max\limits_{i}^{M}\left\{z_{ij}^{u}\right\}-z_{ij}^{l}}{\max\limits_{i}^{M}\left\{z_{ij}^{u}\right\}-\min\limits_{i}^{M}\left\{z_{ij}^{l}\right\}}\right) & \left(i=1,2,\cdots,M;\, j\in BC\right)\end{cases}$$

(16)

where Nz'_{ij} represents the normalized data of z'_{ij}

After this, the normalized decision-making matrix can be obtained, as presented in Eq.17.

$$ND=\begin{array}{c|ccccccccc} & C_1 & \cdots & C_K & C_{K+1} & \cdots & C_{K+L} & C_{K+L+1} & \cdots & C_{K+L+T}\\ A_1 & Nx_{11} & \cdots & Nx_{1K} & Ny^{\pm}_{1(K+1)} & \cdots & Ny^{\pm}_{1(K+L)} & Nz'_{1(K+L+1)} & \cdots & Nz'_{1(K+L+T)}\\ A_2 & Nx_{21} & \cdots & Nx_{2K} & Ny^{\pm}_{2(K+1)} & \cdots & Ny^{\pm}_{2(K+L)} & Nz'_{2(K+L+1)} & \cdots & Nz'_{2(K+L+T)}\\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots\\ A_M & Nx_{M1} & \cdots & Nx_{MK} & Ny^{\pm}_{M(K+1)} & \cdots & Ny^{\pm}_{3(K+L)} & Nz'_{M(K+L+1)} & \cdots & Nz'_{M(K+L+T)}\end{array}$$

(17)

where $ND=\left\{ND_{ij}\right\}_{M(K+L+T)}$ represents the normalized multi-type-data based decision-making matrix. $Nx_{ij}\left(j=1,2,\cdots,K\right)$, $Ny_{ij}^{\pm}=\left[Ny_{ij}^{-}\quad Ny_{ij}^{+}\right]\left(j=K+1,K+2,\cdots,K+L\right)$ and $Nz'_{ij}=\left(Nz_{ij}^{l},Nz_{ij}^{m},Nz_{ij}^{u}\right)\left(j=K+L+1,K+L+2,\cdots,K+L+T\right)$ which represent the normalized data of the *i*-th desalination technology with respect to the *j*-th criterion are crisp numbers, interval numbers and fuzzy numbers.

Step 3: Determine the weighted normalized multi-type data based decision-making matrix.

Each element in the weighted normalized decision-making matrix can be calculated by determining the product of each element in the normalized decision-making matrix and the corresponding weight according to Eqs.18-19.

$$WND = \left\{ WND_{ij} \right\}_{M(K+L+T)} \tag{18}$$

where WND represents the weighted normalized decision-making matrix, and WND_{ij} represents the data of the *i*-th alternative with respect to the *j*-th criterion

$$\begin{aligned} WND_{ij} = \omega_j ND_{ij} &= \begin{cases} \omega_j Nx_{ij} \left(j = 1, 2, \cdots, K \right) \\ \omega_j Ny_{ij}^{\pm} \left(j = K+1, K+2, \cdots, K+L \right) \\ \omega_j Nz'_{ij} \left(j = K+L+1, K+L+2, \cdots, K+L+T \right) \end{cases} \\ &= \begin{cases} \omega_j Nx_{ij} \left(j = 1, 2, \cdots, K \right) \\ \left[\omega_j Ny_{ij}^{-} \quad \omega_j Ny_{ij}^{+} \right] \left(j = K+1, K+2, \cdots, K+L \right) \\ \left(\omega_j Nz_{ij}^{l}, \omega_j Nz_{ij}^{m}, \omega_j Nz_{ij}^{u} \right) \left(j = K+L+1, K+L+2, \cdots, K+L+T \right) \end{cases} \end{aligned} \tag{19}$$

where ω_j represents the normalized crisp weight of the *j*-th criterion

Step 4: Determine the positive ideal solutions and the negative ideal solutions.

The positive ideal solutions which represents that all the criteria can reach to their ideal best status can be determined by Eqs.20-21.

$$V^{+} = \left[v_1^{+} \quad \cdots \quad v_K^{+} \quad v_{K+1}^{+} \quad \cdots \quad v_{K+L}^{+} \quad v_{K+L+1}^{+} \quad \cdots \quad v_{K+L+T}^{+} \right] \tag{20}$$

$$v_j^+ = \begin{cases} \max_{i=1}^{M} \omega_j Nx_{ij}, & \left(j = 1, 2, \cdots, K\right) \\ \left[\max_{i=1}^{M} \omega_j Ny_{ij}^- \quad \max_{i=1}^{M} \omega_j Ny_{ij}^+ \right], & \left(j = K+1, K+2, \cdots, K+L\right) \\ \left(\max_{i=1}^{M} \omega_j Nz_{ij}^l, \max_{i=1}^{M} \omega_j Nz_{ij}^m, \max_{i=1}^{M} \omega_j Nz_{ij}^u \right), & \left(j = K+L+1, K+L+2, \cdots, K+L+T\right) \end{cases} \quad (21)$$

The negative ideal solutions which represents that all the criteria can reach to their ideal worst status can be determined by Eqs.38-39.

$$V^+ = \left[v_1^- \quad \cdots \quad v_K^- \quad v_{K+1}^- \quad \cdots \quad v_{K+L}^- \quad v_{K+L+1}^- \quad \cdots \quad v_{K+L+T}^- \right] (22)$$

$$v_j^- = \begin{cases} \min_{i=1}^{M} \omega_j Nx_{ij}, & \left(j = 1, 2, \cdots, K\right) \\ \left[\min_{i=1}^{M} \omega_j Ny_{ij}^- \quad \min_{i=1}^{M} \omega_j Ny_{ij}^+ \right], & \left(j = K+1, K+2, \cdots, K+L\right) \\ \left(\min_{i=1}^{M} \omega_j Nz_{ij}^l, \min_{i=1}^{M} \omega_j Nz_{ij}^m, \min_{i=1}^{M} \omega_j Nz_{ij}^u \right), & \left(j = K+L+1, K+L+2, \cdots, K+L+T\right) \end{cases}$$

(23)

Step 5: Calculate the positive distance to the ideal best solutions and the negative distance to the absolutely worst solutions.

The positive distance which represents the distance between each alternative and the ideal best solutions can be determined by Eqs.24-27.

$$d\left(A_i, V^+\right) = \sqrt{\sum_{j=1}^{K} \left[d\left(\omega_j Nx_{ij}, v_j^+\right) \right]^2 + \sum_{j=K+1}^{K+L} \left[d\left(\omega_j Ny_{ij}^{\pm}, v_j^+\right) \right]^2 + \sum_{j=K+L+1}^{K+L+T} \left[d\left(\omega_j Nz_{ij}', v_j^+\right) \right]^2}$$

(24)

where $d\left(\omega_j Nx_{ij}, v_j^+\right)$ represents the positive distance between $\omega_j Nx_{ij}$ and v_j^+, $d\left(\omega_j Ny_{ij}^{\pm}, v_j^+\right)$ represents the positive distance between $\omega_j Ny_{ij}^{\pm}$ and v_j^+, and $d\left(\omega_j Nz'_{ij}, v_j^+\right)$ represents the positive distance between $\omega_j Nz'_{ij}$ and v_j^+.

