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Highlights

• A survey of the BWM based on the publications from 2015 to January 2019 is provided. • This paper intends to answer five questions about the BWM. • This paper has guiding significance for the later research related to the BWM.

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The state-of-the-art survey on integrations and applications of the best worst method in decision making: Why, what, what for and what's next?☆

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ABSTRACT

After the first paper regarding the Best Worst Method (BWM) was published in *Omega* in 2015 (*J. Rezaei, Best-worst multi-criteria decision-making method, Omega 53 (2015) 49–57*), it has attracted many scholars' attention due to the efficiency of this method in reducing the times of pairwise comparisons and the good performance in maintaining consistency between judgments. Lots of researches related to this method have been published over the past several years. This paper concentrates on the state-of-the-art survey of the BWM based on the in-depth analysis over the publications concerning this method published from 2015 to 26th, January 2019. This paper intends to answer five questions about the BWM: (1) How does this method perform in bibliometric analysis? (2) Why to propose this method and what is it? (3) Which integrations that the BWM were focused on and which areas did they apply to? (4) What extensions of this method were investigated? (5) What are the challenges and future research directions regarding this method? In view of the fact that the research on this method is still in infancy, this paper has guiding significance for the later research related to the BWM. From the theoretical point of view, the reasonable value of consistency ratio, the inconsistency improving methods, the uncertain extensions of the BWM and the techniques for solving multi-optimality model in the BWM are good research issues that need to be further investigated in the future. From the perspective of application, the software packages for this method, the various integrations of this method, the wider application areas, and the international cooperation on this method are good topics to consider.

1. Introduction

There is no denying that, as a vital and popular research branch of decision-making theory, Multiple Criteria Decision Making (MCDM) has wined great success. The MCDM can be divided into two categories: continuous MCDM, also called as Multiple Objective Decision Making (MODM), and discrete MCDM, also named as Multiple Attribute Decision Making (MADM). The major distinction between MODM and MADM is the number of alternatives under evaluation [1]. In MODM problems, the number of alternatives is not predetermined and the alternatives are restricted by a set of optimal objective constraints; while in MADM problems, the number of alternatives is predetermined and limited. The relationships among MCDM, MODM and MADM within the context of decision-making theory can be illustrated in Fig. 1. In the following, we use the item "MCDM" to represent "discrete MCDM (MADM)" because many scholars take these terms as interchangeable [1].

The MCDM methods help Decision-Makers (DMs) do rational decisions [2]. Basically, there are two categories of MCDM techniques involving either quantitative or qualitative criteria (for a collection of state-of-the-art surveys, please refer to Refs. [3,4]):

(1) Multi-attribute utility and value theories. This kind of methods need to construct decision matrix over alternatives. After experts give evaluations of alternatives over criteria, the rating of each alternative can be obtained by some aggregation functions to combine the scores of the alternative on all criteria with the weights of criteria. The typical techniques of this categories include TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [5], UTA (UTilites Additives) [6], VIKOR (VIse Kriterijumska Optimizacija kompromisno Resenje in Serbian, multiple criteria optimization compromise solution) [7,8], MULTIMOORA (MULTIplicative Multi-Objective Optimization by Ratio Analysis) [9,10], and

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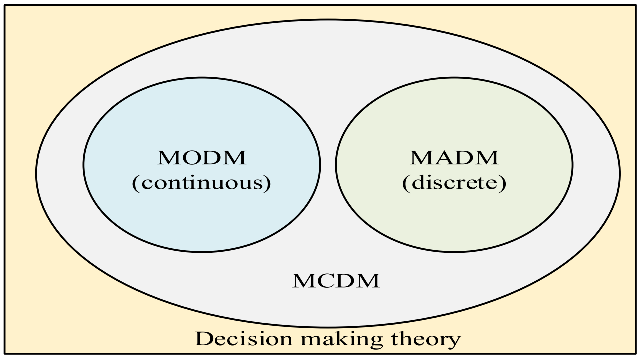

Fig. 1. Relationships among MCDM, MODM and MADM.

MACBETH (Measuring Attractiveness by a Categorical Based Evaluation TecHnique) [11].

(2) Outranking methods. Outranking methods are based on pairwise comparisons among alternatives with respect to each criterion. The outranking relations, which represent the dominance degree of one alternative over others, are acquired by aggregating the pairwise comparisons. The widely-used outranking methods are ELECTRE (ELimination Et Choix Traduisant la REalité in French, ELimination and Choice Expressing the Reality) [12], PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) [13], and GLDS (Gained and Lost Dominance Score) method [14,15].

Although there are two categories of MCDM methods, generally, the steps of the MCDM methods are often resemble, including problem definition, criteria determination, decision matrix construction, criteria weight determination and ranking derivation. It is natural that the selection of suitable MCDM methods is based on the structure of problems. After defining the problem and determining the criteria, establishing a decision matrix and determining criteria weights are significant for any MCDM techniques. Suppose that a MCDM problem consists of a finite set of m feasible alternatives $\{A_1, A_2, \cdots, A_m\}$, whose scores are given with respect to a set of criteria $\{C_1, C_2, \cdots, C_n\}$ and are denoted as s_{ij} for the ith alternative over the jth criterion (i=1, 2, ⋯ , m, j=1, 2, ⋯ , n). Then, a decision matrix D can be obtained as:

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ s_{m1} & s_{m2} & \cdots & s_{mn} \end{pmatrix} \end{array} \quad (1)$$

Based on D, the ranking of alternatives can be derived by the MCDM methods. Thus, how to establish a decision matrix is very important, and the decision matrix would determine the degree of reasonability of the final result. A straightforward way to construct a decision matrix is the pairwise comparison method that was originally proposed by Thurstone [16]. It is especially useful when the scores of alternatives or stimulus on each criterion are not easy to obtain.

AHP (Analytic Hierarchy Process) [17], as a special kind of utility-based MCDM technique, determines the weights of criteria via pairwise comparisons [16]. It decomposes a complex MCDM problem into a multi-level hierarchic structure of goals, criteria, sub-criteria (if necessary) and alternatives. It provides a fundamental scale of relative magnitudes expressed in dominance units to represent judgments in the form of pairwise comparisons. AHP shows efficiency in the situation that providing the estimated scores for candidate alternatives with respect to criteria is unfeasible or meaningless but expressing the relative preferences of the alternatives and criteria by preference relations is possible [1]. It is observed that different ways has been used to transform pairwise comparisons into the elements of a decision matrix, for example, PROMETHEE [13] providing six types of functions to transform preference degrees into scores. AHP [17] uses the prioritization process to obtain the priorities of alternatives on each criterion and then a decision matrix could be established. However, it is impossible to neglect the inconsistency in pairwise comparison matrix since inconsistency usually happens in practice [18]. The inconsistency of the pairwise comparison matrix is the salient drawback of AHP, which may lead to wrong or misleading results. In addition, if there are a large number of criteria or alternatives, the numerous workloads of pairwise comparisons would increase the complexity of solving MCDM problems and also lead to the decrease of consistency for pairwise comparisons. For instance, if there are 6 criteria and 6 alternatives in a MCDM problem, 105 times of pairwise comparisons need to be done by experts. Although AHP is one of the most popular MCDM methods, the high challenge in doing pairwise comparisons and the lack of consistency result in criticisms [1,18].

Rezaei [1] pointed out that these numerous workload and complexity of experts are not necessary, and the reason for this limitation is resulted from the unstructured way of doing pairwise comparisons. To fill this gap, Rezaei [1] proposed a new technique, named the Best Worst Method (BWM), to do pairwise comparisons in a structured way. Since the BWM appears, it has attracted many scholars' attention and lots of researches regarding the BWM have been published. The paper published by Rezaei [1] in 2015 has now turned out to be the third most cited article published since 2014 in *Omega*.[1] It is predicted that the research on BWM will keep increasing in the coming future.

This paper concentrates on the state-of-the-art survey of integrations and applications of the BWM in decision making. After making a bibliometric analysis on the BWM-related publications, we select 124 representative publications concerning the BWM published from 2015 to 26th, January 2019 and analyze them in-depth. This paper intends to answer the following questions: (1) how does the BWM perform in bibliometric analysis? (2) why to propose and what is the BWM? (3) which integrations that the BWM were focused on and which areas did they apply to? (4) what extensions of the BWM were investigated? (5) what are the challenges and future research directions regarding the BWM? In view of the fact that the research on the BWM is still in infancy, this article has guiding significance for the later research related to the BWM.

The rest of this paper is organized as follows: Section 2 provides a bird's eye of the BWM based on bibliometric analysis. Section 3 clarifies why to propose the BWM. Then, Section 4 describes what is the BWM. The integrations of the BWM and their applications are addressed in Section 5. Section 6 concentrates on the challenge and future research directions about the BWM. Some conclusions are listed in Section 7.

2. A bird's eye of the BWM based on bibliometric analysis

This section gives a general introduction to the basic information of the BWM related publications and also some bibliometric analysis in terms of co-citation networks of journals, publications and authors, and the co-occurrence network of keywords.

2.1. Data source: publications related to the BWM

Since the first paper about the BWM was proposed by Rezaei [1] in 2015 in *Omega*, we selected all publications related to the

[1] https://www.journals.elsevier.com/omega/most-cited-articles.

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Table 1
The country/region distributions by countries/regions and citations of the 124 publications.

	Country/Region	Number of publications	Citations in Google scholar
1	Iran	32(2)	240
2	China	30(1)	304
3	Netherlands	23(2)	889
4	India	12(3)	207
5	Turkey	5	6
6	Serbia	3(3)	96
7	Indonesia	3	0
8	Bosnia and Herzegovina	2(1)	44
9	Australia	2(1)	15
10	Algeria	2	22
11	Lithuania	1(5)	48
12	UK	1(3)	13
13	Malaysia	1(1)	34
14	Italy	1(1)	2
15	Spain	1(1)	2
16	Libya	1	12
17	Bangladesh	1	5
18	Canada	1	1
19	Lucknow	1	1
20	Chile	1	0
21	USA	0(4)	120
22	France	0(2)	22
23	Ghana	0(2)	50
24	Denmark	0(1)	38
25	Japan	0(1)	12
26	Saudi Arabia	0(1)	2
27	Germany	0(1)	0
	Subtotal	124	1746

Note: In the third column, the first number indicates the number of first author publications; the number in bracket indicates the number of non-first author publications.

BWM in Web of Science (WoS) published from 2015 to 26th, January 2019 and there are 82 publications, including 78 journal papers and 4 conference papers. For a comprehensive study on the BWM, Google scholar is an additional database since it is updated much faster than WoS. Searching "best worst method" in Google scholar, 17 additional SCI (Sciences Citation Index) journal papers, 17 non-SCI journal papers, 5 conference papers, 1 case study, 1 chapter of handbook and 1 series of book series were obtained after removing the aforementioned 82 publications that have been retrieved from WoS. In total, these 124 publications include four types: 112 journal articles, 9 conference papers, 1 case study, 1 chapter of handbook and 1 series of book series. There exists a regular updated BWM bibliographical database,[2] provided by Rezaei. Among these 112 journal publications, 95 publications were indexed by SCI database in WoS (78 of them have been indexed and the other 17 will be indexed soon). That is to say, 84.82% (95/112) journal publications were published in SCI indexed journals. The 112 journal articles are summarized in Table A.1 in Appendix. This table shows that the 112 journals articles were published in 63 journals. It can provide some useful information for researchers to submit their research manuscripts.

