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Review article

A state of the art literature review of VIKOR and its fuzzy extensions on applications

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ABSTRACT

Multi criteria decision making (MCDM) is one of the research areas of operations research and management science which has widely studied by researchers and practitioners. It finds a compromise solution for evaluating and ranking alternatives from the best to the worst under conflicting criteria with respect to decision maker(s) preferences. In a compromise approach, the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR; that means multi-criteria optimization and compromise solution) continues to be applied satisfactorily across different application areas. This paper conducts a state-of-the-art literature review to categorize, analyze and interpret the current research on VIKOR applications. It also discusses the extensions of VIKOR applied in fuzzy environments. A total of 343 papers are classified into 13 different application areas and a number of sub-application areas. Furthermore, all papers are also categorized with respect to publication year, published journal, country of origin, application type (real case study vs empirical study), and version of fuzzy sets used. This comprehensive literature review provides an insight for researchers and practitioners on VIKOR applications in terms of showing current state and potential areas for future attempts to be focused in the future.

Contents

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1. Introduction

MCDM is one of the research areas of operations research and management science which has been widely studied by researchers and practitioners. It concerns about evaluating, assessing and selecting alternatives from the best to the worst under conflicting criteria with respect to decision maker(s) preferences. The main characteristics of an MCDM method include: (1) alternatives, (2) criteria against which the alternatives are evaluated, (3) scores that reflect the value of an alternative's expected performance on the criteria, and (4) criteria weights that measure the relative importance of each criterion as compared with others [1]. There are several MCDM methods proposed by researchers in literature. VIKOR is one of the famous MCDM methods that ranks alternatives and determines the compromise solution that is the closest to the "ideal". Regarding to the rapid increase in applications of VIKOR among others, we prompted to make this review to contribute to the literature by adding the recent VIKOR applications and draw a path for future studies.

Some studies need to be mentioned here to explain the need for this study. The scope of the earlier review papers on MCDM methods are illustrated in Table 1. Vaidya and Kumar [2] discussed analytic hierarchy process (AHP) that is extensively used as a developed tool. Ho [3] reviewed the literature on the applications of the integrated AHPs. Emrouznejad et al. [4] presented a comprehensive listing and analysis of data envelopment analysis (DEA) papers published between 1978 and 2008. Behzadian et al. [5] conducted a state-of-the-art literature survey to classify the research on technique for order preference by similarity to ideal solution (TOPSIS) applications and methodologies. Hatami-Marbini et al. [6] presented a classification scheme as four primary categories, namely, the tolerance approach, the a-level based approach, the fuzzy ranking approach and the possibility approach for DEA. Zavadskas and Turskis [7] considered decision making in light of the recent developments of MCDM methods in economics. A classification scheme and a comprehensive literature review was presented by Behzadian et al. [8] to uncover, classify, and interpret the current research on preference ranking organization method for enrichment of evaluations (PROMETHEE) methodologies and applications. Yin [9] conducted a bibliometric study on publication and citation patterns of grey system theory for papers published between 1996 and 2010 through a systemic search using the ISI web based databases with a specific focus on grey relational analysis (GRA) and grey prediction. In their literature review, Baležentis and Baležentis [10] focused on the full multiplicative form of multi-objective optimization by ratio analysis (MULTIMOORA) method. Specifically, they discussed its development as well as extensions alongside with an overview of their applications. Govindan and Jepsen [11] investigated how the Elimination et choix traduisant la realité (ELECTRE) and ELECTRE-based methods have been applied in various research

Table 1
Characteristics of earlier review studies.

Paper	Scope	Year	No. of papers
Vaidya and Kumar [2]	AHP application	Up to 2003	150
Ho [3]	Integrated AHP and applications	1995–2009	66
Emrouznejad et al. [4]	DEA bibliography	1978–2007	–
Behzadian et al. [5]	PROMETHEE methods and applications	Up to 2012	217
Hatami-Marbini et al. [6]	Fuzzy DEA	1992–2010	100
Zavadskas and Turskis [7]	MCDM in economics	Up to 2011	–
Behzadian et al. [8]	TOPSIS applications	2000–2012	266
Yin [9]	Grey system theory and GRA bibliography	1996–2010	–
Balezentis and Balezentis [10]	MULTIMOORA methods and applications	Up to 2012	–
Govindan and Jepsen [11]	ELECTRE methods and applications	Up to 2014	686
Kahraman et al. [12]	Fuzzy MCDM methods	1980–2014	–
Mardani et al. [13]	Fuzzy MCDM techniques and methods	1994–2014	403
Yazdani and Graeml [15]	VIKOR applications	2002–2014	198
Celik et al. [14]	MCDM based on IT2FSs	2007–2015	82
Our study	VIKOR applications	1998–2015	343

areas. It includes the application areas, modifications of the methods, comparisons with other methods, and general studies on ELECTRE methods. Kahraman et al. [12] surveyed the latest status of fuzzy MCDM methods and classified these methods by dividing into two parts: fuzzy multiattribute decision-making (MADM) and fuzzy multiobjective decision-making (MODM). Mardani et al. [13] systematically reviewed the applications and methodologies of fuzzy MCDM techniques. This study reviewed a total of 403 papers published between 1994 and 2014 in more than 150 peer reviewed journals. Celik et al. [14] reviewed 82 different papers using various MCDM approaches based on interval type-2 fuzzy sets which are classified into 35 categories. Yazdani and Graeml [15] made a literature review of 198 papers published in more than 100 journals and conference proceedings from 2002 to 2014.

This paper also aims to eliminate some limitation aspects of the existing literature reviews abstracted above. A comprehensive review considering recent year has not appeared yet. Apart from the VIKOR literature by Yazdani and Graeml [15], 343 papers are presented according to 13 main application areas and their sub application areas. We also analyzed the VIKOR extensions based on fuzzy sets. The distribution of papers are retrieved by the points of view as (1) publication year, (2) publication journal, (3) country of origin, (4) main application area and application type, (5) main application area and approach type, (6) version of fuzzy numbers used and (7) VIKOR method extensions. Hopefully, this paper fills the gap on this area.