$d\left(\omega_j Nx_{ij}, v_j^+\right)$, $d\left(\omega_j Ny_{ij}^{\pm}, v_j^+\right)$ and $d\left(\omega_j Nz'_{ij}, v_j^+\right)$ can be calculated by Eqs.25-27, respectively.

$$d\left(\omega_j Nx_{ij}, v_j^+\right) = \left|\omega_j Nx_{ij} - v_j^+\right| \tag{25}$$

$$d\left(\omega_j Ny_{ij}^{\pm}, v_j^+\right) = \sqrt{\frac{\left(\omega_j Ny_{ij}^{-} - \max_{i=1}^{M} \omega_j Ny_{ij}^{-}\right)^2 + \left(\omega_j Ny_{ij}^{+} - \max_{i=1}^{M} \omega_j Ny_{ij}^{+}\right)^2}{2}} \tag{26}$$

$$d\left(\omega_j Nz'_{ij}, v_j^+\right) = \sqrt{\frac{\left(\omega_j Nz_{ij}^{l} - \max_{i=1}^{M} \omega_j Nz_{ij}^{l}\right)^2 + \left(\omega_j Nz_{ij}^{m} - \max_{i=1}^{M} \omega_j Nz_{ij}^{m}\right)^2 + \left(\omega_j Nz_{ij}^{u} - \max_{i=1}^{M} \omega_j Nz_{ij}^{u}\right)^2}{3}} \tag{27}$$

The negative distance which represents the distance between each alternative and the ideal worst solutions can be determined by Eqs.28-31.

$$d\left(A_i, V^-\right) = \sqrt{\sum_{j=1}^{K}\left[d\left(\omega_j Nx_{ij}, v_j^-\right)\right]^2 + \sum_{j=K+1}^{K+L}\left[d\left(\omega_j Ny_{ij}^{\pm}, v_j^-\right)\right]^2 + \sum_{j=K+L+1}^{K+L+T}\left[d\left(\omega_j Nz'_{ij}, v_j^-\right)\right]^2} \tag{28}$$

where $d\left(\omega_j Nx_{ij}, v_j^-\right)$ represents the negative distance between $\omega_j Nx_{ij}$ and v_j^-, $d\left(\omega_j Ny_{ij}^{\pm}, v_j^-\right)$ represents the negative distance between $\omega_j Ny_{ij}^{\pm}$ and v_j^-, and $d\left(\omega_j Nz'_{ij}, v_j^-\right)$ represents the negative distance between $\omega_j Nz'_{ij}$ and v_j^-.

$d\left(\omega_j N x_{ij}, v_j^-\right)$, $d\left(\omega_j N y_{ij}^{\pm}, v_j^-\right)$ and $d\left(\omega_j N z'_{ij}, v_j^-\right)$ can be calculated by Eqs.29-31, respectively.

$$d\left(\omega_j N x_{ij}, v_j^-\right) = \left|\omega_j N x_{ij} - v_j^-\right| \tag{29}$$

$$d\left(\omega_j N y_{ij}^{\pm}, v_j^-\right) = \sqrt{\frac{\left(\omega_j N y_{ij}^- - \min_{i=1}^{M} \omega_j N y_{ij}^-\right)^2 + \left(\omega_j N y_{ij}^+ - \min_{i=1}^{M} \omega_j N y_{ij}^+\right)^2}{2}} \tag{30}$$

$$d\left(\omega_j N z'_{ij}, v_j^-\right) = \sqrt{\frac{\left(\omega_j N z_{ij}^l - \min_{i=1}^{M} \omega_j N z_{ij}^l\right)^2 + \left(\omega_j N z_{ij}^m - \min_{i=1}^{M} \omega_j N z_{ij}^m\right)^2 + \left(\omega_j N z_{ij}^u - \min_{i=1}^{M} \omega_j N z_{ij}^u\right)^2}{3}} \tag{31}$$

Step 6: Calculate the closeness degree and rank the alternatives.

The closeness degree of the *i*-th alternative desalination technology to the ideal solutions can be determined by Eq.32.

$$CD_i = \frac{d\left(A_i, V^-\right)}{d\left(A_i, V^-\right) + d\left(A_i, V^+\right)} \tag{32}$$

where CD_i represents the closeness degree of the *i*-th alternative desalination technology to the ideal solutions

These M alternatives can be prioritized according to their closeness degrees, and the greater the closeness degree is, the more superior the alternative will be.

3. Case Study

Four alternative desalination processes including multi-stage flash system (MSF), low temperature multi-effect distillation (LT-MED), reverse osmosis (RO), and low temperature-vapor compression distillation (LT-VCD) in Chinese conditions were studied by the proposed method. These four desalination technologies are very typical in China, and the selection of the most sustainable desalination also involved different stakeholders, thus, there are usually various kinds of ambiguity, vagueness and hesitation in the decision-making process, especially in the determination of the weights of the criteria for sustainability assessment. Moreover, the performances of these technologies were also described by using multiple types of data and information. These are the main reasons why these four alternative desalination technologies were selected to illustrate the developed method in this study.

These four desalination technologies were specified as follows:

Multi-stage flash system (MSF): The MSF system is a thermal distillation type of desalination (El-Ghonemy, 2017), and it usually includes the flashing stages, the brine heater, the pumping units, the venting system, and the cooling water control loop (El-Dessouky *et al*., 1999; Alhazmy, 2011).

Low temperature multi-effect distillation (LT-MED): The LT-MED system usually consists of the hot water circuiting system, the evaporators, the condenser, and the vacuum system and other auxiliary equipment (Zhang *et al*., 2017), the top brine temperature is usually lower 70 (Qi *et al*., 2014).

Reverse osmosis (RO): The RO process replies on using the RO membrane to obtain the fresh water, and water will go through the membrane to reach the permeate side (Greenlee *et al*., 2009).

Vapor compression distillation (VCD): The energy used for heating the saline water in the VCD system is provided by the vapor compressor, and it can be either a thermal vapor compression or a mechanical vapor compression which depends on the manners for compressing the initial vapor derived from the saline solution (Vivekh, et al., 2016).

Sustainability or sustainability development usually emphasizes economic prosperity, environmental cleanness and social responsibility simultaneously, thus, the criteria in economic, environmental and social aspects as the three main pillars of sustainability are usually used for sustainability assessment (Purvis *et al*., 2018). However, the criteria in technological aspect can significantly affect and influence the criteria in environmental, economic and social pillars (Ren *et al*, 2016). Therefore, the criteria in economic, environmental, social and technological aspects were employed for sustainability assessment of desalination processes. As for the criteria in each aspect for sustainability assessment, they were determined based on three principles (Wang *et al*., 2009): (1) Principle 1: relevancy principle (all the criteria should be related to the definition of each sustainability pillar); (2) Principle 2: independence principle (all the criteria should be independent); and (3) Principle 3: measurable principle (the data with respect to the criteria can be depicted quantitatively or qualitatively). A total of ten criteria in four dissensions, i.e. economic, environmental, technological and social dimensions, were used for sustainability assessment of the four alternative desalination technologies (as presented in Table 3).

Capital cost and production cost were used to measure economic performance, and the data derived from the work of Li (2010) are all crisp numbers. Water utilization efficiency which represents the ratio of the amount of the desalted water to the amount of the seawater input in the desalination process and energy consumption are used to quantify the environmental impacts, and the data with respect to water utilization efficiency are interval numbers, the data with respect to energy consumption are hybrid-some are interval numbers and some are crisp numbers, thus, all the data with respect to the two criteria in environmental dimension can be recognized as interval numbers. There are three criteria in technological dimension including water purity, technology maturity and technology reliability, the data with respect to water purity are interval numbers, but the performances of the four desalination technologies with respect to technology maturity and technology reliability can only be described by using linguistic terms. There are two criteria in social dimension, and they are market share and skills requirement. The performances of the four desalination technologies with respect to these two social criteria are also depicted by using linguistic terms. The performances of the four desalination technologies with respect to these ten criteria were summarized in Table 3.