These 124 publications were distributed in 27 countries/regions (see Table 1). 28 publications were written in the form of international cooperation: 21 publications were written by authors from two different countries/regions and 7 publications were written by authors from three or more than three different countries/regions. In Table 1, if a country/region's author is not the first author of a publication, then this publication will be counted separately. For instance, Netherlands have 23 first-author publications, i.e., there are 23 publications whose first authors are from Netherlands. The figure "2" in the bracket denotes that there is 2 publication that finished by international collaboration, but the first author was not from Netherlands. In total, Netherlands have 25 publications in these 124 studies. As displayed in Table 1, Netherlands takes the third position in the number of publications (25). 889 citations of Netherlands in Google Scholar accounts for almost half of the sums of all 27 countries'/regions' citations (1746). This is mainly because Rezaei, who proposed the BWM, comes from Netherlands. Iran ranks first because of the largest number of publications. Moreover, authors in China also pay much attention to the BWM, similar numbers of publications as Iran but with more citations.

2.2. Bibliometric analysis on the BWM-related publications in WoS

In the following, we use VOSviewer software package [19] to analyze the publications listed in Table A.1. It is worth to note that WoS database only could search the studies published in SCI indexed journals and the conference papers indexed by IEEE, and the update time of WoS database is at the end time of each month. Then, only 82 publications which contain 78 journal articles and 4 conference papers can be searched in WoS database. 16 SCI journal articles cannot be searched in WoS database because the publication time of these 16 SCI journal articles are just online and are not retrieved in WoS. Based on these 82 BWM-related publications, we use VOSviewer to draw four figures regarding co-citation networks of journals, publications and authors, and the co-occurrence network of keywords.

These are altogether 1676 journals that were cited by these 82 publications. We selected the top 30 journals to illustrate in Fig. 2. In this figure, a node represents a journal. The size of the node denotes the frequency of the journal cited by these 82 publications. The grey lines show the relationships between journals. If two nodes are appeared in the reference list in one paper at the same time, then these two nodes establish a co-citation network. The thickness of the line indicates the co-citation frequency. As is demonstrated in Fig. 2, VOSviewer divides these journals into 4 clusters with different colors of nodes. *Journal of Cleaner Production*

[2] http://bestworstmethod.com/wp-content/uploads/2018/11/BWM-bibliographical-database.pdf.

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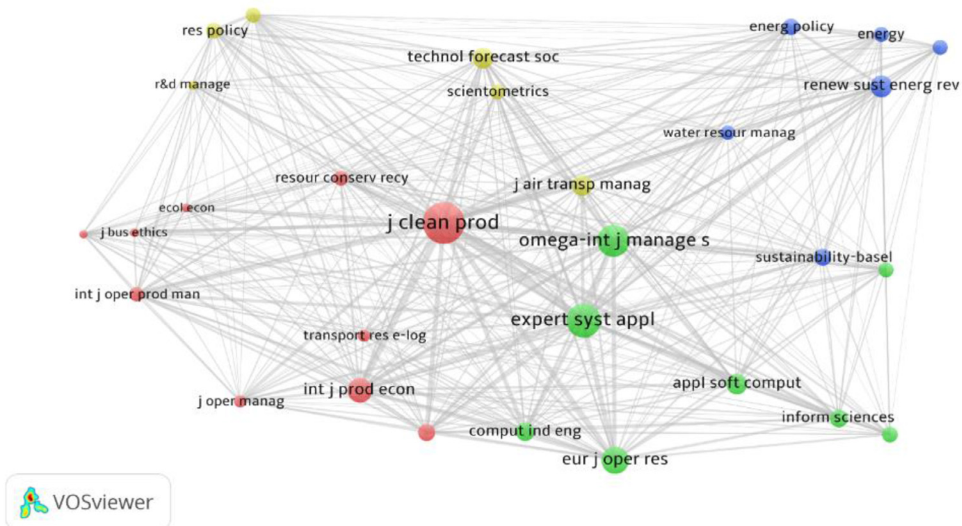

Fig. 2. Journal co-citation network.

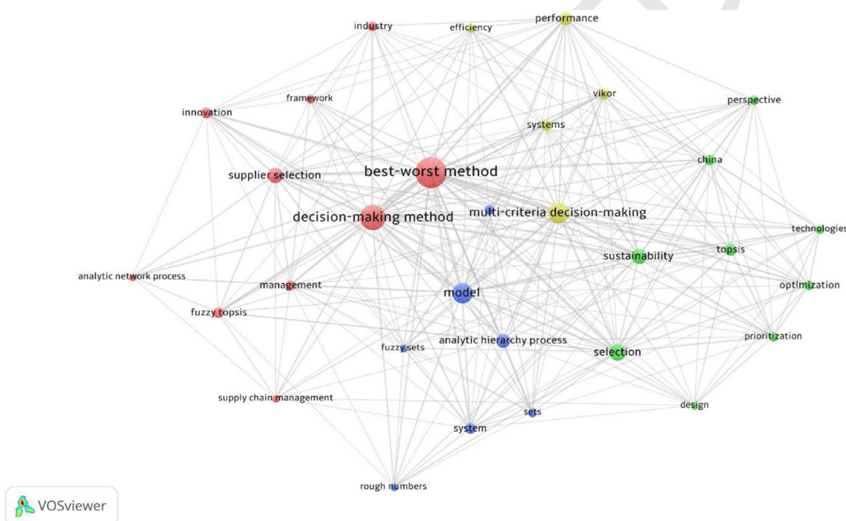

Fig. 3. Keywords co-occurrence network.

is the most popular journal with the maximal number of papers. It is a top influential journal in the field of science & technology, engineering and environmental science. According to the Journal Citation Reports (JCR) in 2017, it ranks 7/50 in the field of engineering and environmental, 21/241 in environmental sciences, 6/33 in green & sustainable, science & technology. Other influential journals contain *Omega*, *Expert Systems with Applications* and *European Journal of Operational Research*. These are very influential journals in their fields, especially in management science and operations research.

Before analyzing the keywords co-occurrence network, we preprocessed the data and merged the words with the same meaning but in different forms before analyzing. For instance, four different keywords such as “best-worst method”, “best worst method”, “best worse method” and “bwm” represent the same meaning, so they were merged into “best-worst method”. In analogous, “multi-criteria decision making”, “multi-criteria decision-making”, “multi-criteria decision- making (MCDM)” were combined as “multi-criteria decision making”; “AHP” and “analytic hierarchy process” were merged into “analytic hierarchy process”; “System” and “systems” were processed as “system”. The top 30 popular keywords of these 82 publications are shown in Fig. 3. From Fig. 3, we can find that the “Best-worst method” is the most popular keyword. “Decision making” and “Multi-criteria decision making” are two popular keywords since BWM is a method to tackle decision-making problems, especially the multi-criteria decision-making problems. China is the only country whose name appears in keywords co-occurrence network. This may imply its leading position in the research direction of BWM.

The reference co-citation network shown as Fig. 4 illustrates the most highly cited papers among these BWM-related publications. In Fig. 4, a node represents a reference. The line is established when two documents appeared in the reference list of a BWM publication at the same time. The thickness of the line is proportional to the co-citation frequency. The first three popular publications were all written by Rezaei, the father of BWM. In Google Scholar, Ref. [1] has received 284 citations till 26th, January 2019. BWM was later implemented in Ref. [20] and Ref. [20] has been cited 129 times. The first application of BWM was shown in Ref. [21] and Ref. [21] has been cited 112 times. These three papers play a vital role in the development of BWM. In the future, these

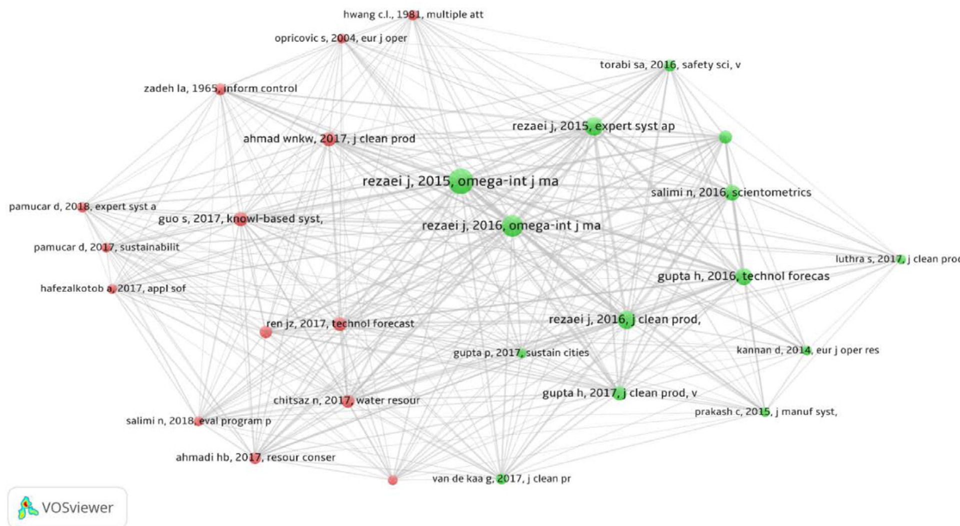

Fig. 4. Reference co-citation network.

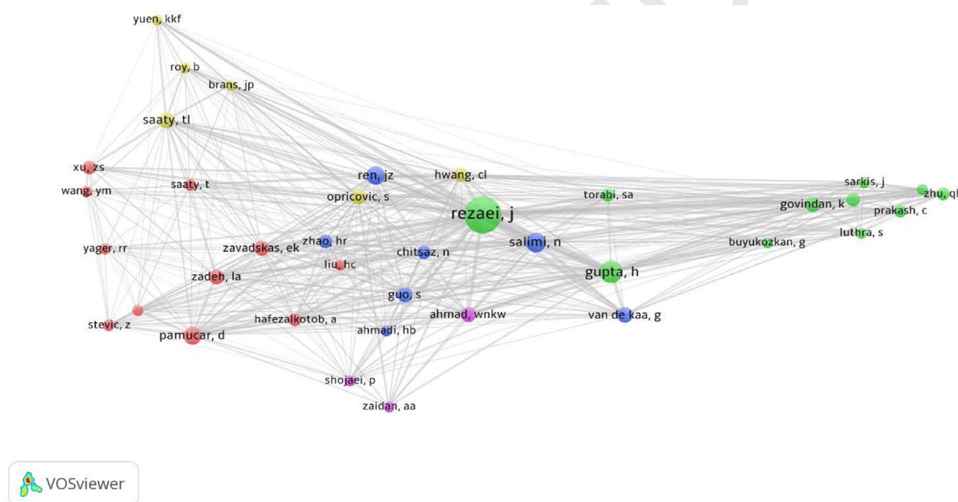

Fig. 5. Author co-citation network.

three papers would be also highly cited in researches related to BWM.