The paper is prepared in the following manner. Section 2 presents the methodology of VIKOR. Section 3 describes the followed literature reviewing methodology. Section 4 reveals the discussion that includes the results of reviewing process. The last section presents conclusions, limitations and future recommendations in this field.

2. The methodology of VIKOR

The VIKOR method was developed [16] as an MCDM method to solve a discrete multi criteria problem with noncommensurable and conflicting criteria [17]. It is aimed to determine a compromise solution for ranking and selecting considering conflicting criteria. The compromise solution is a feasible solution which is the closest to the ideal solution [17]. The compromise ranking algorithm VIKOR has the following steps [16,17]:

Assuming that each alternative is evaluated according to each criterion, the compromise ranking could be done by comparing the measure of closeness to the ideal alternative. Let various n alternatives are denoted as $A_1,A_2,...,A_n$. For alternative A_j, the related rating of the ith criterion is denoted by $f_{ij}(i=1,2,...,m;\ j=1,2,...,n)$.

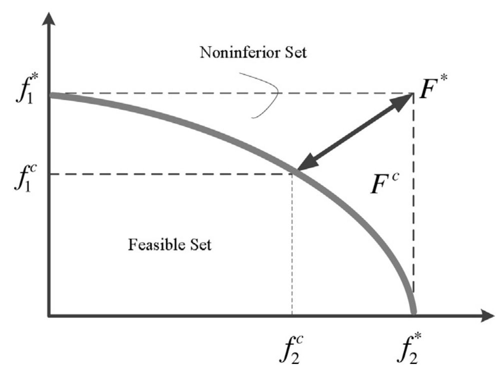

Fig. 1. Ideal and compromise solutions.

The compromise solution F^c is a feasible solution that is the “closest” to the ideal F^*, and compromise solution means an agreement established by mutual concessions, as illustrated in Fig. 1 by $\Delta f_1 = f_1^* - f_1^c$ and $\Delta f_2 = f_2^* - f_2^c$.

The compromise ranking algorithm of the VIKOR method has the following steps:

Step 1. Determine the best f_i^* and the worst f_i^- values of all criterion functions, $i=1,2,...,m$. If the ith function represents a benefit or cost then:

$f_i^* = \max_j f_{ij},\ f_i^- = \min_j f_{ij}$, if the$i$th function represents a benefit,

$f_i^* = \min_j f_{ij},\ f_i^- = \max_j f_{ij}$, ifthe$i$th function represents a cost

Step 2. Compute the values S_j and R_j, by the relations

$$S_j = \sum_{i=1}^{n} w_i \frac{(f_i^* - f_{ij})}{(f_i^* - f_i^-)}$$

$$S_j = \max \left[w_i \frac{(f_i^* - f_{ij})}{(f_i^* - f_i^-)} \right]$$

Step 3. Calculate Q_j values $j=1,2,...,n$, according to the S_j and R_j using Eq. (1).

$$Q_j = v\frac{(S_j - S^*)}{(S^- - S^*)} + (1-v)\frac{(R_j - R^*)}{(R^* - R^*)} \quad (1)$$

where $S^* = \min_j S_j,\ S^- = \max_j S_j,\ R^* = \min_j R_j,\ R^- = \max_j R_j,$ $v \in [0, 1]$ is the weight of the decision making strategy of the “majority of attributes” (or “maximum group utility”).

Step 4. Rank the alternatives, sorting by the values S, R, and Q in decreasing order.

Step 5. Propose a compromise solution to the alternative A_1 which is ranked as the best by the measure Q (minimum) if the following two conditions are satisfied:

Condition 1. The acceptable advantage:$Q_{A_2} - Q_{A_1} \geq DQ$, where A_2 is the alternative with second position in the ranking list by Q; $DQ = 1/(n-1)$.

Condition 2. Acceptable stability in decision making: Alternative A_1 must also be the best ranked by S or/and R. This compromise solution is stable within a decision making process, which could be: "voting by majority rule" (when $v > 0.5$ is needed), or "by consensus" $v \approx 0.5$, or "with veto" ($v < 0.5$). Here, v is the weight of the decision making strategy "the majority of criteria" (or "the maximum group utility").

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Alternatives A_1 and A_2 if only Condition 2 is not satisfied, or
- Alternatives $A_1, A_2, \ldots, A_N$ if Condition 1 is not satisfied; and A_N is determined by the relation $Q_{A_N} - Q_{A_1} < DQ$ for maximum N (the positions of these alternatives are "in closeness").

Aggregation, normalization and preference are fundamental issues of VIKOR method [17,20]. These issues are scrutinized in the following.

2.1. Aggregation

VIKOR method is developed using the following form of $L_{p,j}$:

$$L_{p,j} = \left\{ \sum_{i=1}^{n} \left[w_i \frac{(f_i^* - f_{ij})}{(f_i^* - f_i^-)} \right]^p \right\}^{1/p}, \quad 1 \leq p \leq \infty; \; j = 1, 2, \ldots, n.$$

$L_{p,j}$ is introduced by Duckstein and Opricovic [18] and it represents the distance of the alternative A_j to the ideal solution. The compromise solution, $F^c = (f_1^c, \ldots, f_n^c)$, is the "closest" one to the ideal, F^*,so that is the feasible solution. An agreement established by mutual concessions is meant as compromise, showed by $\Delta f_i = f_i^* - f_i^c$, $i = 1, \ldots, n$.