Table 3: The multi-type data based decision-making matrix with hybrid information

			MSF	LT-MED	RO	VCD
Economic	Capital cost	10^4 Yuan	17,000	15,000	9,000	16,000
	Production cost	Yuan.t^{-1}	5.105	4.825	4.272	5.025
Environmental	Water utilization efficiency	/	12%-25%	15%-40%	0-40%	15%-40%
	Energy Consumption	kWh.m^{-3}	8.0	5.0	5.0-6.0	8.0
Technological	Water purity	Mg.L^{-1}	5-10	5-10	300-500	5-10
	Technology maturity	/	G	G	M	G
	Technology reliability	/	M	G	M	M
	Flexibility	/	M	G	G	G
Social	Market share	/	B	M	G	M
	Skills requirement	/	M	G	M	G

References: the data were adapted from Li (2010), Zhou and Li (2008)

The interval AHP method was firstly used to determine the weights of the four dimensions as well as the local weights of the criteria in each dimension. In order to determine these interval comparison matrices, a total of nine experts in the field of desalination were invited to participate in a focus group meeting to address this, and the focus group meeting includes three senior professors of chemical engineering who have mainly worked in desalination process for more than ten years, three postdoctoral fellows who have PhD degree in chemical engineering and have worked in process development of sustainable desalination for more than three years, and three engineers who worked in a famous seawater desalination company for more than five years. The interval comparison matrix for determining the weights of the four dimensions (economic, environmental, technological and social) was presented in Table 4.

Table 4: The interval comparison matrix for determining the weights of the four dimensions (economic, environmental, technological and social)

	Economic	Environmental	Technological	Social
Economic	1	$\left[1 \quad 2\right]$	$\left[\frac{1}{4} \quad \frac{1}{2}\right]$	$\left[3 \quad 5\right]$
Environmental	$\left[\frac{1}{2} \quad 1\right]$	1	$\left[\frac{1}{5} \quad \frac{1}{3}\right]$	$\left[2 \quad 4\right]$
Technological	$\left[2 \quad 4\right]$	$\left[3 \quad 5\right]$	1	$\left[5 \quad 7\right]$
Social	$\left[\frac{1}{5} \quad \frac{1}{3}\right]$	$\left[\frac{1}{4} \quad \frac{1}{2}\right]$	$\left[\frac{1}{7} \quad \frac{1}{5}\right]$	1

According to the interval comparison matrix presented in Table 4, the consistent approximate matrix can then be calculated by Eqs.3-4. Taking the element in cell (1,2) of the consistent approximate matrix as an example:

$$m_{12} = \left(\frac{1\times1\times1\times2\times\frac{1}{4}\times\frac{1}{2}\times3\times5}{\frac{1}{2}\times1\times1\times1\times\frac{1}{5}\times\frac{1}{3}\times2\times4} \right)^{\frac{1}{2\times4}} = 1.3916 \qquad (33)$$

In a similar way, all the other elements in the consistent approximate matrix can also be determined, and the result was presented in Eq.34.

	Economic	*Environmental*	*Technological*	*Social*	
Economic	1.0000	1.3916	0.4158	3.3470	
Environmental	0.7186	1.0000	0.2988	2.4052	(34)
Technological	2.4052	3.3470	1.0000	8.0503	
Social	0.2988	0.4158	0.1242	1.0000	

According to Eq.5, the weights of economic, environmental, technological and social dimensions can be determined, as presented in Eqs.35-38.

$$\omega_{Economic} = \frac{1}{(1.0000+0.7186+2.4052+0.2988)} = 0.2261 \qquad (35)$$

$$\omega_{Environmental} = \frac{1}{(1.3916+1.0000+3.3470+0.4158)} = 0.1625 \qquad (36)$$

$$\omega_{Techno\log ical} = \frac{1}{(0.4158+0.2988+1.0000+0.1242)} = 0.5438 \qquad (37)$$

$$\omega_{Social} = \frac{1}{(3.3470+2.4052+8.0503+1.0000)} = 0.0.0676 \qquad (38)$$

According to Eq.6 and Eq.7, the negative and positive deviations of the interval comparison matrix to the consistent approximate matrix can be determined, respectively. The results were presented in Eq. 39 and Eq.40.

$$\Delta M_1 = \begin{vmatrix} 0 & 0.3916 & 0.1658 & 0.3470 \\ 0.2186 & 0 & 0.0988 & 0.4052 \\ 0.4052 & 0.3470 & 0 & 3.0503 \\ 0.0988 & 0.1658 & -0.0186 & 0 \end{vmatrix} \quad (39)$$

$$\Delta M_2 = \begin{vmatrix} 0 & 0.6084 & 0.0842 & 1.6530 \\ 0.2814 & 0 & 0.0346 & 1.5948 \\ 1.5948 & 1.6530 & 0 & -1.0503 \\ 0.0346 & 0.0842 & 0.0758 & 0 \end{vmatrix} \quad (40)$$

Then, the negative and positive deviations of the weight of each dimension determined by the interval comparison matrix to that determined by the consistent approximate matrix can be determined by Eq. 8 and Eq.9, respectively. The results were presented in Table 5.

Table 5: the negative and positive deviations of the weight of each dimension determined by the interval comparison matrix to that determined by the consistent approximate matrix

	Economic category	Environmental category	Technological category	Social category
Negative deviation	0.0145	0.0241	0.0141	0.0573
Positive deviation	0.0466	0.0828	0.0115	0.0350

Finally, the interval weights of the four dimensions can be determined by Eq.26, and the results were presented in Table 6.

Table 6: The interval weights of the four dimensions (economic, environmental, technological and social) determined by the interval comparison matrix

	Economic	Environmental	Technological	Social
Interval weights	[0.2116 0.2727]	[0.1384 0.2453]	[0.5297 0.5554]	[0.0102 0.1026]

In a similar way, the criteria in economic, environmental, technological and social dimensions can also be determined, and the results were presented in Table 7. It is worth pointing out that the local weights of the two criteria (market share-S_1 and skills requirement-S_2) are equally important, thus, the local weights are 0.50000. After these, the global weights can be determined. For example, the global of capital cost (EC_1) can be determined by Eq.41.

$$[0.2116\ 0.2727] \times [0.5147\ 0.6863] = [0.1089\ 0.1872] \tag{41}$$

In a similar way, the global weights of all the other criteria can also be determined, and the results were summarized in the Appendix. Finally, the normalized crisp weights of these ten criteria can be determined by Eqs.11-12, and the results were also presented in the Appendix.

The linguistic evaluations presented in Table 3 can be transformed into triangular fuzzy numbers. For example, the linguistic term "Bad (B)" can be transformed into (0.2,0.3,0.4), the linguistic term "Moderate (M)" can be transformed into (0.4,0.5,0.6), and the linguistic term "Good (G)" can be transformed into (0.6.0.7,0.8). The decision-making matrix representing the relative performances of the four desalination processes by using multiple types of data were presented in Table 7.