There are 3152 authors in total that were once cited by these 82 publications. As mentioned above, the first three highly cited papers were written by Rezaei. As displayed in Fig. 5, the biggest node is Rezaei, which is consistent with the result of reference co-citation analysis. Gupta has written seven papers about BWM [22–28]. Gupta has applied BWM to overcome the barriers in buildings with respect to energy efficiency, and also in choosing MSMEs (Micro-small and Medium Enterprises) and SMEs (Small and Medium Enterprises). Ren [29–32] applied BWM to manage polygeneration system, urban sewage sludge and technology selection for ballast water treatment. Salimi has written three papers [33–35] related to education area, research and development performance of firms, and scientific outputs quality evaluation. Based on the number of papers and the ranges of application area, Gutpa, Ren and Salimi becomes the top popular authors just behind Rezaei.

3. Why to propose the BWM?

This section introduces the motivation of the BWM. The comparison between AHP and BWM is provided as well.

In AHP, to compare the importance of n criteria, a reciprocity preference relation shown below can be constructed based on the pairwise comparisons using Saaty's 1/9–9 scale [5]:

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix}$$

where a_{jt} denotes the preference degree of criterion C_j over criterion C_t. Especially, $a_{jt} = 1/9$ implies that criterion C_t is absolutely preferred to criterion C_j; $a_{jt} = 9$ implies that criterion C_j is absolutely preferred to criterion C_t; $a_{jt} = 1$ means that criterion C_j is equally important to criterion C_t. In the pairwise comparison matrix A, a_{tj} can be derived by the reciprocity $a_{tj} = 1/a_{jt}$. In addition, for the 1/9–9 scale, the transitivity $a_{jt} = a_{jk} \times a_{kt}$ holds for any $j, t \in n$.

As an MCDM method, BWM was proposed by Razaei [1] to fill the challenges of AHP in numerous pairwise comparisons and lacking of consistency. Razaei [1] gave the reason why AHP is criticized for complexity of pairwise comparisons and low consistency. Inconsistency is unavoidable in pairwise comparisons due to the fact

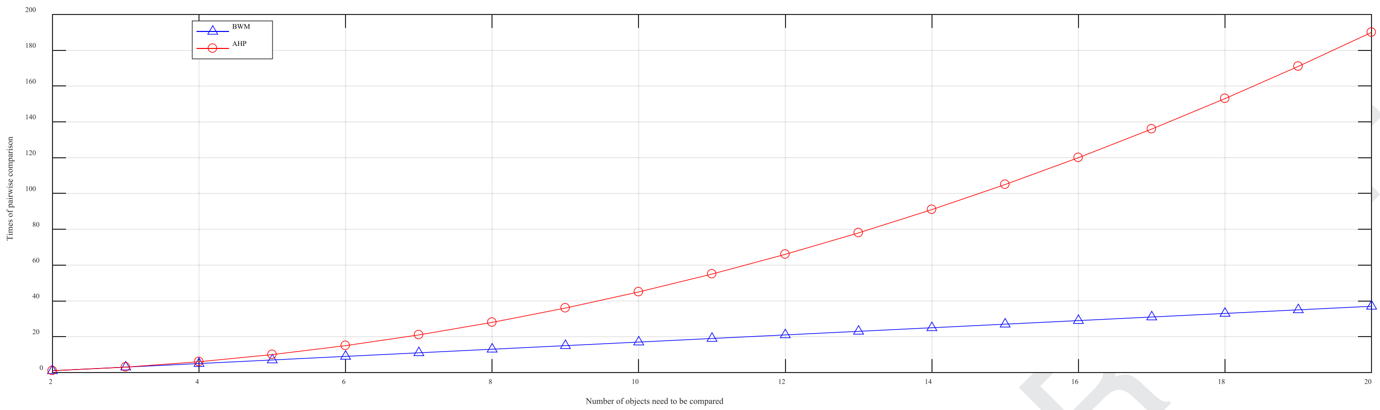

Fig. 6. The times of pairwise comparisons of BWM and AHP.

that the structure of doing pairwise comparisons in AHP is unreasonable [1,18].

To overcome these defects, Razaei [1] established a new structure of doing pairwise comparisons. The best (the most important or the most desirable) and the worst (the least important or the least desirable) objects are the predefined benchmarks or references for all the rest objects. In the BWM, only reference comparisons are necessary. The concept of reference comparisons is that the elements of pairwise comparisons should have at least a reference, i.e., the worst or the best object. Experts only do reference comparisons in decision-making process. It forms a new structure of pairwise comparisons in BWM, which is quite different from the pairwise comparisons in AHP.

In AHP, each criterion should be compared with all the other criteria. In this sense, for n criteria, using reciprocity, at least $n(n-1)/2$ pairwise comparisons need to be executed by expert. The $n(n-1)/2$ pairwise comparisons contains the reference comparisons and other comparisons which do not include the reference criteria. These other comparisons just lead to the inconsistent comparisons.

In the BWM, for n criteria, the best criterion C_B and the worst criterion C_W are predetermined by expert. Then, on the one hand, the reference comparisons include the best criterion C_B with all the other criteria except the best criterion C_B, i.e., $\{C_1, C_2, \cdots, C_n\}/\{C_B\}$. $n-1$ times of pairwise comparisons are done in the reference comparisons regarding the best criterion C_B. On the other hand, the reference comparisons regarding the worst criterion C_W consists the worst criterion C_W with all the other criteria except the best criterion C_B and the worst criterion C_W because the comparison between the best criterion and the worst criterion has been done in the process of the reference comparisons regarding the best criterion C_B, i.e., $\{C_1, C_2, \cdots, C_n\}/\{C_B, C_W\}$. Hence, in the framework of BWM, we only need to do $2n-3$ times of pairwise comparisons. It is worth to note that the information about the other pairwise comparisons exclude the reference criteria could be derived by the known reference comparisons in BWM. Therefore, the time of pairwise comparisons in BWM is $2n-3$ in total.

Fig. 6 clearly shows the difference in times of pairwise comparisons between BWM and AHP. The X-axis is designed to denote the number of objects to be compared in the decision-making process. The Y-axis refers to the times of pairwise comparisons using different methods. The blue line represents the BWM and the mathematical function is $f(n) = 2n-3$. While the red line denotes the AHP and the mathematical function is $f(n) = n(n-1)/2$. When the number of objects increases, the complexity of the BWM is linearly growing while the complexity of the AHP method increases exponentially. This figure intuitively shows the better performance of the BWM than the AHP in terms of decreasing the times of pairwise comparisons.

4. What is the BWM?

This section addresses what is the BWM. The clear steps of the BWM, the consistency ratio for the BWM and the linear model for the BWM are presented in details.

4.1. The steps of the BWM

BWM uses five steps to derive the weights of criteria [1]. The weights of alternatives on each criterion can be derived in the same process. Hence, we focus on the solving process regarding the weights of criteria. Below we summarize the five steps of the BWM [1].

Step 1. Determine a set of decision criteria.

Step 2. Choose the best criterion C_B and the worst criterion C_W from the set of decision criteria. If there is more than one best criterion or worst criterion, the best and worst criteria can be chosen arbitrarily.

Step 3. Do pairwise comparisons between the best criterion C_B and the other criteria. Then, the Best to Others (BO) vector could be established as:

$$BO = \left(a_{B1}, a_{B2}, \cdots, a_{Bj}, \cdots, a_{Bn}\right) \quad (2)$$

where a_{Bj} denotes the preference degree of the best criterion C_B over criterion C_j, and $a_{Bj} \geq 1,\ j = 1, 2, \cdots, n;\ \ j \neq B$.

Step 4. Do pairwise comparisons between the worst criterion C_W and the other criteria. Then, the Others to Worst (OW) vector could be established as:

$$OW = \left(a_{1W}, a_{2W}, \cdots, a_{jW}, \cdots, a_{nW}\right)^T \quad (3)$$

where a_{jW} denotes the preference degree of criterion C_j over the worst criterion C_W, and $a_{jW} \geq 1,\ j = 1, 2, \cdots, n;\ \ j \neq B \text{ or } W$. In this step, $n-2$ pairwise comparisons need to be done because a_{BW} is known in the BO vector. It is worth to note that OW is a $n \times 1$ vector.

Step 5. Derive the weights of criteria by optimization models. For each reference comparison, the optimal weights of criteria satisfy $w_B/w_j = a_{Bj}$ and $w_j/w_W = a_{jW}$. Thus, the maximum absolute differences $|w_B/w_j - a_{Bj}|$ and $|w_j/w_W - a_{jW}|$ should be minimized. Then, a min-max model (Model 1) could be established:

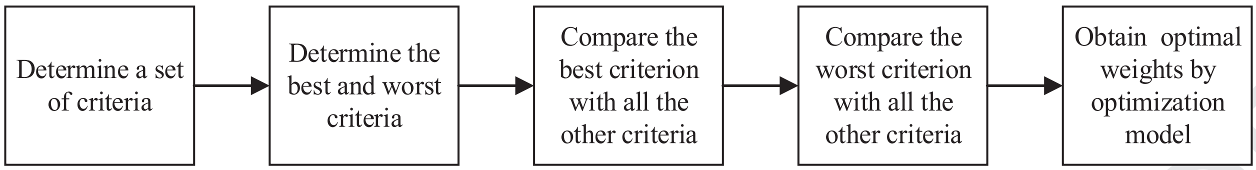

Fig. 7. The five steps of the BWM.

Model 1 [1]

$$\min \max_j \left\{ \left| w_B/w_j - a_{Bj} \right|, \left| w_j/w_W - a_{jW} \right| \right\}$$
$$s.t. \quad \sum_{j=1}^{n} w_j = 1, w_j \geq 0, j = 1, 2, \cdots, n$$

Using ξ to denote the maximum absolute difference, Model 1 can be equivalently transformed into Model 2:

Model 2 [1]

$$\begin{aligned} &\min \ \xi \\ &s.t. \quad \sum_{j=1}^{n} w_j = 1, w_j \geq 0, j = 1, 2, \cdots, n \\ &\quad \left| w_B/w_j - a_{Bj} \right| \leq \xi \\ &\quad \left| w_j/w_W - a_{jW} \right| \leq \xi \end{aligned}$$

The solution space of Model 1 could be non-empty when the value of ξ takes an enough great value from mathematical point of view. Solving Model 2, the weights of criteria and the corresponding maximum absolute difference could be derived.

The five steps of the BWM can be summarized in Fig. 7.

Generally, the BWM has three advantages over the AHP:

(1) One is the less times of comparisons in BWM than those in AHP, because the BWM derives the weights of criteria based on the vectors of pairwise comparisons shown as Eqs. (2) and (3) while the AHP utilizes the whole matrix of comparisons. Based on the reciprocity and transitivity of pairwise comparisons, after obtaining the reference comparisons regarding the best criterion and the worst criterion, the preference degrees among other criteria except the best criterion and the worst criterion could be derived.

(2) Secondly, in the structured comparing process of the BWM, only the integers, i.e., 1–9 scale, are used, while in the AHP, the 1/9–9 scale is used. In this regard, the complexity of comparisons reduces again. In addition, the integral grades are much closer to human perceptions and cognition, and this further makes the evaluation process much easier.

(3) The third benefit is that the BWM has better performance in maintaining the consistency of pairwise comparisons since the redundant comparisons are eliminated. This makes the results derived by the BWM more reliable than those derived by the AHP. We shall further highlight this issue in Section 4.2.