L_p-metric represents the distance function as an aggregating function, which is called the group regret for a decision. A regret that the ideal cannot be selected [19]. Here, L_1 is the sum of all individual regrets (disutility), and L_∞ is the maximal regret that an individual could have [17,20]. In VIKOR method $L_{1,j}$ (as S_j) and $L_{\infty,j}$ (as R_j) are used to formulate ranking measures. The solution obtained by min S_j has a maximum group utility ("majority" rule), and the solution obtained by min R_j has a minimum individual regret of the opponent. The merit function Q aggregates S and R with weight v. Aggregating function should be used with an extreme caution since comparison may involve potentially incomparable quantities (noncommensurable criteria). The main difference appears in the aggregation approaches. VIKOR method uses an aggregation function representing the distance from the ideal solution. On the other hand, TOPSIS method uses the ranking index including the distances from the ideal point and the negative-ideal point. The highest ranked alternative determined by VIKOR is the closest to the ideal solution. However, the highest ranked alternative determined by TOPSIS is the best in terms of the ranking index, which does not mean that it is always the closest to the ideal solution. The PROMETHEE method offers six types of preference functions, while the VIKOR method introduces linear normalization. A result by PROMETHEE is based on the maximum of group utility, whereas the VIKOR method integrates maximum group utility and minimal individual regret. ELECTRE II is compared with VIKOR in order to point out the VIKOR's background. The ELECTRE II method provides good pairwise comparisons, which are based on the outranking relation, that use concordance and discordance matrices. Results obtained by ELECTRE II are relatively similar to the results of VIKOR.

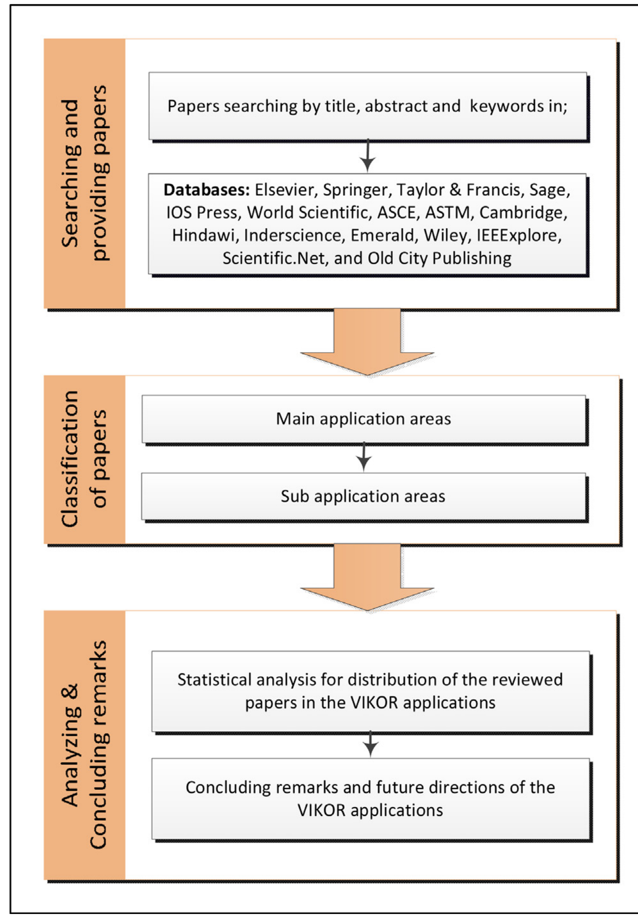

Fig. 2. Research methodology flow of the literature review.

Regarding the development of the fundamental issues of VIKOR method, various aggregation calculations are proposed as in Table 2. For example, in order to eliminate error calculation when some criteria have no difference among alternatives, a new aggregation function in regret and utility calculation was proposed [198,204,340]. Vahdani et al. [228] and Anvari et al. [98] used a new aggregation method considering the ideal and negative-ideal separation feature of TOPSIS method. Tsai et al. [281], Ou Yang et al. [269] and Liou et al. [245] proposed a different regret calculation function that does not consider the importance weights of criteria. Jahan et al. [43] proposed a new exponential function for regret and utility calculations.

2.2. Normalization

To add values of noncommensurable criteria, all criteria have to be converted into the same units. In MCDM problems, normalization is applied to eliminate the units of criterion functions, so that all the criteria are dimensionless. In linear normalization, the normalized value is determined by dividing the value of criterion function by its maximum value. While VIKOR method uses linear normalization, distinctively, TOPSIS method uses vector normalization [17]. Linear normalization used in VIKOR is based on old ideas of compromise programming [18,19]. Comparative studies are presented for VIKOR and TOPSIS [17,20], VIKOR and PROMETHEE, and VIKOR and ELECTRE [20]. The linear normalization and normalized value

Table 2
Development of the fundamental issues of VIKOR method.

Study	Aggregation related novelty	Normalization related novelty	Explanation
Chang [340], Chang [198], Chang and Hsu [204]	√		A new aggregation function in regret and utility calculation is proposed to eliminate error calculation when some criteria have no difference among alternatives
Vahdani et al. [228]	√	√	Vector normalization is used instead of linear normalization and a new aggregation benefiting from the ideal and anti-ideal separation feature of TOPSIS method is preferred
Tsai et al. [281]	√		They propose different regret calculation function that does not consider the importance weights of criteria
Ou Yang et al. [269], Liou et al. [245]	√	√	They propose aspired and tolerable levels for benefit and cost criteria, respectively. Then, they calculate a new normalization measure using absolute differences. Also, the importance weights of criteria are not considered when calculating regret function
Anvari et al. [98]	√		They use a new aggregation considering the ideal and negative-ideal separation feature of TOPSIS method
Jahan et al. [43]	√		They propose a new exponential function for regret and utility calculations

Table 3
Preference issues of VIKOR method.