Table 7: The multi-type data based decision-making matrix under hybrid information

			MSF	LT-MED	RO	VCD
Economic (EC)	Capital cost (EC_1)	10^4 Yuan	17,000	15,000	9,000	16,000
	Production cost (EC_2)	Yuan.t^{-1}	5.105	4.825	4.272	5.025
Environmental (EN)	Water utilization efficiency (EN_1)	/	12%-25%	15%-40%	0-40%	15%-40%
	Energy Consumption (EN_2)	kWh.m^{-3}	8.0-8.0	5.0-5.0	5.0-6.0	8.0-8.0
Technological (T)	Water purity (T_1)	Mg.L^{-1}	5-10	5-10	300-500	5-10
	Technology maturity (T_2)	/	(0.6.0.7,0.8)	(0.6.0.7,0.8)	(0.4,0.5,0.6)	(0.6.0.7,0.8)
	Technology reliability (T_3)	/	(0.4,0.5,0.6)	(0.6.0.7,0.8)	(0.4,0.5,0.6)	(0.4,0.5,0.6)
	Flexibility (T_4)	/	(0.4,0.5,0.6)	(0.6.0.7,0.8)	(0.6.0.7,0.8)	(0.6.0.7,0.8)
Social (S)	Market share (S_1)	/	(0.2,0.3,0.4)	(0.4,0.5,0.6)	(0.6.0.7,0.8)	(0.4,0.5,0.6)
	Skills requirement (S_2)	/	(0.4,0.5,0.6)	(0.6.0.7,0.8)	(0.4,0.5,0.6)	(0.6.0.7,0.8)

The data of the four alternative desalination processes with respect to capital cost (EC_1) and production cost (EC_2) are crisp numbers, and both of the criteria are cost-type criteria, and Eq.14 can be used to normalize these data. Taking the four elements respect to capital cost as an example:

$$\begin{cases} \dfrac{17000-17000}{17000-9000}=0 \\ \dfrac{17000-15000}{17000-9000}=0.2500 \\ \dfrac{17000-9000}{17000-9000}=1.0000 \\ \dfrac{17000-16000}{17000-9000}=0.1250 \end{cases} \quad (42)$$

The data of the four alternative desalination processes with respect to water utilization efficiency (EN_1), energy consumption (EN_2) and water purity (T_1) are interval numbers, water utilization efficiency and water purity are benefit-type criteria, energy consumption is benefit-type criterion, and these data can be normalized by Eq.15. Taking the data with respect to water utilization efficiency (EN_1) as an example,

$$\begin{cases} \left[\dfrac{12\%-0}{40\%-0} \quad \dfrac{25\%-0}{40\%-0}\right]=\left[0.3000 \quad 0.6250\right] \\ \left[\dfrac{15\%-0}{40\%-0} \quad \dfrac{40\%-0}{40\%-0}\right]=\left[0.3750 \quad 1.0000\right] \\ \left[\dfrac{0-0}{40\%-0} \quad \dfrac{40\%-0}{40\%-0}\right]=\left[0.0000 \quad 1.0000\right] \\ \left[\dfrac{15\%-0}{40\%-0} \quad \dfrac{40\%-0}{40\%-0}\right]=\left[0.3750 \quad 1.0000\right] \end{cases} \quad (43)$$

The data of the four alternative desalination processes with respect to the other five criteria including technology maturity (T_2), technology reliability (T_3), flexibility (T_4), market share (S_1) and skills requirement (S_2) are all triangular fuzzy numbers, and these can be normalized by Eq.16. Taking the data with respect to water purity (T_1) as an example,

$$\begin{cases} \left(\frac{0.6-0.4}{0.8-0.4} \quad \frac{0.7-0.4}{0.8-0.4} \quad \frac{0.8-0.4}{0.8-0.4}\right) = \left(0.5000 \quad 0.7500 \quad 1.0000\right) \\ \left(\frac{0.6-0.4}{0.8-0.4} \quad \frac{0.7-0.4}{0.8-0.4} \quad \frac{0.8-0.4}{0.8-0.4}\right) = \left(0.5000 \quad 0.7500 \quad 1.0000\right) \\ \left(\frac{0.4-0.4}{0.8-0.4} \quad \frac{0.5-0.4}{0.8-0.4} \quad \frac{0.6-0.4}{0.8-0.4}\right) = \left(0.0000 \quad 0.1250 \quad 0.5000\right) \\ \left(\frac{0.6-0.4}{0.8-0.4} \quad \frac{0.7-0.4}{0.8-0.4} \quad \frac{0.8-0.4}{0.8-0.4}\right) = \left(0.5000 \quad 0.7500 \quad 1.0000\right) \end{cases} \tag{44}$$

In a similar way, all the data presented in the decision-making matrix can be determined, and the results were presented in the Appendix.

The weighted normalized multi-type data based decision-making matrix can be determined by Eq.18 and Eq.19, and the results were presented in Table 11. The positive can be determined by Eqs.20-21, and the negative ideal solutions can also be determined by Eqs.22-23, and the results were also presented in the Appendix.

Then, the distance of each alternative desalination processes to the ideal solutions can be determined according to Eqs.24-25, and the results were presented in Table 8. Finally, the closeness degrees of the four desalination processes to the ideal solutions can be determined by Eq.32, and the results were also presented in Table 8.

Table 8: The closeness degrees of the four desalination processes to the ideal solutions

	MSF	LT-MED	RO	VCD
Distance to the ideal best solutions	0.1931	0.1209	0.2519	0.1977
Distance to the ideal worst solutions	0.2460	0.2684	0.1762	0.2303
CD_i	0.5602	0.6894	0.4116	0.5381
Ranking	2	1	4	3

The sustainability ranking of the four alternative desalination process from the best to the worst is low temperature multi-effect distillation (LT-MED), multi-stage flash system (MSF), compression distillation (VCD) and reverse osmosis (RO) in the descending order.

4. Discussion

The application of interval AHP and TOPSIS for sustainability prioritization of alternative desalination processes can effectively use all the information including crisp numbers, interval numbers and triangular fuzzy numbers without any approximations or ay loss of useful information. In order to compare the differences of the results determined by the proposed method which can effectively use all the information in this study with that determined by the MCDA methods using approximations to deal with the interval and fuzzy numbers, the weighted sum method was also employed to determine the sustainability ranking of the four alternative desalination processes. This method consistent of two main steps based on the normalized decision-making matrix presented in Eq.17.

Step 1: Transform each interval number into its midpoint and defuzzy the triangular fuzzy number into crisp numbers. After step 1, the normalized decision-making matrix with hybrid information can be transformed into the decision-making matrix with crisp numbers (as presented in Eq.45).

$$CD = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_M \end{array} \begin{array}{ccccccccc} C_1 & \cdots & C_K & C_{K+1} & \cdots & C_{K+L} & C_{K+L+1} & \cdots & C_{K+L+T} \\ Cx_{11} & \cdots & Cx_{1K} & Cy_{1(K+1)} & \cdots & Cy_{1(K+L)} & Cz_{1(K+L+1)} & \cdots & Cz_{1(K+L+T)} \\ Cx_{21} & \cdots & Cx_{2K} & Cy_{2(K+1)} & \cdots & Cy_{2(K+L)} & Cz_{2(K+L+1)} & \cdots & Cz_{2(K+L+T)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ Cx_{M1} & \cdots & Cx_{MK} & Cy_{M(K+1)} & \cdots & Cy_{M(K+L)} & Cz_{M(K+L+1)} & \cdots & Cz_{M(K+L+T)} \end{array}$$
(45)

where $CD = \left\{CD_{ij}\right\}_{M(K+L+T)}$ represents the normalized crisp-number based decision-making matrix. $Cx_{ij}\left(j = 1, 2, \cdots, K\right)$, $Cy_{ij}\left(j = K+1, K+2, \cdots, K+L\right)$ and $Cz_{ij}\left(j = K+L+1, K+L+2, \cdots, K+L+T\right)$ which represent the normalized data of the *i*-th desalination technology with respect to the *j*-th criterion are all crisp numbers.