We should note that scholars also proposed different formulas to model the deviation between w_B/w_j and a_{Bj}, and the deviation between w_j/w_W and a_{jW}. For example, Brunelli and Rezaei [36] proposed the multiplicative norm of the deviation, shown as $\{a_{ij}/\frac{w_i}{w_j}, \frac{w_i}{w_j}/a_{ij}\}$. Unlike the Hamming distance in the objective function of Model 1, Koçak, Çağlar and Öztaş [37] proposed the Euclidean norm of the deviation, shown as $\sqrt{(w_B/w_W - a_{BW})^2 + \sum_{j \neq W}(w_B/w_j - a_{Bj})^2 + \sum_{j \neq B}(w_j/w_W - a_{jW})^2}$. However, it is observed that Model 1 is based on a min-max formulation. This formulation is one of the most important features of the BWM, but this feature was neglected in Koçak, Çağlar and Öztaş [37]'s model since the objective function is not in min-max form any more. The min-max formulation guarantees the consistency of each comparison in the BWM method, while the model in Ref. [37] has a similar problem to AHP in terms of consistency since both of them calculate the consistency of the whole problem but do not care about the consistency between individual comparisons.

4.2. The consistency ratio for the BWM

After obtaining the weights of criteria, the reliability of the results should be taken into consideration. ξ^*, obtained from Model 2, is the maximum absolute difference and it can be used in deriving the Consistency Ratio (CR). Intuitively, the greater the value of ξ^* is, the less reliable the comparisons are. Razaei [1] proposed a formula of CR for the BWM, shown as follows:

$$CR = \xi^*/Consistency\ Index \tag{4}$$

where $CR \in [0, 1]$ and ξ^* is the maximum absolute difference derived from Model 2. The Consistency Index, denoted as $\xi_{\max}$, is the maximum value of ξ when the greatest preference degree a_{BW} of criterion C_B over criterion C_W is determined.

The absolute consistency of a pairwise comparison matrix could be justified as: for all j, $a_{Bj} \times a_{jW} = a_{BW}$ always holds. When the condition $a_{Bj} \times a_{jW} = a_{BW}$ is not satisfied for some criteria C_j, the consistency degree of the pairwise comparison matrix would decrease. $a_{Bj} \times a_{jW} \neq a_{BW}$ has two conditions: $a_{Bj} \times a_{jW} > a_{BW}$ or $a_{Bj} \times a_{jW} < a_{BW}$. The maximum value of ξ is resulted from the maximum values of a_{Bj} and a_{jW}. When the condition $a_{Bj} = a_{jW} = a_{BW}$ is true, the consistency degree of a pairwise comparison matrix has the smallest value. In this sense, the values of a_{Bj} and a_{jW} should minus the value of ξ, and the value of a_{BW} should plus the value of ξ:

$$\left(a_{Bj} - \xi\right) \times \left(a_{jW} - \xi\right) = a_{BW} + \xi \tag{5}$$

As for the highest inconsistency situation $a_{Bj} = a_{jW} = a_{BW}$, Eq. (5) can be transformed to

$$(a_{BW} - \xi) \times (a_{BW} - \xi) = a_{BW} + \xi \tag{6}$$

Eq. (6) is a one-quadratic equation, with ξ being the variable and a_{BW} being the constant parameter.

Solving Eq. (6), we can obtain two non-negative solutions of Eq. (6) when the constant parameter a_{BW} is determined by expert. Table 2 shows the small values of roots of Eq. (6).

Another group of large possible roots corresponding to different a_{BW} are 3.00, 4.56, 6.00, 7.37, 8.70, 10.00, 11.27, 12.53, 13.77, respectively. In Table 2, there is only one kind of consistency index values, corresponding to the small solution of Eq. (6), respectively. Generally, the smaller the value of CR is, the better the consistency of a pairwise comparison matrix should be. For the same maximum absolute difference $\xi_{\max}$ of a pairwise comparison matrix, the value of CR using the small possible root is greater than that of the CR using the large possible root. Given that the maximal absolute deviation $\xi_{\max}$ should be smaller than the value of a_{BW}, the large possible root should not be used to restrict the consistency degree. It is reasonable and helpful to use the small possible root as the Consistency Index $\xi_{\max}$, i.e., the denominator of Eq. (4).

In Ref. [1], the value of Consistency Index is used in comparing the consistency property of BWM with that of AHP. Rezaei [1] applied the BWM into a real-world problem concerning choosing mobile phone. The results derived from the BWM and the AHP were

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Table 2
The values of consistency index.

a_{BW}	1	2	3	4	5	6	7	8	9
Consistency Index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Table 3
Original cases and fuzzy consistency ratio.

Case	BWM			Fuzzy BWM					
	ξ	CI	CR	ξ_f	CI-F	CR-F	CI-T	CR-T
Example 1 in Ref. [1]	0.260	4.47	0.0582	0.4495	8.04	0.0559	1.96	0.2293
Example 3 in Ref. [20]	1.000	4.47	0.2237	0.7913	8.04	0.0984	1.96	0.4037
Example in Ref. [21]	1.146	3.00	0.3820	0.2361	6.69	0.0353	1.31	0.1802

compared from four aspects: consistency ratio, minimum violation, total deviation and conformity. In terms of these four aspects, the BWM performs better than the AHP [1]. Generally speaking, the BWM owns the advantages in requiring less times of comparisons and obtaining more reliable and consistent results than the AHP.

Scholars have extended the BWM to fuzzy context. For the CR under fuzzy conditions, Guo and Zhao [38] used three case studies to show that the fuzzy extension of the BWM owns higher consistency ratio than the original BWM. In our perspective, this conclusion may be not true because different rules were used in these methods to choose the consistency index and wrong consistency index was chosen in fuzzy BWM. To clearly illustrate the difference, we tabulate the important data of those three case studies used in Refs. [1,20,21,38] in Table 3.

Given that Eq. (6) has two feasible solutions from mathematical point of view, in Refs. [1,20,21], the minimal solutions of Eq. (6), called as CI-T (Consistency index-True), were chosen for strict consistency ratio. While in Ref. [38], the maximal solutions of Eq. (6), named as CI-F (Consistency index-False), were taken in calculating the CR. If the maximal solutions of Eq. (6) were taken into account, the CR-T (Consistency Ratio-True) in Ref. [38] would be changed to 0.2293, 0.4037, 0.1802. In Example 1 in Ref. [1] and Example 3 in Ref. [20], the original BWM shows better than the fuzzy BWM proposed in Ref. [38] in terms of CR. Only in the example of the comparisons of willingness [21], the fuzzy BWM performs better than the original BWM. Even though the fuzzy extension of the BWM may performs better as indicated by some scholars, we should note that the original BWM has high consistency than the fuzzy extensions of BWM because the fuzzy extensions of BWM contains uncertain information which may result in inconsistency.

4.3. How to handle the multi-optimality of the weight determining model in the BWM

After proposing the BWM [1], Razaei [20] further investigated the multi-optimality of the BWM, and established a linear model for the BWM from interval and linear aspects. In this section, we address this model briefly.

Why do we need to transform the min-max non-linear model into a linear model? Since the pairwise comparison is not always fully consistent, multi-optimality could be derived from Model 2. The multi-optimality of Model 2 could provide more information than the singleton optimal solution. However, in some situations, decision-makers prefer the unique optimal solution. In this case, Razaei [20] presented two ways to tackle this issue: one is based on interval analysis and the other is to convert the min-max non-linear model into a linear model.

How does the multi-optimality exist in the BWM? The reason of multi-optimality in Model 2 could be explained in terms of linear algebra. The multi-optimality of Model 2 results from the inconsistency of pairwise comparison matrix when the number of criteria is greater than three. In the case that the number of criteria is two, the pairwise comparison matrix is totally consistent since $a_{Bj} \times a_{jW} = a_{BW}$ always holds.

In fully consistent situation, the inequality constraints can be converted into corresponding equality constraints. For example, $|w_B/w_j - a_{Bj}| \le \xi$ can be converted to $w_B/w_j - a_{Bj} = 0$, and $|w_j/w_W - a_{jW}| \le \xi$ can be converted to $w_j/w_W - a_{jW} = 0$. In addition, the condition of $a_{Bj} \times a_{jW} = a_{BW}$ always holds in fully consistent situation. In this sense, there is only $n-1$ independent comparison constraints and $n-1$ comes from the number of criteria, n, minus the criterion itself. Considering the constraint on the summation of weights, there are n independent constraints with respect to n variables. Thus, in fully consistent situation, Model 2 has a unique solution.

In not-fully consistent situation, each inequality constraint can be converted into two corresponding constraints of inequalities. For example, $|w_B/w_j - a_{Bj}| \le \xi$ can be transformed to $w_B - a_{Bj}w_j \le w_j\xi$ and $w_B - a_{Bj}w_j \ge w_j\xi$. Similarly, $|w_j/w_W - a_{jW}| \le \xi$ can be converted into $w_j - a_{jW}w_W \le w_W\xi$ and $w_j - a_{jW}w_W \ge w_W\xi$. As we discussed previously, there are $2n-3$ pairwise comparisons in the BWM. Hence, in not-fully consistent situation, Model 2 has $4n-5$ constraints in total including the constraint on the summation of weights. In addition, there are n variables of the weights of criteria and $4n-8$ slack variables in Model 2. That is to say, Model 2 has $5n-8$ variables in total. In linear algebra, if the number of variables is greater than that of constraints in a model, the model has multi-optimality. Then, we discuss the relations between these $4n-5$ constraints and $5n-8$ variables.

Case 1. If the number of criteria is three, $4n-5 = 5n-8$;

Case 2. If the number of criteria is greater than three, $4n-5 < 5n-8$, that is to say, the number of constraints is less than that of variables.

Case 2 may lead to the multi-optimality of Model 2.

To solve this multi-optimality of Case 2, Rezaei [20] proposed two models, i.e., Models 3 and 4, to obtain the interval weights of criteria.

Model 3 [20]

$$\begin{aligned} \min\ & w_j \\ s.t.\ & \textstyle\sum_{j=1}^{n} w_j = 1, w_j \ge 0, j = 1, 2, \cdots, n \\ & \left| w_B/w_j - a_{Bj} \right| \le \xi^* \\ & \left| w_j/w_W - a_{jW} \right| \le \xi^* \end{aligned}$$

Model 4 [20]

$$\begin{aligned} \max\ & w_j \\ s.t.\ & \textstyle\sum_{j=1}^{n} w_j = 1, w_j \ge 0, j = 1, 2, \cdots, n \\ & \left| w_B/w_j - a_{Bj} \right| \le \xi^* \\ & \left| w_j/w_W - a_{jW} \right| \le \xi^* \end{aligned}$$

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Models 3 and 4 are solved after obtaining the value of ξ^* from Model 2. Then, the interval values of the weights of criteria can be derived. If the pairwise comparison vectors are fully consistent, the results of Models 3 and 4 are unique values and the intervals become crisp values. Therefore, the boundaries of Models 3 and 4 are reasonable.

Another approach to obtain the unique solution of Case 2 is to transform the min-max model (Model 1) into a linear model, by converting the initial min-max objective function $\min \max_j \{|w_B/w_j - a_{Bj}|, |w_j/w_W - a_{jW}|\}$ into a linear min-max objective function $\min \max_j \{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$. Then, Model 2 can be rewritten as Model 5:

Model 5 [20]

$$\begin{aligned} &\min \xi^L \\ &s.t. \quad \textstyle\sum_{j=1}^{n} w_j = 1, w_j \geq 0, j = 1, 2, \cdots, n \\ &\qquad \left| w_B - a_{Bj} w_j \right| \leq \xi^L \\ &\qquad \left| w_j - a_{jW} w_W \right| \leq \xi^L \end{aligned}$$

It is not difficult to find that Model 5 is a linear model, which leads to a unique solution. Solving Model 5, the unique solution about the weights of criteria $w = (w_1, w_2, \cdots, w_n)^T$ and the minimum absolute difference ξ^{L*} could be obtained. In Ref. [20], Rezaei used several examples to prove that the unique solution of Model 5 is very close to the center of the interval weights of criteria derived from Models 3 and 4.