Weights generating method(s)	Related studies
DEMATEL + ANP	[57,86,88,103,109,126–132,160,174,177,178,196,253,261–263,267,268,272–274,280,286,295,311–313,320,323]
AHP	[29,37,73,75,87,96,108,112,137,155,243,251,294,298,316,328,330,360]
FAHP	[23,59,63,79,81,82,101,114,115,118–120,133–136,159,167,171,186,192,208,222,252,260,264,265,276,277,285,288,292,297,314,332–335,337]
ANP	[189,221,225,259,280,281,304,336]
Entropy	[24,143,145,173,187,199,296,302,359]
AHP + Entropy	[26,35,325]
DEMATEL + ANP + BSC	[132,288,289]
SWARA	[164,172,238]

that VIKOR uses does not depend on the evaluation unit of a criterion. Differently, the TOPSIS method uses vector normalization. In some VIKOR related papers, various normalization techniques are proposed. While Vahdani et al. [228] used vector normalization instead of linear normalization; Ou Yang et al. [269] and Liou et al. [245] proposed aspired and tolerable levels for benefit and cost criteria, respectively. They calculated a new normalization measure using absolute differences.

2.3. Preference

Weighting coefficients are presented to express the relative importance of different criteria considering decision makers' preferences. These weights give the opportunity for modeling the actual decision making process. The importance weights of criteria are used to evaluate stability of the ranking. In VIKOR method, the importance weight of each criterion ranges between 0 and 1 and the sum of all is equal to 1. While generating criteria weights, different methods decision-making trial and evaluation laboratory (DEMATEL + ANP, AHP, FAHP, ANP, Entropy, AHP + Entropy, DEMATEL + ANP + BSC, SWARA) are used in the VIKOR related studies as presented in Table 3.

3. Research methodology for literature review

This literature review was carried out to present articles in notable journals that provide important insights to researchers and practitioners studying on the VIKOR method. With this scope, we followed a research methodology consisting of three steps as shown in Fig. 2.

The first step is about collecting relevant papers from significant databases with the keyword of VIKOR (or vikor). In this way we conducted an extensive search for VIKOR in the title, abstract, and keywords of scholarly papers. The following databases are reviewed: Elsevier, Springer, Taylor & Francis, Sage, IOS Press, World Scientific, ASCE, ASTM, Cambridge, Hindawi, Inderscience, Emerald, Wiley, IEEExplore, Scientific.Net, and Old City Publishing. Conference proceeding papers, book chapters, master's thesis, doctoral dissertations, textbooks, and unpublished working papers were excluded from the literature review. The number of potentially relevant papers, identified initially for this review by title, abstract, and keywords, were 1475 in the library databases published between 2000 and 2015. As the most scholarly papers on VIKOR have been published after 2000, we choose this year as a starting year for search. We then excluded 1129 papers by title, abstract, and keywords since they did not include the application, development or modification of the VIKOR method or a performance comparison of VIKOR with other MCDM methods. Within this scope, we retrieved 346 papers as full text reviewing process. Three papers were excluded after full text reviewing process. As a result, we included 343 papers in this review study as shown in Fig. 3.

The papers were analysed, classified, coded, and recorded on an Excel sheet. Each paper was classified by several categories: paper ID, paper name, publication year, authors' nationality, journal title, database name, method type (single or hybrid), version of fuzzy sets whether the VIKOR method is used with fuzzy sets, main application area, sub application area, methods whether it is combined or compared with other MCDM methods, and general focus of the study.

The second step is about the classification of the papers in terms of application and sub application areas. In this step we followed the categorization method of Govindan and Jepsen's [11]. We categorized the papers into one of 13 categories. The categories are: (1) Design, mechanical engineering and manufacturing, (2) Business management, (3) Logistics and supply chain management,