Step 2: Determine the integrated sustainability performance (ISP) of each alternative. The integrated sustainability performance of the *i*-th alternative can be determined by Eq.46.

$$ISP_i = \sum_{j=1}^{K+L+T} \omega_j CD_{ij} \quad (46)$$

where ISP_i represents the integrated sustainability performance of the *i*-th alternative.

The results determined by the weighted sum method were presented in Table 9. It is apparent that the results determined by TOPSIS under hybrid information are the same with that determined by the weighted sum method. To some extent, it reveals that the proposed method is feasible for prioritizing the alternative desalination processes under hybrid information. However, the TOPSIS under hybrid information does not need to transfer the interval numbers or fuzzy numbers into crisp numbers, and there is not any loss in information.

Table 9: The integrated sustainability performance of the four alternatives

	MSF	LT-MED	RO	VCD
ISP	0.5200	0.7260	0.4326	0.5186
Ranking bye the weighted sum method	2	1	4	3
Ranking by the TOPSIS under hybrid information	2	1	4	3

In order to investigate how the weights of the evaluation criteria on the final sustainability ranking of the four desalination processes, a comprehensive sensitivity analysis was carried out by setting different weights to the ten evaluation criteria, and the following cases were studied:

(1) All the ten evaluation criteria play an important role: an equal weight (0.1000) was assigned to each of the ten criteria;

(2) One criterion was recognized as the most important, the so-called “dominant criterion”, by assigning 0.3700 to this criterion, and the other criteria were assigned an equal weight (0.0700).

The following eleven cases (as summarized in Table 10) were studied.

Table 10: The eleven cases in the sensitivity analysis

	EC_1	EC_2	EN_1	EN_2	T_1	T_2	T_3	T_4	S_1	S_2
Case 1	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000
Case 2	0.3700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700
Case 3	0.0700	0.3700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700
Case 4	0.0700	0.0700	0.3700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700
Case 5	0.0700	0.0700	0.0700	0.3700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700
Case 6	0.0700	0.0700	0.0700	0.0700	0.3700	0.0700	0.0700	0.0700	0.0700	0.0700
Case 7	0.0700	0.0700	0.0700	0.0700	0.0700	0.3700	0.0700	0.0700	0.0700	0.0700
Case 8	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.3700	0.0700	0.0700	0.0700
Case 9	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.3700	0.0700	0.0700
Case 10	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.3700	0.0700
Case 11	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.3700

The results of sensitivity analysis were presented in Figure 2. It is apparent that It is apparent that the low temperature multi-effect distillation process was recognized as the most sustainable technology among these four desalination processes, but reverse osmosis (RO) in case 2 and case 10 and multi-stage flash system (MSF) in case 3 were recognized as the most sustainable scenarios. The main reason is that capital cost (EC_1) as the dominant criterion was assigned a relatively greater weight (0.3700) in case 2 and market share (S_1) as the dominant criterion was assigned a relatively greater weight (0.3700) in case 10, and the reverse osmosis technology also performs the best with respect to these two criteria. Similarly, production cost (EC_2) as the dominant criterion was assigned a relatively greater weight (0.3700) in case 3, and the production cost of the multi-stage flash system is the least, thus, it was recognized as the most sustainable in this case. Therefore, the weights of the criteria for sustainability assessment of desalination technologies representing the relative importance in the sustainability prioritization have great effects on the rankings of the four alternative desalination technologies, and this is the reason why the interval AHP was employed to achieve accurate determination of the weights in this study.

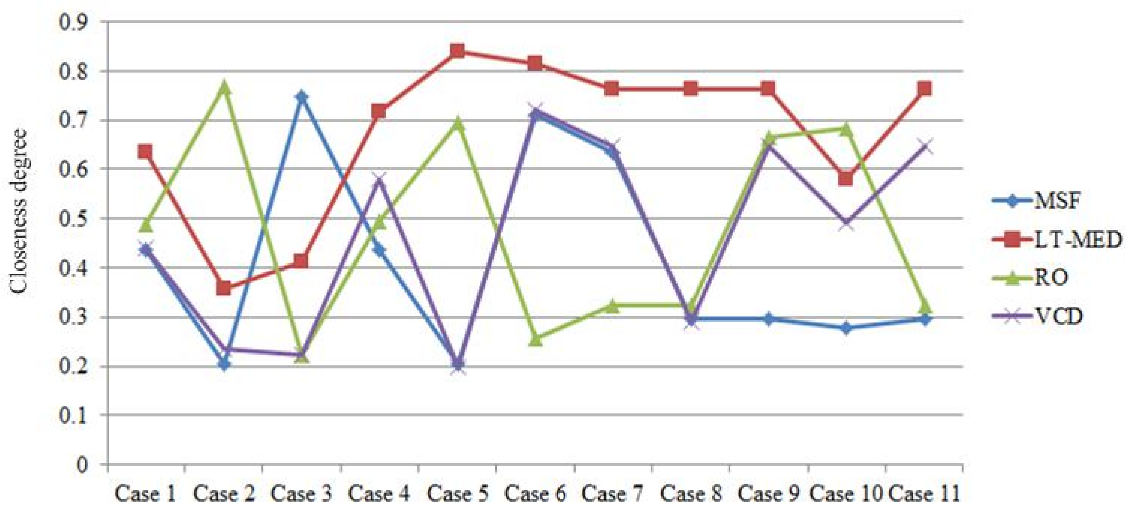

Figure 2: The results of sensitivity analysis

The average closeness degrees of multi-stage flash system (MSF), low temperature multi-effect distillation (LT-MED), reverse osmosis (RO) and compression distillation (VCD) are 0.4128, 0.6734, 0.4774 and 0.4652, respectively. Therefore, the recognition of low temperature multi-effect distillationlow temperature multi-effect distillation as the most sustainable desalination technology is robust.

5. Conclusions

Sustainability prioritization of sustainable desalination processes is beneficial for the users to select the most sustainable desalination process. However, the methods developed in the previous studies for sustainability assessment or sustainability ranking of desalination processes cannot handle with the decision-making matrix with multiple types of data. In other words, these methods cannot consider situation of sustainability ranking under hybrid information. In order to fill this research gap, this study proposed a multi-criteria decision analysis method which can address the decision-making matrix with multiple types of data for sustainability ranking of desalination processes.

The interval AHP method was used to determine the weights of the evaluation criteria based on the interval comparison matrices determined by the users, and interval numbers which can represent the preferences and the vagueness of the users were used to establish the interval comparison matrices. The TOPSIS method under hybrid information was used to determine the sustainability rankings of the alternative desalination processes. The decision-making matrix can be composed by multiple types of data, and this can successfully solve two problems: (i) the uncertainties in the decision-making process can be represented by using the interval numbers; (ii) the data of the alternative desalination processes regarding the soft criteria for sustainability assessment.

Multi-stage flash system (MSF), low temperature multi-effect distillation (LT-MED), reverse osmosis (RO), and vapor compression distillation (VCD) were studied by the proposed method in this study, and LT-MED) was recognized as the most sustainable desalination process, MSF was recognized the secondly most sustainable process, followed by VCD and RO. The weights of the evaluation criteria were changed in the decision-making process for sensitivity analysis, and the results reveal that low temperature multi-effect distillation was recognized as the most sustainable desalination process in most of the cases. The following managerial implications can be obtained for practitioners, decision-makers and stakeholders in China:

(1) From the perspective of practical application: the low temperature multi-effect distillation technology should be selected for industrial application to promote the sustainable development of desalination industry in China;

(2) From the perspective of personal selection: different practitioners, decision-makers and stakeholders having different interests, preferences and willingness may select different technologies as the most sustainable solution, and the integrated consideration of the preferences of different stakeholders is prerequisite for accurate decision-making; and

(3) From the perspective of future planning: the desalination process with the best economic performance may not be the most sustainable if consider the economic, environmental, social and technological pillars simultaneously.