It is worth to note that, with the linear Model 5 of the BWM, Eq. (4) is replaced by the value of ξ^{L*}. The value of ξ^{L*} close to zero means a minimal inconsistency of a pairwise comparison matrix.

5. Integrations of the BWM and their applications: What for?

The BWM, as a theoretical model, has been tested in real-life applications. Among the 124 publications, 83 of them concerned the integrations of the BWM. Among these 83 publications, 40 of them concentrated on the singleton integrations of the BWM and 43 of them integrated more than one method with the BWM. In this section, we introduce the applications of the stand-alone BWM, and the single integrations, multiple integrations and their corresponding applications, respectively.

5.1. Applications of the stand-alone BWM

Over the past years since the BWM was initially proposed in 2015, many researches related to the BWM have been published. There are 41 publications focused only on the BWM. Table 4 shows the applications of the stand-alone BWM.

5.2. Singleton integration of the BWM and their applications

There are 40 publications addressing the singleton integration of the BWM, including 36 journal articles, 2 conference papers, 1 case study and 1 chapter of handbook. The most popular singleton integrations of the BWM are listed in Table 5.

In Table 5, the most popular integration of the BWM is the uncertain condition. Two categories, fuzzy information [71–76] and interval values [32,77,78], were used to combine with the BWM. Fuzzy sets [71,74], triangular fuzzy number with membership functions [76], interval-valued multiplicative sets [72], probabilistic hesitant fuzzy sets [73] and Z-numbers [75], have been used to represent uncertainty in the BWM. Anyway, we should note that the interval weights, coming from the not-fully consistent nonlinear BWM, are totally different from the interval used in the input data of fuzzy BWM. The former is valid since the weight is a ratio scale, while the latter may be questionable as the 1–9 scale is not a ratio scale. This is still an open question and more discussion should be given in this regard in the future.

The second stream of the combination about the BWM is with the TOPSIS method. Refs. [24–26,28,79,80] investigated the BWM with the variants of the TOPSIS method. Gupta and Barua [24–26] focused on SMEs' supplier selection in terms of innovation ability and overcame barriers of green innovation, respectively. Gupta [28] used the BWM and the fuzzy TOPSIS method to evaluate service quality of airline industry. You et al. [79] combined the BWM with the TOPSIS method to evaluate the performances of power grid enterprises to advocate the sustainable development. Askarifar et al. [80] used the BWM and the TOPSIS method to evaluate investment opportunities in a region.

Moreover, the VIKOR method has been combined with the BMW in one journal paper [27] to evaluate service quality of airline industry, one conference paper [81] to select web services and one journal paper [82] regarding both strategic and operational aspects of the selected criteria and proposed managerial implications, respectively. Garg and Sharma [83] focuses on the outsourcing partner selection and evaluation. Furthermore, two papers [86,87] focused on the combination of the fuzzy-Delphi method with the BWM.

Except the popular singleton integrations of the BWM, there are other singleton integrations of the BWM. These methods and their corresponding applications are shown in Table 6. These singleton integration of the BWM and their corresponding applications appeared in various kinds of publications, including 13 journal articles, 1 conference paper, 1 chapter of handbook and 1 case study. In Table 6, Bayesian network, fuzzy ANP, SAW and SERVQUAL are useful approaches. In the future, these singleton integrations could be mixed with other MCDM techniques to tackle complex decision-making problems.

5.3. Multiple integrations of the BWM and their applications

There are 43 publications which addressed the multiple integrations of the BWM. All of them are journal articles. Table 7 lists the information of the 28 journal articles concerning two integrations with the BWM and their corresponding applications. From Table 7, it is not difficult to find that fuzzy logic and Group Decision Making (GDM) are two popular and interesting research issues with the BWM. Multi-experts help to improve the quality of decision result, which is an essential part in MCDM. Hafezalkotob and Hafezalkotob [14] used the fuzzy extension of the BWM to obtain the weights of experts in GDM process. Mou et al. [104] adopted the intuitionistic multiplicative weighted geometric aggregation operator to get the collective evaluations about the GDM problem. Mou et al. [105] first obtain the best and the worst criteria by graph theory and acquired the collective evaluations after fusing the acceptable consistency intuitionistic fuzzy preference relations by intuitionistic fuzzy weighted aggregation operator. You et al. [106] combined the ELECTRE III with intuitionistic multiplicative and the interval-valued fuzzy BWM in GDM process. Safarzadeh, Khansefid and Rasti-Barzoki [102] used the weights and perspectives of experts to acquire the best and the worst criteria. Then, two mathematical models to deduce priorities and consistency ratio by two mathematical models.

In addition, there are 14 papers [105,106,129–140] which focused on the combination with three or more than three techniques, shown in Table 8. Here we take several papers as a clarification. Ref. [135] combined the BWM with the QFD, fuzzy MULTIMOORA and fuzzy logic to evaluate the performance of smart bike-sharing program. Ref. [137] combined the PHFLTS and PT to fill the gap of the traditional QFD. In this paper, the customer requirements were converted into corresponding engineering characteristics and the weights of the customer requirements were de-

Table 4
The applications of the stand-alone BWM.

Authors	Year	Applications areas	Specific problems
Rezaei [1]	2015	Manufacturing	Mobile phone selection
Rezaei et al. [21]	2015	Supplier development	Link supplier development to supplier segmentation
Sadaghiani et al. [39]	2015	Supply chain sustainability	Evaluate external forces affecting supply chain sustainability in oil and gas industry
Gupta and Barua [22]	2016	Micro-small and medium enterprises	Identify enablers of technological innovation for Indian MSMEs
Rezaei et al. [40]	2016	Supplier selection	Evaluate a supplier selection life cycle
Rezaei [20]	2016	Manufacturing	Select Car
Torabi et al. [41]	2016	Risk assessment	An enhanced risk assessment framework for business continuity management systems
Salimi and Rezaei [33]	2016	Education	Measure efficiency of university-industry Ph.D. projects
Ahmadi et al. [42]	2017	Supply chain	Assess the social sustainability of supply chains
Alhubaishy and Benedicenti [43]	2017	Agile development	Emotion influences on agile decision making
Ghaffari [44]	2017	Technology	Key success factors evaluation in technological innovation development
Gupta, Anand and Gupta [23]	2017	Consumption of energy	Develop a roadmap to overcome barriers to energy efficiency in buildings
Mohaghar et al. [45]	2017	Supply chain	Appraise humanitarian supply chain risks
Praditya and Janssen[46]	2017	Sharing arrangements	Assess factors' influencing information sharing arrangements
Rezaei et al. [47]	2017	Airline industry	Complex bundling configurations in surface transportation of air freight
Salimi [34]	2017	Quality assessment	Assess quality of scientific outputs
Kaa et al. [48]	2017	Biology	Select biomass thermochemical conversion technology
Ahmad et al. [49]	2017	Supply chain	Evaluate the external forces affecting the sustainability of oil and gas supply chain
Kaa et al. [50]	2017	Automotive	The battle between battery and fuel cell powered electric vehicles
Zhao et al. [51]	2017	Eco-industrial parks	Comprehensive benefit evaluation of eco-industrial parks
Salimi and Rezaei [35]	2018	Performance evaluation	Evaluate firms' R & D performance
Yadollahi et al. [52]	2018	Banking service	Prioritize the factors of service experience in banks
Kaa, Janssen and Rezaei [53]	2018	Technology	Evaluate the most attractive technology in the R&D department of a high-tech company
Rezaei et al. [54]	2018	Logistics	Measure the importance of logistics performance indicators
Kaa et al. [55]	2018	Energy	Assign the relative importance to factors
Moktadir et al. [56]	2018	Manufacturing	Identify challenges for implementing Industry 4.0
Groenendijk, Rezaei and Correia [57]	2018	Transportation	Incorporate the travelers' experience value in assessing the quality of transit nodes
Rezaei et al. [58]	2018	Transportation	Assess the port performance measurement
Rezaei and Lajimi [59]	2018	Supply chain	Realize combined purchasing portfolio matrix-supplier potential matrix segmentation
Bonyani and Alimohammadlou [60]	2018	Performance evaluation	Evaluate foreign EPC companies
Sharma, Mangla and Patil [61]	2018	Transportation	Evaluate the transportation challenges of the dairy industry
Beemsterboer, Hendrix and Claassen [62]	2018	Manufacturing	Mobile phone selection
Rezaei et al. [63]	2018	Supply chain	Evaluate the environmental, economic and social criteria for packaging
Kusi-Sarpong, Gupta and Sarkis [64]	2018	Supply chain	Evaluate sustainable innovation criteria for sustainable supply chains in manufacturing companies
Vishnupriyan and Manoharan [65]	2018	Verification	The BWM is used to verification for other methods
Liu et al. [66]	2018	Environment	Obtain the objective and credible indicator weights
Zavadskas [67]	2018	Verification	The BWM is used to verification for other methods
Ajrina, Sarno and Ginardi [68]	2018	Mining	Decide the significance and weighting criteria.
Setyono and Sarno [69]	2018	Supply chain	Evaluate performance and technical capability criteria
Brunelli and Rezaei [36]	2018	Mathematics	Propose a way to denote the inconsistency deviation
Kaa et al. [70]	2019	Technology	Compare relevant standard dominance factors of three types of communication technologies

termined by the BWM. Ref. [134] combined the BWM with three techniques, namely, TOPSIS, GRA and WSA. It aimed to test and optimize a turning operation. Ref. [138] used VIKOR, relative entropy and fuzzy BWM at the same time to do FMEA in manufacturing.

Based on the information in Tables 4–8, the application areas of the BWM can be summarized in Table A.3 in Appendix. It is not hard to find that supply chain is one of the most popular application areas of the BWM. Manufacturing, performance evaluation, airline industry, energy, transportation, education and technology are also widely applied areas of the BWM. The rest application areas may be popular soon after.

In total, for all 124 publications with respect to the BWM, Table 9 counts the number of publications by year about different kinds of integrations of the BWM. We can find that the number of singleton integration of the BWM is increasing by year and the number of multiple integrations of the BWM is also raising.

6. Challenges and future research directions related to the BWM: What's next?

The challenges and future research directions of the BWM can be discussed from theory aspect and application aspect, respectively.

From the perspective of theory, the reasonable values of CR, the inconsistency improving methods, the uncertain extensions of the BWM and the techniques to solve multi-optimality model in the BWM are good research issues that need to be further investigated.

Table 5
The most popular singleton integrations of the BWM.