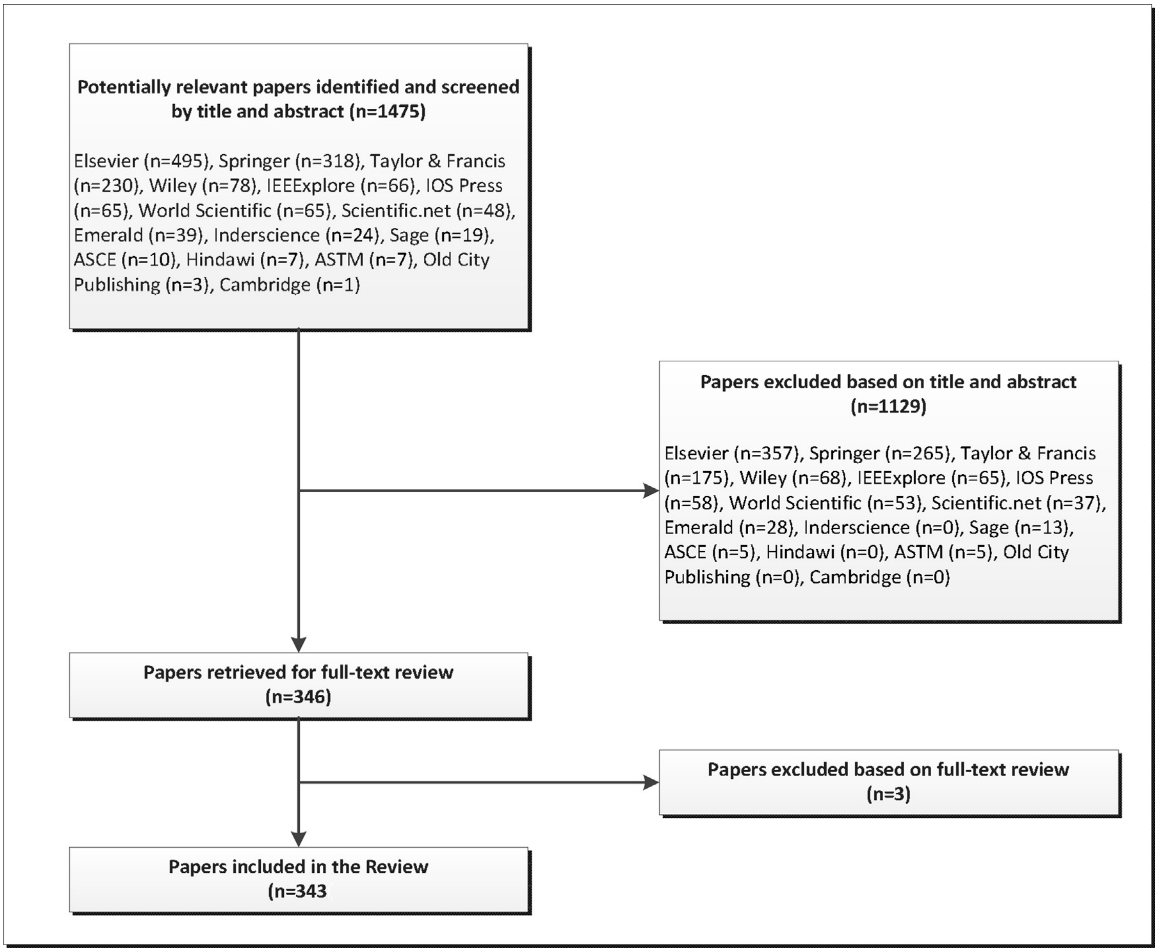

Fig. 3. Diagram of included and excluded papers from the literature review.

(4) Natural resources and environmental management, (5) Structural, construction and transportation engineering, (6) Information technology, (7) Policy, social and education, (8) Energy management, (9) Financial management, (10) Health, safety and medicine, (11) Chemical and biochemical engineering, (12) Agriculture, (13) Other areas and non-specific applications. The third step is about analysing the statistical results for distribution of the papers and concluding remarks for the future VIKOR studies.

4. Application areas

In this section, 343 papers are presented according to 13 main application areas and their sub application areas as presented in Fig. 4.

4.1. Design, mechanical engineering and manufacturing

Design, mechanical engineering and manufacturing category is by far the most popular application area for VIKOR methods with 87 papers. Material selection, robot selection, new product development and machine tool selection are some of the most prevalent sub application areas in this main category. Other papers consider various problems related to maintenance of manufacturing systems and sustainability. Fig. 5 shows the distribution of the papers in the design, mechanical engineering and manufacturing category according to sub application areas.

4.1.1. Material selection

To select the optimal material among a wide variety of material alternatives seems like a very complex process [1]. Various criteria are considered for selecting a material, such as material properties, material cost and availability, processing and environment. Toward this end, VIKOR method gained a high importance in this field. Material selection sub category is the most popular sub application area among others with 37 papers. While 19 of them present real case applications, the remaining gives empirical examples that are applied by past researchers. The studies including real case applications focus on the selection of various material types. For instance; Mohantya and Mahapatra [21] applied VIKOR approach to office chair selection, Girubha and Vinodh [22] for an automotive component material selection, Anojkumar et al. [23] to pipe material selection in sugar industry, Chauhan and Vaish [24] to magnetic material selection, Vats and Vaish [25] to piezoelectric material selection, Çalıskan [26] to coating material selection, Athawale et al. [27] to gear material selection, Vats and Vaish [28] to lead-free piezoelectric ceramics selection, Wang et al. [29] to low-temperature phase-change materials for thermal energy storage, and Maity and Chakraborty [30] to tool steel material selection. Lin et al. [31] combined the fuzzy weighted average (FWA) with fuzzy inference system (FIS) for material substitution selection in the electronics industry. Cavallini et al. [32] and Vats et al. [33] proposed integrated quality function deployment (QFD)-VIKOR methods for material selection problem. While Cavallini et al. [32] presented a case study for the identification of the best coating for the protection of an aluminium alloy substrate (Al-7075) from the effects of abrasive wear against an alternating counter-

Fig. 4. Distribution of papers according to main application areas.

Fig. 5. Distribution of papers in the design, mechanical engineering and manufacturing category according to sub application areas.

part made by a high-strength cast iron. Vats et al. [33] focused on the selection of ferroelectric ceramics for transducer and energy storage applications. Darji and Rao [34] disclosed the application of four intelligent MCDM methods for solving material selection of pipes in sugar industry. Extended TODIM (an acronym in Portuguese of Interactive and Multicriteria Decision Making), additive ratio assessment (ARAS), operational competitiveness rating analysis (OCRA), evaluation of mixed data (EVAMIX) are used for the best material selection among five alternative materials. A comparison of TOPSIS, VIKOR, ELECTRE, and PROMETHEE methods is also provided in the paper. Similarly, Çalışkan et al. [35] used a decision model including extended PROMETHEE II, TOPSIS and VIKOR methods for the selection of the best material for the tool holder used in hard milling. The criteria weighting is performed by AHP and Entropy methods. The candidate materials are ranked using these methods and the results obtained by each method are compared. Bahraminasab and Jahan [36] considered the selection of the best material among the set of alternatives for femoral component of total knee replacement (TKR) byVIKOR approach. It is concluded that the use of new materials over the existing ones is suggested, and porous and dense NiTi shape memory alloys are ranked as the first and second alternatives, respectively. Bahraminasab et al. [37] investigated the effect of material choice and geometrical configuration used in the design of location pegs on the performance of the femoral component in a TKR. Jahan [38] proposed a material selection model solved with VIKOR and mixed 0–1 goal programming. The proposed model is justified by ranking the candidate materials for a rigid pin which is implanted in the shaft of the femur, and comparing the result with other methods.

Eighteen papers in material selection sub category present new VIKOR based methods considering empirical examples. Chauhan and Vaish [39] developed TOPSIS, cross entropy, and VIKOR with interval data for material selection. Chauhan and Vaish [40] and Yazdani and Payam [41] compared TOPSIS, VIKOR and Ashby approaches for selecting proper material. Respectively, Jahan et al. [42], Jahan et al. [43] and Jahan et al. [44] proposed linear assignment method, a new calculation for utility and regret of VIKOR approach and fuzzy VIKOR. All methods were compared with extended TOPSIS. Jahan et al. [45] proposed an aggregation technique for optimal decision making in material selection. In this approach, ranking orders are obtained by various MCDM methods, and then they were used as the inputs for the suggested procedure to obtain aggregation rankings. Jahan and Edwards [46] presented a new VIKOR method for ranking materials with simultaneous availability of interval data. Shanian and Savadogo [47] applied different MCDM approaches for material selection problem.