Besides the application on sustainable desalination process selection, it can also be popularized for sustainability ranking of some other industrial systems under hybrid information.

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Appendix

Appendix A Preliminary

Definition 1 Assume that x_1 and x_2 are two real numbers with $x_1 \le x_2$ and $x_1, x_2 \in R$, then, the closed interval $x^{\pm} = [x_1 \quad x_2]$ is called an interval number. x_1 represents the lower bound of the interval number $x^{\pm}$, and x_2 is the upper bound of the interval number (Sengupta and Pal, 2000; Sengupta *et al.*, 2001).

Definition 2 Assume that $x^{\pm} = [x_1 \quad x_2]$ and $y^{\pm} = [y_1 \quad y_2]$ are two interval numbers with $0 < x_1 \le x_2$ and $0 < y_1 \le y_2$.

The arithmetic operations between $x^{\pm} = [x_1 \quad x_2]$ and $y^{\pm} = [y_1 \quad y_2]$ were presented as follows:

Addition (Sengupta and Pal, 2000; Sengupta *et al.*, 2001; Chang *et al.*, 2004)

$$x^{\pm} + y^{\pm} = [x_1 \quad x_2] + [y_1 \quad y_2] = [x_1 + y_1 \quad x_2 + y_2] \tag{A1}$$

Subtraction (Sengupta and Pal, 2000; Sengupta *et al.*, 2001; Chang et al., 2004)

$$x^{\pm} - y^{\pm} = [x_1 \quad x_2] - [y_1 \quad y_2] = [x_1 - y_2 \quad x_2 - y_1] \tag{A2}$$

Multiplication (Hafezalkotob *et al.*, 2016)

$$x^{\pm} \times y^{\pm} = [x_1 \quad x_2] \times [y_1 \quad y_2] = [x_1 y_1 \quad x_2 y_2] \tag{A3}$$

$$\lambda x^{\pm} = \lambda [x_1 \quad x_2] = [\lambda x_1 \quad \lambda x_2] \tag{A4}$$

where λ represents an arbitrary positive number

Division (Hafezalkotob *et al*., 2016)

$$x^{\pm} \div y^{\pm} = [x_1 \quad x_2] \div [y_1 \quad y_2] = [x_1 / y_2 \quad x_2 / y_1] \tag{A5}$$

Definition 3 Width, radius and midpoint (Sengupta and Pal, 2000; Sengupta *et al*., 2001) .

Assume that $x^{\pm} = [x_1 \quad x_2]$ is an interval number. Then,

(1) The width $x^{\pm} = [x_1 \quad x_2]$ is defined as $x_2 - x_1$;

(2) The radius is defined as half of the width, namely $\frac{x_2 - x_1}{2}$; and

(3) The midpoint of the interval number is defined as $\frac{x_1 + x_2}{2}$.

Definition 4 Interval comparison matrix (Xu and Yang, 1998)

$A^{\pm} = \{a_{ij}^{\pm}\}_{n \times n}$ with $a_{ij}^{\pm} = [a_{ij}^{-} \quad a_{ij}^{+}]$ can be recognized as the interval comparison matrix if it can satisfy the following three rules:

(1) $a_{ij}^{\pm} = 1$ when $i = j$, and $i = 1, 2, \cdots, n$;

(2) $\forall i, j, a_{ij}^{\pm}$ is an interval number and $\frac{1}{9} \leq a_{ij}^{-} \leq a_{ij}^{+} \leq 9$; and

(3) $a_{ij}^{\pm} = \frac{1}{a_{ji}^{\pm}}$.

Definition 5 Triangular fuzzy number (Chang, 1996)

$a' = \left(a^l, a^m, a^u\right)$ can be used to represent the triangular fuzzy number a', and the corresponding membership function was described in Eq.(A6).

$$\mu_{a'}(x) = \begin{cases} 0 & x \le a^l \\ \dfrac{x - a^l}{a^m - a^l} & a^l < x \le a^m \\ \dfrac{x - a^u}{a^m - a^u} & a^m < x \le a^u \\ 0 & x \ge a^u \end{cases} \tag{A6}$$

where $x \in R$, $0 < a^l \le a^m \le a^u$.

Eq.A7 can be used to transform the triangular fuzzy number $a' = \left(a^l, a^m, a^u\right)$ into the traditional crisp number.

$$De(a') = \frac{a^l + 2a^m + a^u}{4} \tag{A7}$$

Definition 6 Assume that $a' = \left(a^l, a^m, a^u\right)$ and $b' = \left(b^l, b^m, b^u\right)$ are two fuzzy numbers, the arithmetic operations between these two fuzzy number were presented as follows:

Addition (Chang, 1996)

$$a' + b' = \left(a^l, a^m, a^u\right) + \left(b^l, b^m, b^u\right) = \left(a^l + b^l, a^m + b^m, a^u + b^u\right) \tag{A8}$$

Subtraction (Tsaur *et al*., 2002; Cheng and Lin, 2002)

$$a' - b' = \left(a^l, a^m, a^u\right) - \left(b^l, b^m, b^u\right) = \left(a^l - b^l, a^m - b^m, a^u - b^u\right) \tag{A9}$$

Multiplication (Chang, 1996; Van Laarhoven and Pedrycz, 1983)

$$a' \times b' = \left(a^l, a^m, a^u\right) \times \left(b^l, b^m, b^u\right) = \left(a^l b^l, a^m b^m, a^u b^u\right) \tag{A10}$$

$$\lambda a' = \lambda\left(a^l, a^m, a^u\right) = \left(\lambda a^l, \lambda a^m, \lambda a^u\right) \tag{A11}$$

where $\lambda > 0$, $\lambda \in R$

Division (Cheng and Lin, 2002)

$$a' / b' = \left(a^l, a^m, a^u\right) / \left(b^l, b^m, b^u\right) = \left(a^l / b^u, a^m / b^m, a^u / b^l\right) \tag{A12}$$

Reciprocal (Chang, 1996)

$$\left(a'\right)^{-1} = \left(a^l, a^m, a^u\right)^{-1} = \left(\frac{1}{a^u}, \frac{1}{a^m}, \frac{1}{a^l}\right) \tag{A13}$$

Definition 7 Distance

The distance between two real numbers x and y can be determined by Eq. 14.

$$d(x, y) = \left|x - y\right| \tag{A14}$$

where $d(x, y)$ represents the distance between x and y.

The distance between two interval numbers $x^{\pm} = \left[x_1 \quad x_2\right]$ and $y^{\pm} = \left[y_1 \quad y_2\right]$ can be determined by Eq.15 (Zhang, 2014).

$$d\left(x^{\pm}, y^{\pm}\right) = \sqrt{\frac{\left(x_1 - y_1\right)^2 + \left(x_2 - y_2\right)^2}{2}} \tag{A15}$$

The distance between two fuzzy numbers $a' = \left(a^l, a^m, a^u\right)$ and $b' = \left(b^l, b^m, b^u\right)$ can be determined by Eq.A16 (Awasthi *et al*., 2011; Chen, 2000).

$$d\left(a', b'\right) = \sqrt{\frac{\left(a^l - b^l\right)^2 + \left(a^m - b^m\right)^2 + \left(a^u - b^u\right)^2}{3}} \qquad \text{(A16)}$$