Technique	Approach	Authors	Year	Applications areas
Uncertainty	Fuzzy information	Raj and Srivastava [71]	2018	Manufacturing
	Fuzzy information	Yang et al. [72]	2018	Education
	Fuzzy information	Li, Wang and Hu [73]	2018	Investment
	Fuzzy information	Torbati and Sayadi [74]	2018	Performance evaluation
	Fuzzy information	Aboutorab et al. [75]	2018	Supply Chain
	Fuzzy information	Khanmohammadi, Zandieh and Tayebi [76]	2018	Performance evaluation
	Interval analysis	Ren [32]	2018	Manufacturing
	Interval analysis	Ren et al. [77]	2018	Manufacturing
	Interval analysis	Sadjadia and Karimi [78]	2018	Manufacturing
TOPSIS	Fuzzy TOPSIS	Gupta and Barua [24]	2017	Supplier selection
	Fuzzy TOPSIS	Gupta and Barua [25]	2017	Supplier selection
	Fuzzy TOPSIS	Gupta and Barua [26]	2018	SMEs
	Fuzzy TOPSIS	Gupta [28]	2018	Performance evaluation
	TOPSIS	You et al. [79]	2017	Power Grid Enterprise
	TOPSIS	Askarifar et al. [80]	2018	Investment
VIKOR	VIKOR	Serrai et al. [81]	2016	Web Service
	VIKOR	Gupta [27]	2018	Airline industry
	VIKOR	Cheraghalipour, Paydar and Hajiaghaei-Keshteli [82]	2018	Supply Chain
	VIKOR	Garg and Sharma [83]	2018	Outsourcing adoption
	VIKOR	Liu, Hu and Zhang [84]	2018	Manufacturing
	VIKOR	Alsalem [85]	2018	Health care
FDM	Fuzzy-Delphi method	Nafari et al. [86]	2017	Higher education
	Fuzzy-Delphi method	Sahebi et al. [87]	2017	Humanitarian supply chain

Note: All abbreviations can find corresponding explanations in Table A.2 in Appendix.

Table 6
The other singleton integrations of the BWM and their corresponding applications.

Approach	Authors	Year	Application area	Specific problem
Expected marginal seat revenue	Joshi and Lohiya [88]	2016	Film/Movie Theatre	Increase revenue for movie theatre based on improved seating plans
PLS method	Sadeghi et al. [89]	2016	Supply Chain	Identify and prioritize contributing factors in supply chain competitiveness
Bayesian network	Abolbashari et al. [90]	2017	Procurement	Adjust the impact of each KPI on the procurement performance
Cognitive network process	Zhang et al. [91]	2017	Transportation	Select a freight transportation company
RIM	Sofuoğlu et al. [92]	2017	Turning operation	Optimize cut parameters
SWOT	Abadi et al. [93]	2018	Medical tourism	Evaluate medical tourism development strategy
SERVQUAL	Rezaei et al. [94]	2018	Quality assessment	Assess airline baggage handling systems' quality
K-means clustering	Kara and Firat [95]	2018	Supply chain	Supplier risk assessment
PROMETHEE II	Alimohammadlou and Bonyani [96]	2018	Food industry	Financial performance evaluation in Iran's food industry
RMCGP	Cheraghalipour and Farsad [97]	2018	Supply chain	Sustainable supplier selection and order allocation
ZOLP	Mokhtarzadeh et al. [98]	2018	Technology	Technology selection in information technology industry
ELECTRE III	Yadav et al. [99]	2018	Outsourcing adoption	Offshore outsourcing adoption
Euclidean BWM	Koçak, Çağlar and Öztaş [37]	2018	Manufacturing	Car selection
Markov chains	Nawaz et al. [100]	2018	Cloud service selection	Develop a cloud broker architecture
LSM	Safarzadeh and Rasti-Barzoki [101]	2018	Car selection	Select a car selection with four criteria and four alternatives
GDM	Safarzadeh, Khansefid and Rasti-Barzoki [102]	2018	Piping selection	Choose piping by four criteria: total cost, security, social costs and environmental costs
SWARA	Zolfani and Chatterjee [103]	2019	Materials selection	Choose the sustainable household furnishing materials

(1) How to determine an acceptable value of CR in the BWM is still an open question. 0.1 is usually taken as a consistency threshold regarding the pairwise comparison matrix of Saaty [17]. However, in the BWM, less comparisons are required to execute and thus the BWM should have higher consistency than the AHP. There is no research about whether 0.1 is a suitable consistency threshold or not in the BWM. Statistical approach such as Monte Carlo stimulation may be a good technique to determine a reasonable value of CR in the BWM.

(2) The inconsistency repairing methods in uncertain situations of the BWM should be further investigated. Even though Rezaei [1] have provided a way to improve the inconsistent vectors of BWM, detailed inconsistency improving techniques in uncertain situations or in group decision making scenario should be proposed for the reliability of final results. On the condition that the consistency degree of a pairwise comparison matrix is not high, the results derived from this pairwise comparison matrix may be not reliable. Results with low credibility or reasonability could not be utilized in decision-making process.

(3) In uncertain situations, there are several papers about the fuzzy extensions of the BWM. Triangular fuzzy numbers, intuitionistic fuzzy numbers, interval-valued fuzzy numbers and rough numbers have been investigated with the BWM in indeterminate environment. Based on these initial combi-

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Table 7
The integrations of the BWM with two techniques and their corresponding applications.

Approach	Authors	Year	Applications area	Specific problem
SWOT/AHP	Chitsaz and Azarnivand [107]	2017	Water management	Water scarcity management in arid regions
Fuzzy BWM/GMIR	Guo and Zhao [38]	2017	Transportation	Select optimal transportation mode to deliver products
Fuzzy BWM/GDM	Hafezalkotob and Hafezalkotob [108]	2017	Investment	Investment decision process of innovation projects
Intuitionistic fuzzy multiplicative BWM/GDM	Mou et al. [104]	2017	Healthcare management	Evaluation of severity of patients infected with emphysema
MAIRCA/Rough numbers and fuzzy information	Pamučar et al. [109]	2017	Location selection	Select location for wind farms
Extension theory/Combined weights	Ren [30]	2017	Technology selection	Technology selection for ballast water treatment by multi-stakeholders
TOPSIS/SAW	Ren et al. [31]	2017	Technology selection	Sustainability assessment of technologies
Fuzzy BWM/Interval TOPSIS	Wang et al. [29]	2017	Polygeneration	Develop a method for sustainability assessment of polygenerations
TLF/VIKOR	Fatrias et al. [110]	2017	Supply Chain	Obtain a compromised supplier ranking list
Rough BWM/SAW	Stević et al. [111]	2017	Location selection	Rationalize of logistics activities and processes for wagons selection
MABAC/interval-valued fuzzy-rough numbers	Pamučar et al. [112]	2018	Airline industry	Evaluate fire fighting aircraft
TLF/VIKOR	Shojaei et al. [113]	2018	Airline industry	Airports evaluation and ranking
Fuzzy BWM/Fuzzy ANP	Alimohammadloua and Bonyani [114]	2018	Manufacturing	Performance evaluation of companies in product development
Fuzzy TOPSIS/Fuzzy MOLP	Lo et al. [115]	2018	Supply chain	Green supplier selection and order allocation
Entropy methods/RIM	Sofuoğlu [116]	2018	Manufacturing	Material and process selection in engineering environment
WASPAS/MULTIMOORA	Hafezalkotob et al. [117]	2018	Agriculture	Determine the weights of criteria about olive harvesting machines
Fuzzy BWM/COPRAS	Mahdiraji et al. [118]	2018	Building	Analyzing key factors of sustainable architecture
FMEA/Linguistic distribution assessment	Nie et al. [119]	2018	Water management	Risk evaluation of supercritical water gasification system
FDM/VIKOR	Zhao, Zhao and Guo [120]	2018	Performance evaluation	Assess the performances of electricity grid corporations
ELECTRE III/PROMETHEE II	Bonyani and Alimohammadlou [121]	2018	Performance evaluation	Prioritize foreign companies in post-sanctions Iranian energy sector
Rough BWM/Rough SAW	Stević et al. [111]	2018	Transportation	Evaluate potential locations for roundabout construction
Rough BWM/MAIRCA	Badi and Ballem [122]	2018	Supply chain	Identify suppliers in pharmaceutical industry
2-tuple linguistic BWM/QFD	Mei, Liang and Tu [123]	2018	Emergency routes evaluation	Choose the emergency route in the Wuhan metro station
Fuzzy BWM/AD	Maghsoodi et al. [124]	2018	Product design	Evaluate aesthetic, practical, technical and cost criteria
DEA/PROMETHEE II	Alimohammadlou and Bonyani [125]	2018	Performance evaluation	Weight the financial ratios
Fuzzy BWM/MACBETH	Pourhejazy, Sarkis and Zhu [126]	2018	Product deletion	Evaluate criteria for product deletion of fast-consuming goods
SWOT/QFD	Vahidi, Torabi and Ramezankhani [127]	2018	Supply chain	Find the weight vector of each supplier' resilience score
AQM/FMEA	Liu et al. [128]	2018	Water treatment plant	Obtain the weights of risk factors

Table 8
The integrations of the BWM with three or more than three techniques and their applications.

Approach	Authors	Year	Applications areas
Intuitionistic multiplicative BWM/ ELECTRE III/GDM	You et al. [106]	2016	Location selection
AHP/VIKOR/SAW/TOPSIS/COPRAS	Serrai et al. [133]	2017	Web service selection
TOPSIS/GRA/WSA	Sofuoğlu and Orak [134]	2017	Turning operations
Intuitionistic fuzzy BWM /Graph theory/GDM	Mou et al. [105]	2017	Healthcare management
QFD/Fuzzy MULTIMOORA/Fuzzy BWM/Maximizing deviation method	Tian et al. [135]	2018	Smart bike-sharing program
SAW/TOPSIS/COPRAS	Sotoudeh-Anvari et al. [136]	2018	Search problem
PHFLTS/PT/QFD	Huang et al. [137]	2018	Manufacturing
VIKOR/Relative entropy/Fuzzy BWM	Tian et al. [138]	2018	Manufacturing
Linguistic distribution assessment/TOPSIS/DEMATEL	Nie et al. [139]	2018	Water management
Entropy/QFD/Fuzzy MULTIMOORA	Liu et al. [129]	2018	Supply chain
Entropy/CPT/Grey theory	Zhao, Guo and Zhao [140]	2018	Energy
Fuzzy BWM/TOPSIS/Taguchi method/Neutral network	Omrani, Alizadeh and Emrouznejad [130]	2018	Energy
Interval rough BWM/WASPAS/MABAC	Pamucara, Chatterjee and Zavadskasc [131]	2018	Logistics
FDM/Entropy weight determination method/VIKOR	Zhao, Guo and Zhao [132]	2018	Energy
Interval BWM/Interval MULTIMOORA method/Interval Borda rule	Hafezalkotob et al. [141]	2019	Vehicle engine selection

Table 9
The number of publications during 2015–2019 (January).

Years	Number of publications			Total
	Stand-alone BWM	Singleton integration	Multiple integrations	
2015	3	1	–	3
2016	5	4	1	10
2017	12	8	13	33
2018	20	27	28	75
2019	1	1	1	3
Total	41	40	43	124

nations, the future research should focus on the membership functions of fuzzy numbers. Hesitant fuzzy number shows good performance in representing uncertain information by using a set of possible values to characterize the membership degree. Moreover, linguistic variables and linguistic expressions are expedient when the cost to obtain numbers is too high. Hence, hesitant fuzzy information and linguistic information with membership functions (hesitant fuzzy linguistic information and probabilistic linguistic information) are good research points with the BWM extensions. Given that uncertainty may lead to higher inconsistency, the inconsistency improving process and the corresponding CR should be determined in uncertain situation as well.