ELECTRE, VIKOR, complex proportional assessment of alternatives (COPRAS), EVAMIX, PROMETHEE II, complex proportional assessment of alternatives with grey relations (COPRAS-G), organization, rangement et synthese de donnes relationnelles (ORESTE) and OCRA are used for material selection problems by Chatterjee et al. [48], Chatterjee et al. [49] and Chatterjee and Chakraborty [50]. Chatterjee et al. [48] used ELECTRE and VIKOR methods. Chatterjee and Chakraborty [50] focused on the application of four preference ranking-based MCDM methods (PROMETHEE II, COPRAS-G, ORESTE and OCRA methods) for solving a gear material selection problem. Chatterjee et al. [49] explored the applicability and capability of COPRAS and EVAMIX methods for materials selection. The ranking performances of these methods were also compared with that of the past researchers. Rao [51] and Rao and Patel [52] applied VIKOR for material selection problem. Rao and Patel [52] proposed a novel approach that uses fuzzy logic to convert the qualitative attributes into the quantitative ones.

Karande and Chakraborty [53] applied MOORA method to solve common material selection problems and compared the results with VIKOR, ELECTRE, and TOPSIS. Athawale and Chakraborty [54] used a comparative analysis between 10 most commonly used MCDM methods while solving three real time material selection problems. Their relative performances were compared with respect to the rankings of the alternatives while selecting suitable materials for (a) a sailing boat mast, (b) a flywheel, and (c) a cryogenic storage tank. It is concluded that VIKOR method has a relatively better performance than the others due to its computational simplicity.

Liu et al. [55] proposed an integrated induced ordered weighted averaging VIKOR method to solve MCDM problems with conflicting and non-commensurable criteria, specifically considering the complex attitudinal character of the decision maker. In their study, a numerical example for material selection problem was given, and a comparison with other MCDM methods and types of standardized distance aggregation operators were made. Liu et al. [56] presented an interval 2-tuple linguistic VIKOR method for solving a material selection problem under uncertain and incomplete information. Liu et al. [57] proposed a novel hybrid MCDM model combining DEMATEL-based analytic network process (ANP) and modified VIKOR to solve a material selection problem.

Based on the comprehensive review on the material selection subsection, VIKOR is a good choice in material selection problems, because it has the advantages in theory and application as follows: (1) it is a useful method when dealing with a large number of alternatives and criteria and, also, applying linguistic values by using fuzzy logic to handle the uncertainty in real situations. (2) It is able to use qualitative and quantitative data for the selection process. (3) It presents a systematic process that solves problems easily and fast. (4) It obtains an output that is a preferential ranking of the material alternatives with a numerical value and provides a better understanding of differences and similarities among alternatives. (5) The main advantage of VIKOR method is that it introduces the ranking based on the measure of "closeness" to the ideal solution, and compromises solution which provides a maximum group utility for the "majority" and a minimum individual regret for the "opponent" [56]. However, it has some restrictions. Since materials researchers frequently study under crisp data, they rarely prefer fuzzy based VIKOR methods. Therefore, various material selection problems can be dealt with the progress in fuzzy set theory aided with VIKOR for future studies.

4.1.2. Robot selection

Robot selection is one of the most studied sub category under design, mechanical engineering and manufacturing main area. Competitiveness in the sector in terms of the productivity of the facilities and quality of the products are affected by appropriate robot selection [58]. The selection of the most appropriate robot considering multiple conflicting qualitative and quantitative criteria is a challenge for the decision makers. Hence, VIKOR based studies are available in the literature that are applied for robot selection problems.

Five of the papers in this sub category present real case applications in robot selection problems. Ic et al. [59] developed a robot selection approach based on fuzzy AHP. The results of the case study are compared with AHP-TOPSIS and VIKOR methods. Samantra et al. [60] proposed an interval-valued trapezoidal fuzzy VIKOR for industrial robot selection. Chatterjee et al. [61] presented robot selection problem using two most appropriate MCDM methods (ELECTRE II, VIKOR) and compared their relative performances for a given industrial application. Athawale et al. [62] focused on solving the industrial robot selection problem using VIKOR method. Bairagi et al. [63] employed three fuzzy MCDM methodologies (fuzzy VIKOR, fuzzy TOPSIS, COPRAS-G) in the evaluation and selection of robots for automated foundry operations. Fuzzy AHP is used to estimate the fuzzy weights of the considered selection criteria.

Devi [64] proposed an intuitionistic fuzzy VIKOR to solve MCDM problems in which the performance rating values as well as the weights of criteria are linguistic terms, which are expressed by triangular intuitionistic fuzzy sets. Rao et al. [65] proposed a novel decision making method considering objective and subjective preferences and three examples in material selection. The result of proposed method was compared with other methods. Liu et al. [66] proposed an interval 2-tuple linguistic TOPSIS method to handle a robot selection problem under uncertain and incomplete information. The results are compared with fuzzy hierarchical structure analysis, fuzzy TOPSIS, the interval-valued fuzzy modified TOPSIS, the intuitionistic fuzzy VIKOR and the ELECTRE. Bairagi et al. [67] proposed a De Novo multi-approaches multi-criteria decision making method namely technique of precise order preference. Parameshwaran et al. [58] presented an integrated approach for the optimal selection of robots considering both objective and subjective criteria. The approach utilizes fuzzy Delphi method, fuzzy AHP, fuzzy modified TOPSIS, fuzzy VIKOR and Brown–Gibson model for robot selection. Ghorabaee [68] proposed an interval type-2 fuzzy VIKOR method for robot selection problem. They compared the results with interval type-2 fuzzy TOPSIS, interval type-2 fuzzy COPRAS and other three different MCDM methods.