Appendix B The tables in the results

Table B1: The local weights of the criteria in each of the four dimensions

	EC_1	EC_2		EN_1	EN_2
Capital cost (EC_1)	1	[1 2]	Water utilization efficiency (EN_1)	1	[1/3 1]
Production cost (EC_2)	[1/2 1]	1	Energy Consumption (EN_1)	[1 3]	1
Weights	[0.5147 0.6863]	[0.3431 0.5147]	Weights	[0.2679 0.5359]	[0.5359 0.8038]
	T_1	T_2	T_3	T_4	
Water purity (T_1)	1	[2 3]	[3 5]	[4 6]	
Technology maturity (T_2)	[1/3 1/2]	1	[1 3]	[2 3]	
Technology reliability (T_3)	[1/5 1/3]	[1/3 1]	1	[1 2]	
Flexibility (T_4)	[1/6 1/4]	[1/3 1/2]	[1/2 1]	1	
Weights	[0.5196 0.5397]	[0.2068 0.2821]	[0.0934 0.2096]	[0.0550 0.1524]	

Table B2: The global weights of the ten criteria

		Local interval weights of the criteria	Global interval weights of the criteria	Global crisp weights of the criteria
Economic [0.2116 0.2727]	Capital cost	[0.5147 0.6863]	[0.1089 0.1872]	0.1357
	Production cost	[0.3431 0.5147]	[0.0726 0.1404]	0.0976
Environmental [0.1384 0.2453]	Water utilization efficiency	[0.2679 0.5359]	[0.0371 0.1315]	0.0772
	Energy Consumption	[0.5359 0.8038]	[0.0742 0.1972]	0.1243
Technological [0.5297 0.5554]	Water purity	[0.5196 0.5397]	[0.2752 0.2997]	0.2634
	Technology maturity	[0.2068 0.2821]	[0.1095 0.1567]	0.1220
	Technology reliability	[0.0934 0.2096]	[0.0495 0.1164]	0.0760
	Flexibility	[0.0550 0.1524]	[0.0291 0.0846]	0.0521
Social [0.0102 0.1026]	Market share	0.5000	[0.0051 0.0513]	0.0258
	Skills requirement	0.5000	[0.0051 0.0513]	0.0258

Table B3: The normalized data for ranking the four desalination processes

			MSF	LT-MED	RO	VCD
Economic (EC)	Capital cost (EC_1)	0.1357	0.0000	0.2500	1.0000	0.1250
	Production cost (EC_2)	0.0976	1.0000	0.3361	0.0000	0.0960
Environmental (EN)	Water utilization efficiency (EN_1)	0.0772	[0.3000 0.6250]	[0.3750 1.0000]	[0 1.0000]	[0.3750 1.0000]
	Energy Consumption (EN_2)	0.1243	[0 0]	[1 1]	[0.6667 1]	[0 0]
Technological (T)	Water purity (T_1)	0.2634	[0.9899 1]	[0.9899 1]	[0 0.4040]	[0.9899 1]
	Technology maturity (T_2)	0.1220	(0.5, 0.75,1.0)	(0.5, 0.75,1.0)	(0, 0.125,0.50)	(0.5, 0.75,1.0)
	Technology reliability (T_3)	0.0760	(0, 0.125,0.50)	(0.5, 0.75,1.0)	(0, 0.125,0.50)	(0, 0.125,0.50)
	Flexibility (T_4)	0.0521	(0, 0.125,0.50)	(0.5, 0.75,1.0)	(0.5, 0.75,1.0)	(0.5, 0.75,1.0))
Social (S)	Market share (S_1)	0.0258	(0,0.1667,0.3333)	(0.3333,0.50,0.6667)	(0.5, 0.8333,1.0)	(0.3333,0.50,0.6667)
	Skills requirement (S_2)	0.0258	(0, 0.125,0.50)	(0.5, 0.75,1.0)	(0, 0.125,0.50)	(0.5, 0.75,1.0)

Table B4: The weighted normalized multi-type data for ranking the four desalination processes

		MSF	LT-MED	RO	VCD	Best ideal solutions	Worst ideal solutions
	Capital cost (EC_1)	0	0.0339	0.1357	0.0170	0.1357	0
Economic (EC)	Production cost (EC_2)	0.0976	0.0328	0	0.0094	0.0976	0
Environmental (EN)	Water utilization efficiency (EN_1)	[0.0232 0.0483]	[0.0290 0.0772]	[0 0.0772]	[0.0290 0.0772]	[0.0290 0.0772]	[0 0.0483]
	Energy Consumption (EN_2)	[0 0]	[0.1243 0.1243]	[0.0829 0.1243]	[0 0]	[0.1243 0.1243]	[0 0]
Technological (T)	Water purity (T_1)	[0.2607 0.2634]	[0.2607 0.2634]	[0 0.1064]	[0.2607 0.2634]	[0.2607 0.2634]	[0 0.1064]
	Technology maturity (T_2)	(0.0610, 0.0915,0.1220)	(0.0610, 0.0915,0.1220)	(0, 0.0153,0.0610)	(0.0610, 0.0915,0.12	(0.0610, 0.0915,0.1	(0, 0.0153,

					20)	220)	0.0610)
	Technology reliability (T_3)	(0, 0.0095,0.0380)	(0.0380, 0.0570,0.0760)	(0, 0.0095,0.0380)	(0, 0.0095,0.0380)	(0.0380, 0.0570,0.0760)	(0, 0.0095, 0.0380)
	Flexibility (T_4)	(0, 0.0065,0.0261)	(0.0261, 0.0391,0.0521)	(0.0261, 0.0391,0.0521)	(0.0261, 0.0391,0.0521)	(0.0261, 0.0391,0.0521)	(0, 0.0065, 0.0261)
Social (S)	Market share (S_1)	(0, 0.0043, 0.0086)	(0.0086, 0.0129,0.0172)	(0.0129, 0.0215,0.0258)	(0.0086,0.0129,0.0172)	(0.0129, 0.0215,0.0258)	(0, 0.0043, 0.0086)
	Skills requirement (S_2)	(0, 0.0032,0.0129)	(0.0129, 0.0193,0.0258)	(0, 0.0032,0.0129)	(0.0129, 0.0193,0.0258)	(0.0129, 0.0193,0.0258)	(0, 0.0032, 0.0129)

References

Afify, A. (2010). Prioritizing desalination strategies using multi-criteria decision analysis. Desalination, 250(3), 928-935.

Alhazmy, M. M. (2011). Multi stage flash desalination plant with brine–feed mixing and cooling. Energy, 36(8), 5225-5232.

An, D., Xi, B., Ren, J., Ren, X., Zhang, W., Wang, Y., Dong, L. (2018). Multi-criteria sustainability assessment of urban sludge treatment technologies: Method and case study. Resources, Conservation and Recycling, 128, 546-554.

Arce, M. E., Saavedra, Á., Míguez, J. L., Granada, E. (2015). The use of grey-based methods in multi-criteria decision analysis for the evaluation of sustainable energy systems: A review. Renewable and Sustainable Energy Reviews, 47, 924-932.

Awasthi, A., Chauhan, S. S., Goyal, S. K. (2011). A multi-criteria decision making approach for location planning for urban distribution centers under uncertainty. Mathematical and Computer Modelling, 53(1-2), 98-109.

Chang, D. Y. (1996). Applications of the extent analysis method on fuzzy AHP. European journal of operational research, 95(3), 649-655.

Chang, H. C., Yao, J. S., Ouyang, L. Y. (2004). Fuzzy mixture inventory model with variable lead-time based on probabilistic fuzzy set and triangular fuzzy number. Mathematical and Computer Modelling, 39(2-3), 287-304.

Chen, C. T. (2000). Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy sets and systems, 114(1), 1-9.

Cheng, C. H., Lin, Y. (2002). Evaluating the best main battle tank using fuzzy decision theory with linguistic criteria evaluation. European journal of operational research, 142(1), 174-186.