(4) The way to solve multi-optimality model in the BWM was as follows: Rezaei [20] converted the original non-linear model (Model 1) into a linear model (Model 5) and used two models (Models 3 and 4) to calculate the upper and lower bound of the interval weights. Rezaei [20] thought that the central value of interval weight is close to the solution of the linear model based on three numerical examples. There is a lack of proof of relation between the central value of interval weight solutions of the Model 2 and the unique weight solutions of Model 5 from mathematical perspective. Other possible techniques to analyze the multi-optimality of Model 2 are interesting and challengeable.

From the perspective of application, the software package for the BWM, the various integrations of the BWM, the different application areas and the international cooperation on the BWM are good topics to consider in the future.

(1) There is a necessary to develop the software packages for the BWM. Software packages of the BWM would contribute to reducing complexity of calculation and accelerating the presentation of results. The software package of the BWM helps people use the BWM in practice efficiently and widely. Actually Rezaei provides an excel solver[3] for calculating weights by using the linear models in Ref. [20]. Many MCDM methods, such as AHP, ELECTRE and PROMETHEE have their corresponding software packages, which are more flexible than the excel solver. Thanks to the availability and effectivity of their software packages, these MCDM methods are being used more and more widely. If an excellent software package of the BWM is developed, the applications related to the BWM would also become popular.

(2) The integrations of the BWM should be enriched. Until now, 33.06% (41/124) publications used the stand-alone BWM into applications. Given that the BWM shows excellent performance in deriving weights of criteria, other MCDM techniques without weight-deriving process can be combined with the BWM, such as TODIM [142]. Multiple integrations combining other useful techniques and the BWM to tackle complex decision-making problems are also potential research areas.

(3) The application areas of the BWM can be extended. Supply chain is a popular application area with the BWM currently. Other application areas, such as artificial intelligence, robots choose for "Industry 4.0" strategy and big data analyze, are good application areas [143].

(4) Scholars who focus on the BWM should strengthen international cooperation. Only 16.93% (21/124) publications came from two countries'/regions' collaboration and only 7 publication came from three or more than three countries'/regions' collaboration. It is noted that some publications' citations are zero. International cooperation with scholars from other countries/regions may improve the quality of publications and increase citations of publications to some extent.

7. Conclusion

Among the MCDM methods, AHP is a most extensively used approach. However, AHP suffers from various drawbacks, such as the redundant pairwise comparisons and the lack for consistency. The BWM is designed to overcome the disadvantages of AHP. Given the less pairwise comparisons and the high consistency of the pairwise comparison matrix in the BWM that those in AHP, the BWM will be as popular as AHP soon after. To identify the status and trends of research related to the BWM and help researchers to improve future researches, a state-of-the-art survey of researches related to the BWM was conducted in this paper. Given that the BWM just has been proposed in three years, there are only 124 publications related to the BWM. We reviewed the contents of these 124 publications. Firstly, we summarized the journals and authors' countries/regions related to the BWM publications. Then, bibliometric analysis with respect to BWM publications in WoS database was done based on the VOSviewer software package. After that, why to propose the BWM and what is the BWM were answered. Later, various integrations and applications of the BWM were summarized to help researchers extract quick information. Furthermore, we introduced the extensions of the BWM from fuzzy logic and group decision making aspects. Finally, the challenge and future research directions related to the BWM were analyzed in detail.

In future, researches of the BWM could be carried from theoretical level and application level in-depth. For the BWM itself, the acceptable consistency ratio value and the inconsistency improving methods can be addressed. The BWM within other contexts, uncertainty or multigranularity, could be investigated. The multi-optimality solution of the model in the BWM could be solved from other perspectives. For applications with the BWM, the software package of the BWM should be developed. The multiple integrations of the BWM should be studied and the other application areas could be extended.

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[3] http://bestworstmethod.com/software/.

Appendix

Table A.1
Summary of the BWM-related journal articles published from 2015–2019 (January).

No.	Journal name	SCI or not	No. of articles	Authors	Year
1	Journal of Cleaner Production	√	10	Rezaei et al. [40]	2016
				Gupta and Barua [24]	2017
				Kaa et al. [48]	2017
				Ahmad et al. [49]	2017
				Wang et al. [29]	2017
				Tian et al. [135]	2018
				Lo et al. [115]	2018
				Nie et al. [139]	2018
				Omrani, Alizadeh and Emrouznejad [130]	2018
				Vahidi, Torabi and Ramezankhani [127]	2018
2	Sustainability	√	8	Pamučar et al. [109]	2017
				You et al. [79]	2017
				Kara and Firat [95]	2018
				Mahdiraji et al. [118]	2018
				Zhao, Zhao and Guo [120]	2018
				Liu et al. [129]	2018
				Stević et al. [144]	2018
				Liu et al. [66]	2018
3	Decision Science Letters	✗	7	Ghaffari [44]	2017
				Abadi et al. [93]	2018
				Askarifar et al. [80]	2018
				Alimohammadloua and Bonyani [114]	2018
				Yadollahi et al. [52]	2018
				Sotoudeh-Anvari et al. [136]	2018
				Sadjadia and Karimi [78]	2018
4	Computers & Industrial Engineering	√	5	Mou et al. [105]	2017
				Cheraghalipour and Saba [97]	2018
				Safarzadeh, Khansefid and Rasti-Barzoki [108]	2018
				Pamucara, Chatterjee and Zavadskasc [131]	2018
				Maghsoodi et al. [124]	2018
5	Symmetry	√	5	Yang et al. [72]	2016
				You et al. [106]	2016
				Stević et al. [111]	2017
				Mei, Liang and Tu [123]	2018
				Zolfani and Chatterjee [103]	2019
6	Expert Systems With Applications	√	4	Rezaei et al. [21]	2015
				Pamučar et al. [112]	2018
				Aboutorab et al. [75].	2018
				Pourhejazy, Sarkis and Zhu [126]	2018
7	Energies	√	3	Kaa et al. [50]	2017
				Zhao, Guo and Zhao [140]	2018
				Zhao, Guo and Zhao [132]	2018
8	International Journal of Production Research	√	3	Yadav et al. [99]	2018
				Huang et al. [137]	2018
				Kusi-Sarpong, Gupta and Sarkis [64]	2018
9	Journal of Air Transport Management	√	3	Rezaei et al. [47]	2017
				Gupta [27]	2018
				Shojaei et al. [113]	2018
10	Knowledge-Based Systems	√	3	Guo and Zhao [38]	2017
				Nie et al. [119]	2018
				Nawaz et al. [100]	2018
11	Technological Forecasting & Social Change	√	3	Gupta and Barua [22]	2016
				Ren et al. [31]	2017
				Kaa, Janssen and Rezaei [53]	2018
12	Applied Soft Computing	√	2	Hafezalkotob and Hafezalkotob [108]	2017
				Tian et al. [138]	2018
13	Environment, Development and Sustainability	√	2	Zhao et al. [51]	2017
				Garg and Sharma [83]	2018
15	International Journal of Logistics Research and Applications	√	2	Gupta and Barua [25]	2017
				Rezaei and Lajimi [59]	2018
16	Mathematical Problems in Engineering	√	2	Zhang et al. [91]	2017

(continued on next page)

Table A.1 (*continued*)

No.	Journal name	SCI or not	No. of articles	Authors	Year
				Liu, Hu and Zhang [84]	2018
17	Omega	√	2	Rezaei [1] Rezaei [20]	2015 2016
18	Scientometrics	√	2	Salimi and Rezaei [33] Salimi [34]	2016 2017
19	Aiche Journal	√	1	Ren et al. [77]	2018
20	Accounting and Financial Control	✗	1	Alimohammadlou and Bonyani [96]	2017
21	American Journal of Finance and Accounting	✗	1	Alimohammadlou and Bonyani [125]	2018
22	Anadolu University Journal of Science & Technology A-Applied Sciences & Engineering	✗	1	Sofuoğlu et al. [92]	2017
22	Benchmarking: An International Journal	√	1	Raj and Srivastava [145]	2018
23	Case Studies on Transport Policy	√	1	Groenendijk, Rezaei and Correia [57]	2018
24	Chemosphere	√	1	Ren [30]	2017
25	Computers and Electronics in Agriculture	√	1	Hafezalkotob et al. [117]	2018
26	Decision Making: Applications in Management and Engineering	✗	1	Badi and Ballem [122]	2018
27	Energy Strategy Reviews	√	1	Bonyania and Alimohammadlou	2018
28	Evaluation and Program Planning	√	1	Salimi and Rezaei [35]	2018
29	Global Journal of Flexible Systems Management	✗	1	Khanmohammadi, Zandieh and Tayebi [76]	2018
30	IEEE Transactions on Reliability	√	1	Liu et al. [128]	2018
31	IEEE Transactions on Cybernetics	√	1	Hafezalkotob et al. [141]	2019
32	Information Sciences	√	1	Mou et al. [104]	2017
33	International Journal of Applied Decision Sciences	✗	1	Cheraghalipour, Paydar and Hajiaghaei-Keshteli [82]	2018
34	International Journal of Construction Management	√	1	Bonyani and Alimohammadlou [60]	2018
35	International Journal of Disaster Risk Reduction	√	1	Sahebi et al. [87]	2017
36	International Journal of Energy Research	√	1	Ren [32]	2018
37	International Journal of Information Technology & Decision Making	√	1	Koçak, Çağlar and Öztaş [37]	2018
38	International Journal of Intelligent Systems and Applications in Engineering	✗	1	Sofuoğlu and Orak [134]	2017
39	International Journal of Machine Learning and Cybernetics	√	1	Li, Wang and Hu [73]	2018
40	International Journal of Social, Behavioral, Educational, Economic, Business and Industrial Engineering	✗	1	Mohaghar et al. [45]	2017
41	Journal of Computational Science	√	1	Serrai et al. [133]	2017
42	Journal of Decision Systems	√	1	Safarzadeh and Rasti-Barzoki [101]	2018
43	Journal of Environmental Management	√	1	Gupta [28]	2018
44	Journal of Medical Systems	√	1	Alsalem [85]	2018
45	Journal of Soft Computing and Decision Support Systems	✗	1	Torbati and Sayadi [146]	2018
46	Management Decision	√	1	Rezaei et al. [58]	2018
47	Operations Research Letters	√	1	Brunelli and Rezaei [36]	2018
48	Packaging Technology and Science	√	1	Rezaei et al. [63]	2018
49	Process Safety and Environmental Protection	√	1	Moktadir et al. [56]	2018
50	Renewable and Sustainable Energy Reviews	√	1	Kaa et al. [70]	2019
51	Renewable Energy	√	1	Vishnupriyan annd Manoharan [65]	2018
52	Resources, Conservation and Recycling	√	1	Ahmadi et al. [42]	2017
53	Safety Science	√	1	Torabi et al. [41]	2017
54	SAGE Open	√	1	Nafari et al. [86]	2017
55	Science of the Total Environment	√	1	Gupta and Barua [26]	2018
56	Studies in Informatics and Control	√	1	Zavadskas [67]	2018
57	Sustainable Cities and Society	√	1	Gupta, Anand and Gupta [23]	2017
58	Technologies	√	1	Mokhtarzadeh and Mahdiraji [98]	2018
59	Technology Analysis & Strategic Management	√	1	Kaa et al. [55]	2018
60	The Online Journal of Science and Technology	✗	1	Sofuoğlu [116]	2018
61	Tourism Management	√	1	Rezaei et al. [94]	2018
62	Transport Policy	√	1	Rezaei et al. [54]	2018
63	Water Resources Management	√	1	Chitsaz and Azarnivand [107]	2017
Subtotal		112			

Table A.2
Abbreviations and explanations.