Unlike the material selection problem, fuzzy based VIKOR approaches are mostly studied in the robot selection problems. Integration of hesitant fuzzy sets with the concept of VIKOR method can be addressed as a future research for robot selection problems.

4.1.3. New product development

New product development (NPD) and selection is an important task driving the competitive advantage of manufacturing companies [69]. Since it is a complex problem, which involves risks and uncertainties in nature, researchers consider NPD in MCDM environment and develop several VIKOR based models. In this sub application area, new product design, concept selection, rapid prototyping technology selection and product development partner selection are handled by papers.

Mousavi et al. [69] proposed fuzzy VIKOR for new product design. Vinodh et al. [70] applied fuzzy VIKOR for concept selection in an agile environment and compared the results with the fuzzy TOPSIS results. Vinodh et al. [71] examined fuzzy VIKOR for selecting the appropriate rapid prototyping technologies in an agile environment. Wang and Wu [72] presented a three-phase approach; first, customer preferences were captured, second, conjoint analysis was employed to extract customer utilities of core attributes and Kano model was utilized to elicit customer perceptions of optional attributes, finally, product varieties were systematically assessed based on maximizing overall customer satisfaction by VIKOR. Büyüközkan and Görener [73] applied AHP and VIKOR for product development partner selection problem.

Lin et al. [74] integrated fuzzy DEMATEL and VIKOR for evaluating product concept under fuzziness. Zhu et al. [75] presented a systematic evaluation method by integrating AHP and VIKOR to evaluate design concepts under a subjective environment. Vinodh et al. [76] applied fuzzy VIKOR method for the best fit concept selection.

Within the current studies, fuzzy VIKOR based concept selection problems are performed. In the future studies, the problems can be solved using VIKOR with various fuzzy set versions such as interval type-2 fuzzy sets, hesitant fuzzy sets and intuitionistic fuzzy sets; also hybrid MCDM methods can be explored for new NPD solutions.

4.1.4. Machine tool selection

Machine tool selection sub category is the third most popular sub application area among others with 14 papers. While 9 of them present real case applications, the remaining gives empirical examples. In this sub application area, weft-knitting machine efficiency, CNC machine tool selection, apt machine tool selection, polishing tool process selection, biodiesel blend selection, electronic toll collection system and optimization problems of some machines are handled in papers.

Fallahpour and Moghassem [77] ranked spinning machine parameters among available alternatives on the basis of the yarn quality parameters by the VIKOR and introduced the best alternative for increasing weft-knitting machine efficiency. Sahu et al. [78] proposed trapezoidal fuzzy sets based VIKOR method to CNC machine tool selection. Illangkumaran et al. [79] presented a hybrid fuzzy AHP and fuzzy VIKOR model for the selection of an apt machine tool among various alternatives. The fuzzy AHP is used for determining the criteria weights whereas fuzzy VIKOR is used to obtain the final ranking of machine tool alternatives. Chaturvedi and Singh [80] benefited from VIKOR method in multi response optimization of process parameters of abrasive water jet machining for stainless steel AISI 304. Arunachalam et al. [81] applied two MCDM methods, AHP and fuzzy VIKOR, to select the process of a polishing tool. Sakthivel et al. [82] proposed a hybrid fuzzy AHP-TOPSIS and fuzzy AHP-VIKOR methodologies to select the best biodiesel blend for IC engines. Vats et al. [83] proposed a fuzzy VIKOR based model for optimal electronic toll collection system in India. Koyee et al. [84] applied coupled Taguchi-VIKOR with firefly algorithm neural network system to model and optimize the machining duplex stainless steels. Ray [85] developed a combination of GRA with principal component analysis (PCA) method to solve multi response parameter optimization problems of green manufacturing. The results of fuzzy-TOPSIS and VIKOR methodologies were compared with the results of the proposed methodology.

Azaryoon et al. [86] proposed a combination of DEMATEL, ANP, and VIKOR methods for selection of non-conventional machining processes. Ray [87] aimed to select the optimum cutting fluid that considers minimization of the environmental impact, cost and the maximization of the quality. The criteria weights were obtained using AHP and ranking of the alternatives, which is calculated using VIKOR method. Liao et al. [88] proposed DEMATEL based ANP and VIKORframework for evaluating and enhancing an appropriate three-dimensional printing based rapid prototyping service provider. Feng et al. [89] applied VIKOR method to compute the ranking values of three schemes of the paper feeding mechanism in a card punching machine. Zhang and Xu [90] proposed a VIKOR method including model for optimal design of a numerical control machine tool.

4.1.5. Other papers on design, mechanical engineering and manufacturing

Other papers consider various problems related to maintenance of manufacturing systems, material handling equipments, risk evaluation of machinery systems, flexible manufacturing system selection and sustainability in this sub application area. Peng et al. [91] proposed an efficient VIKOR method that optimizes multi-response problems in intuitionistic fuzzy environments. Salmasnia et al. [92] proposed an approach that minimizes maximum deviation of responses from their targets by employing the VIKOR method to select optimal step size. Kazemzadeh et al. [93] used VIKOR method to extract optimal compromise solution that leads to a minimum variation in relative deviations of responses. Nezamia and Yildirim [94] utilised a fuzzy VIKOR method to rate the maintenance strategy alternatives using sustainability factors. Gauri and Chakraborty [95] considered GRA, multiple-response signal to- noise (MRSN) ratio, weighted signal-to-noise (WSN) ratio, and VIKOR methods, and then the optimal performances of these methods were compared using two sets of past experimental data of WEDM processes. Rao [96] integrated AHP and VIKOR approaches considering the environmentally conscious manufacturing program selection attributes and their relative importances. Emovon et al. [97] applied VIKOR and compromise programming for prioritising risk of failure modes of marine machinery systems and other related engineering systems. Anvari et al. [98] developed VIKOR method to solve MCDM problems with conflicting and noncommensurable criteria. The developed new VIKOR method is able to derive and rank all alternatives within the common/same criteria; moreover, each alternative, through its own criteria, can help practitioners strengthen their selection of tools and techniques. Gauri and Pal [99] compared the optimization performances of five prospective approaches, which are WSN ratio, GRA, MRSN ratio, VIKOR, and weighted principal component (WPC), for the multi-response optimization. Vinodh et al. [100] presented the application of fuzzy VIKOR for selecting the best sustainability concept. Jain and Raj [101] integrated fuzzy AHP and VIKOR methods in order to evaluate the most appropriate flexible manufacturing system. Vahdani et al. [102] presented an interval-valued fuzzy VIKOR method aiming at solving MCDM problems in which the weights of criteria are unequal, using interval-valued fuzzy set concepts. A numerical example was given and the proposed method was compared with interval-valued fuzzy TOPSIS. Liu et al. [103] developed a new failure mode and effect analysis (FMEA) framework for evaluation, prioritization and improvement of failure modes. A hybrid MCDM method combining VIKOR, DEMATEL and AHP was used to rank the risk of the failure modes identified in FMEA.