Dweiri, F., Khan, S. A., Almulla, A. (2018). A multi-criteria decision support system to rank sustainable desalination plant location criteria. Desalination, 444, 26-34.

El-Dessouky, H. T., Ettouney, H. M., Al-Roumi, Y. (1999). Multi-stage flash desalination: present and future outlook. Chemical Engineering Journal, 73(2), 173-190.

El-Ghonemy, A. M. K. (2017). Performance test of a sea water multi-stage flash distillation plant: Case study. Alexandria Engineering Journal. (in press).

Eltawil, M. A., Zhengming, Z., Yuan, L. (2009). A review of renewable energy technologies integrated with desalination systems. Renewable and sustainable energy reviews, 13(9), 2245-2262.

Fei, L., Deng, Y., Hu, Y. (2018). DS-VIKOR: A new multi-criteria decision-making method for supplier selection. International Journal of Fuzzy Systems, 1-19.

Georgiou, D., Mohammed, E. S., Rozakis, S. (2015). Multi-criteria decision making on the energy supply configuration of autonomous desalination units. Renewable Energy, 75, 459-467.

Ghaffour, N., Missimer, T. M., Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. Desalination, 309, 197-207.

Ghassemi, S. A., Danesh, S. (2013). A hybrid fuzzy multi-criteria decision making approach for desalination process selection. Desalination, 313, 44-50.

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., Moulin, P. (2009). Reverse osmosis desalination: water sources, technology, and today's challenges. Water research, 43(9), 2317-2348.

Hafezalkotob, A., Hafezalkotob, A., Sayadi, M. K. (2016). Extension of MULTIMOORA method with interval numbers: an application in materials selection. Applied Mathematical Modelling, 40(2), 1372-1386.

Hajeeh, M. A. (2010). Water desalination plants performance using fuzzy multi-criteria decision making. WSEAS Transactions on Systems, 9(4), 422-431.

Heck, N., Paytan, A., Potts, D. C., Haddad, B., Petersen, K. L. (2017). Management priorities for seawater desalination plants in a marine protected area: A multi-criteria analysis. Marine Policy, 86, 64-71.

Ibrahim, Y., Arafat, H. A., Mezher, T., AlMarzooqi, F. (2018). An integrated framework for sustainability assessment of seawater desalination. Desalination, 447, 1-17.

Kellner, F., Lienland, B., Utz, S. (2019). An a posteriori decision support methodology for solving the multi-criteria supplier selection problem. European Journal of Operational Research, 272(2), 505-522.

Li. X., 2010. Techno-economic analysis and comparison of the primary seawater desalination technologies. Cfhi Technology, 2, 64-70. (in Chinese). DOI: 10.3969/j.issn.1673-3355.2010.02.019

Lior, N. (2017). Sustainability as the quantitative norm for water desalination impacts. Desalination, 401, 99-111.

Lior, N., Kim, D. (2018). Quantitative sustainability analysis of water desalination–A didactic example for reverse osmosis. Desalination, 431, 157-170.

Mousavi-Nasab, S. H., Sotoudeh-Anvari, A. (2018). A new multi-criteria decision making approach for sustainable material selection problem: A critical study on rank reversal problem. Journal of cleaner production, 182, 466-484.

Özcan, T., Çelebi, N., Esnaf, Ş. (2011). Comparative analysis of multi-criteria decision making methodologies and implementation of a warehouse location selection problem. Expert Systems with Applications, 38(8), 9773-9779.

Purvis, B., Mao, Y., Robinson, D. (2018). Three pillars of sustainability: in search of conceptual origins. Sustainability Science, 1-15.

Qi, C. H., Feng, H. J., Lv, Q. C., Xing, Y. L., Li, N. (2014). Performance study of a pilot-scale low-temperature multi-effect desalination plant. Applied Energy, 135, 415-422.

Ren, J., Xu, D., Cao, H., Wei, S. A., Dong, L., Goodsite, M. E. (2016). Sustainability decision support framework for industrial system prioritization. AIChE Journal, 62(1), 108-130.

Ren, J. (2018a). Technology selection for ballast water treatment by multi-stakeholders: A multi-attribute decision analysis approach based on the combined weights and extension theory. Chemosphere, 191, 747-760.

Ren, J. (2018b). Multi-criteria decision making for the prioritization of energy systems under uncertainties after life cycle sustainability assessment. Sustainable Production and Consumption, 16, 45-57.

Ren, J., Toniolo, S. (2018). Life cycle sustainability decision-support framework for ranking of hydrogen production pathways under uncertainties: An interval multi-criteria decision making approach. Journal of Cleaner Production, 175, 222-236.

Rújula, A. A. B., Dia, N. K. (2010). Application of a multi-criteria analysis for the selection of the most suitable energy source and water desalination system in Mauritania. Energy Policy, 38(1), 99-115.

Saaty, T.L., 1980. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation McGraw-Hill, New York (1980).

Sengupta, A., Pal, T. K. (2000). On comparing interval numbers. European Journal of Operational Research, 127(1), 28-43.

Sengupta, A., Pal, T. K., Chakraborty, D. (2001). Interpretation of inequality constraints involving interval coefficients and a solution to interval linear programming. Fuzzy Sets and systems, 119(1), 129-138.

Subramani, A., Jacangelo, J. G. (2015). Emerging desalination technologies for water treatment: a critical review. Water research, 75, 164-187.

Tsaur, S. H., Chang, T. Y., Yen, C. H. (2002). The evaluation of airline service quality by fuzzy MCDM. Tourism management, 23(2), 107-115.

Van Laarhoven, P. J., Pedrycz, W. (1983). A fuzzy extension of Saaty's priority theory. Fuzzy sets and Systems, 11(1-3), 229-241.

Vivekh, P., Sudhakar, M., Srinivas, M., Vishwanthkumar, V. (2016). Desalination technology selection using multi-criteria evaluation: TOPSIS and PROMETHEE-2. International Journal of Low-Carbon Technologies, 12(1), 24-35.

Wang, J. J., Jing, Y. Y., Zhang, C. F., Zhao, J. H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and Sustainable Energy Reviews, 13(9), 2263-2278.

Xia, Y., Wu, Q., 2004. A technique of order preference by similarity to ideal solution for hybrid multiple attribute decision making problem. Journal of Systems Engineering, 19(6), 630-634. (in Chinese).

Xu, X., Yang, Y., 1998. The consistency approximation and weight calculation method of the judgment matrix in the uncertain type of AHP. System Engineering Theory and Practice, 2, 19-22. (in Chinese).

Xu, D., Lv, L., Dong, L., Ren, J., He, C., Manzardo, A. (2018). Sustainability assessment framework for chemical processes selection under uncertainties: a vector-based algorithm coupled with multicriteria decision-making approaches. Industrial & Engineering Chemistry Research, 57(23), 7999-8010.

Yang, K., Zhu, N., Chang, C., Wang, D., Yang, S., Ma, S. (2018). A methodological concept for phase change material selection based on multi-criteria decision making (MCDM): A case study. Energy, 165, 1085-1096.

Zhang, Z., 2014. Multiple attribute decision-making for hybrid information. Computer & Digital Engineering, 42(12), 2433-2438. (in Chinese).

Zhang, F., Xu, S., Feng, D., Chen, S., Du, R., Su, C., Shen, B. (2017). A low-temperature multi-effect desalination system powered by the cooling water of a diesel engine. Desalination, 404, 112-120.

Zhou, C., Li, Y., 2008. Analysis an comparison between current major technologies of seawater desalination. Power station auxiliary equipment, 4, 1-5. (in Chinese).