Abbreviation	Explanation
AD	Axiomatic Design
AHP	Analytic Hierarchical Process
ANP	Analytic Network Process
AQM	Alternative Queuing Method
BWM	Best Worst Method
COPRAS	COmplex PRoportional ASsessment
CPT	Cumulative Prospect Theory
DEMATEL	DEcision MAking Trial and Evaluation Laboratory
EDAS	Evaluation based on Distance from Average Solution
ELECTRE	ELimination Et Choix Traduisant la REalité in French, ELimination and Choice Expressing the Reality
FDM	Fuzzy-Delphi Method
FMEA	Failure Mode and Effects Analysis
GDM	Group Decision Making
GMIR	Graded Mean Integration Representation
GRA	Grey Relational Analysis
IVFRN	Interval-Valued Fuzzy-Rough Numbers
LSM	Lexicographic Semi-order Model
MABAC	Multi-Attributive Border Approximation area Comparison
MADM	Multiple Attribute Decision Making
MAIRCA	Multi-Attributive Ideal-Real Comparative Analysis
MCDM	Multiple Criteria Decision Making
MODM	Multiple Objective Decision Making
MOLP	Multi-Objective Linear Programming
MULTIMOORA	Multi-Objective Optimization by Ratio Analysis plus the full MULTIplicative form
PHFLTS	Proportional Hesitant Fuzzy Linguistic Term Sets
PLS	Partial Least Squares
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
PT	Prospect Theory
QFD	Quality Function Deployment
RIM	Reference Ideal Method
RMCGP	Revised Multi-Choice Goal Programming
SAW	Simple Additive Weighting
SERVQUAL	SERVice QUALity
SWARA	Step-wise Weight Assessment Ratio Analysis
SWOT	Strengths, Weaknesses, Opportunities and Threats
TLF	Taguchi Loss Function
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
VIKOR	VIse Kriterijumska Optimizacija kompromisno Resenje, in Serbian (multiple criteria optimization compromise solution)
WASPAS	Weighted Aggregated Sum Product Assessment
WSA	Weighted Sum Approach
ZOLP	Zero or One Linear Programming

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Table A.3
Summary of the applications of the BWM and its extensions.

Application areas	Approaches	No of publications	References
Supply chain	Z number/BWM	24	Aboutorab et al. [75]
	Bayesian Network/BWM		Abolbashari et al. [90]
	BWM		Ahmadi et al. [42]
	Fuzzy TOPSIS/BWM		Gupta and Barua [24]
	BWM		Mohaghar et al. [45]
	BWM		Rezaei et al. [40]
	BWM/PLS method /BWM		Rezaei et al. [21]
	FDM/BWM		Sadaghiani [39]
	BWM		Sadeghi et al. [89]
	K-means clustering analysis/BWM		Sahebi et al. [87]
	TOPSIS/Fuzzy MOLP/BWM		Ahmad et al. [49]
	RMGP/BWM		Kara and Fırat [95]
	TLF/VIKOR/BWM		Lo et al. [115]
	VIKOR/Sensitive analysis/BWM		Cheraghalipoura and Farsad [97]
	Fuzzy BWM/Entropy/QFD/MULTIMOORA		Fatrias et al. [110]
	Rough BWM/MAIRCA		Cheraghalipour, Paydar and Hajiaghaei-Keshteli [82]
	BWM		Liu et al. [129]
	BWM		Badi and Ballem [122]
	BWM		Rezaei and Lajimi [59]
	BWM/VIKOR		Rezaei et al. [63]
	BWM/SWOT/QFD		Kusi-Sarpong, Gupta and Sarkis [64]
	BWM		Liu, Hu and Zhang [84]
			Vahidi, Torabi and Ramezankhani [127]
			Setyono and Sarno [69]
Manufacturing	BWM	13	Rezaei [20]
	Fuzzy BWM/GMIR		Guo and Zhao [38]
	Fuzzy ANP/BWM		Alimohammadloua and Bonyani [114]
	QFD/PT/PHFLTS/BWM		Huang et al. [137]
	RIM/Entropy/BWM		Sofuoğlu [116]
	Interval BWM		Ren [32]
	Interval BWM		Ren et al. [77]
	Fuzzy BWM		Raj and Srivastava [145]
	Euclidean BWM		Koçak, Çağlar and Öztaş [37]
	BWM		Moktadir et al. [56]
	Fuzzy BWM/Entropy/VIKOR/FEMA		Tian et al. [138]
	BWM		Beemsterboer, Hendrix and Claassen [62]
	Interval BWM		Sadjadia and Karimi [78]
Performance evaluation	BWM		Salimi and Rezaei [35]
	FDM/VIKOR/BWM		Zhao, Zhao and Guo [120]
	ELECTRE III/PROMETHEE II/BWM	8	Bonyani and Alimohammadlou [121]
	Fuzzy BWM		Torbati and Sayadi [74]
	Fuzzy TOPSIS/BWM		Gupta [28]
	BWM		Bonyani and Alimohammadlou [60]
	BWM/DEA/PROMETHEE II		Alimohammadlou and Bonyani [125]
	Fuzzy BWM		Khanmohammadi, Zandieh and Tayebi [76]
Airline industry	VIKOR/BWM	6	Gupta [27]
	MABAC/IVFRN/BWM		Pamučar et al. [112]
	BWM		Rezaei et al. [47]
	VIKOR/TLF/BWM		Shojaei et al. [113]
	SERVQUAL/BWM		Rezaei et al. [94]
	BWM		Gupta and Barua [22]
Energy	TOPSIS/BWM	5	You et al. [79]
	BWM		Kaa et al. [55]
	Entropy method/CPT/Grey theory		Zhao, Guo and Zhao [140]
	Fuzzy BWM/TOPSIS/Taguchi method/Neutral network		Omrani, Alizadeh and Emrouznejad [130]
	FDM/Entropy weight determination/VIKOR		Zhao, Guo and Zhao [132]
Transportation	Cognitive Network Process/BWM	5	Zhang et al. [91]
	BWM		Groenendijk, Rezaei and Correia [57]
	Rough BWM/Rough WASPAS		Stević et al. [144]
	BWM		Rezaei et al. [58]
	BWM		Sharma, Mangla and Patil [61]
Education	Fuzzy-Delphi Method/BWM	4	Nafari et al. [86]
	BWM		Salimi [34]
	BWM		Salimi and Rezaei [33]
	BWM		Yang et al. [72]
Technology	Extension theory/Combined weights/BWM	4	Ren [30]
	TOPSIS/SAW/BWM		Ren et al. [31]
	ZOLP/BWM		Mokhtarzadeh et al. [98]
	BWM		Kaa, Janssen and Rezaei [53]

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Table A.3 (*continued*)

Application areas	Approaches	No of publications	References
Health care	intuitionistic fuzzy multiplicative/group decision making/BWM/GDM	3	Mou et al. [104]
	Intuitionistic fuzzy/Graph theory/BWM		Mou et al. [105]
	BWM/VIKOR		Alsalem [85]
Investment	TOPSIS/BWM	3	Askarifar et al. [80]
	Fuzzy/GDM/BWM		Hafezalkotob and Hafezalkotob [108]
	Probabilistic hesitant fuzzy BWM		Li, Wang and Hu [73]
Location selection	MAIRCA/Rough numbers and fuzzy logic/BWM	3	Pamučar et al. [109]
	ELECTRE III/GDM/BWM		You et al. [106]
	Rough BWM/Rough SAW		Stević [111]
SMEs	BWM	3	Gupta and Barua [22]
	Fuzzy TOPSIS/BWM		Gupta and Barua [25]
	Fuzzy TOPSIS/BWM		Gupta and Barua [26]
Water management	AHP/SWOT/BWM	3	Chitsaz and Azarnivand [107]
	FMEA/Linguistic distribution assessment/BWM		Nie et al. [119]
	Linguistic distribution assessment/TOPSIS/DEMATEL/BWM		Nie et al. [139]
Building	BWM	2	Gupta, Anand and Gupta [23]
	COPRAS/BWM		Mahdiraji et al. [118]
Logistic	BWM	2	Rezaei et al. [54]
	Interval rough BWM/WASPAS/MABAC		Pamucara, Chatterjee and Zavadskasc [131]
Outsourcing adoption	ELECTRE/BWM	2	Yadav et al. [99]
	BWM/VIKOR		Garg and Sharma [83]
Sharing Arrangements	BWM	2	Praditya and Janssen [46]
	QFD/fuzzy MULTIMOORA/fuzzy BWM		Tian et al. [135]
Turning operations	TOPSIS/Grey relational analysis/Weighted sum approach/BWM	2	Sofuoğlu and Orak [134]
	BWM		Sofuoğlu et al. [92]
Verification	BWM	2	Vishnupriyan and Manoharan [65]
	BWM		Zavadskas [67]
Web service selection	AHP/Borda/BWM	2	Serrai et al. [81]
	VIKOR/BWM		Serrai et al. [133]
Agriculture	MULTIMOORA/WASPAS/BWM	1	Hafezalkotob et al. [117]
Automotive	BWM	1	Kaa et al. [50]
Banking service	BWM	1	Yadollahi et al. [52]
Biology	BWM	1	Kaa et al. [48]
Car selection	Lexicographic semi-ordermodel (LSM)/Sensitive analysis	1	Safarzadeh and Rasti-Barzoki [101]
Cloud service selection	Markov chains/BWM	1	Nawaz et al. [100]
Eco-industrial parks	BWM	1	Zhao et al. [51]
Emergency routes evaluation	2-tuple linguistic BWM/QFD	1	Mei, Liang and Tu [123]
Emotion management	BWM	1	Alhubaishy and Benedicenti [43]
Environment	BWM	1	Liu et al. [66]
Film/Movie Theater	EMSR-B/BWM	1	Joshi and Lohiya [88]
Food industry	PROMETHEE II/BWM	1	Alimohammadlou and Bonyani [96]
Mathematics	BWM	1	Brunelli and Rezaei [36]
Medical tourism	SWOT/BWM	1	Abadi et al. [93]
Mining	BWM	1	Ajrina, Sarno and Ginardi [68]
Mobile phone selection	BWM	1	Rezaei [1]
Piping selection	BWM/GDM	1	Safarzadeh, Khansefid and Rasti-Barzoki [102]
Polygeneration	Interval TOPSIS/Fuzzy BWM	1	Wang et al. [29]
Product deletion	Fuzzy BWM/MACBETH	1	Pourhejazy, Sarkis and Zhu [126]
Product design	Fuzzy BWM/AD	1	Maghsoodi et al. [124]
Risk assessment	BWM	1	Torabi et al. [41]
Search problem	simple additive weighting/BWM	1	Sotoudeh-Anvari et al. [136]
Water treatment plant	BWM/AQM/FMEA	1	Liu et al. [128]

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