İç and Yıldırım [104] proposed a MOORA-based Taguchi approach to solve multi-response optimisation problems. The proposed method was simple and robust comparing with other MADM methods, such as TOPSIS, VIKOR and GRA. Zheng [105] aimed to propose a new multi-sensor target recognition method based on VIKOR method. The criteria weights were determined by G1 method. Sun et al. [106] aimed to propose a recommendation system using fuzzy VIKOR method based on different distance measures. Mousavi et al. [107] developed a new fuzzy grey MCDM method to handle material handling equipment selection.

4.2. Business management

Business management is the second largest main application category like logistics and supply chain management among reviewed papers, with 45 papers. The sub application categories are as follows: Performance and benchmarking; human resources; investment decisions; other business management applications. Others category includes some papers for new service development [108], enterprise crisis improvement [109] and a few new method based papers [110,111]. Fig. 6 shows the distribution of the papers in the business management category according to sub application areas.

4.2.1. Performance and benchmarking

Papers in this sub application category make performance analyses with respect to some key performance indicators, mostly financial and service quality, in order to determine a ranking of the alternatives using VIKOR related methods. Tsai et al. [360] integrated AHP and VIKOR to improve service quality in airlines. Hsieh et al. [113] assessed international tourist hotels by applying DEA to measure their operational efficiency and effectiveness. They also aimed to rank the hotels by VIKOR with entropy weight. Yalcin et al.

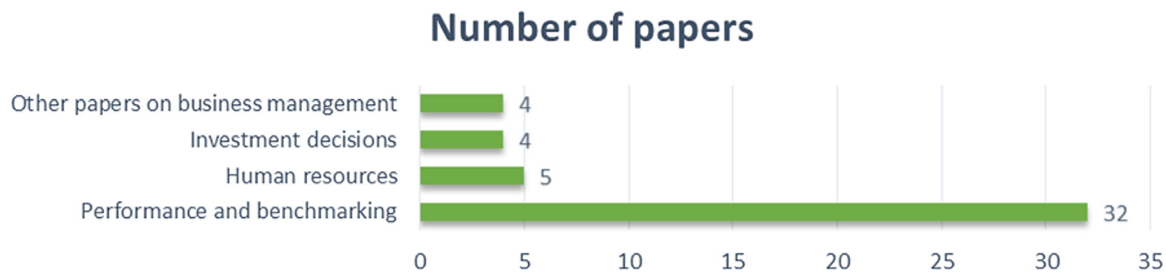

Fig. 6. Distribution of papers in the business management category according to sub application areas.

[114] proposed a new financial performance evaluation approach to rank the companies in different sectors in Turkish manufacturing industry. Fuzzy AHP was used to determine the weights of the criteria. The companies were ranked according to their own manufacturing sectors by using TOPSIS and VIKOR comparatively. Ghadikolaei et al. [115] ranked Iran automotive companies by using fuzzy VIKOR, fuzzy ARAS and fuzzy COPRAS for financial performance evaluation. Fuzzy AHP was applied to determine the criteria weights.

Lee and Pai [116] employed an improved DEA and VIKOR to evaluate the dynamic operation performances of TFT–LCD manufacturers in Taiwan, South Korea and Japan between 2002 and 2009. Ginevicius and Podvezko [117] evaluated financial performances of construction enterprises using TOPSIS, COPRAS, simple additive weighting (SAW), geometric mean (GM), and VIKOR methods. Shaverdi et al. [118] proposed an approach based on MCDM and balanced scorecard (BSC) for evaluating performances of three non-governmental Iranian banks. By fuzzy AHP the relative weights of each criterion are calculated, and TOPSIS, VIKOR, and ELECTRE were adopted to rank the banking performances. Rezaie et al. [119] evaluated financial performances of the 27 cement firms in Iran within 2 years (2009 and 2010) using an approach based on fuzzy AHP and VIKOR. Dincer and Hacioglu [120] proposed a fuzzy VIKOR and AHP based model to evaluate the performance levels of Turkish banks registered in Borsa Istanbul. Hsu [121] aimed to design a decision-making model for evaluating the efficiencies and operating performances of Taiwan's listed semiconductor companies in 2010 to provide a basis for improving business performance. Chen and Mujtaba [122] employed the five-dimensional structure of SERVQUAL to evaluate the service quality of 3C (computer, communication and consumer electronics) wholesalers in Taiwan. Fuzzy VIKOR method was utilised to select the best firms as service providers. Yücenur and Demirel [123] analysed five Turkish insurance companies for a foreign investor who wants to purchase a local insurance company using a trapezoidal fuzzy numbers based VIKOR method. Chen and Chen [124] aimed to explore the rankings of five university types in terms of innovative development from an intellectual capital (IC) perspective and provide recommendations for future improvements, taking basic development trends into account by using GM and VIKOR methods. Ginevičius et al. [125] applied SAW, TOPSIS, and VIKOR for partial competitive strategies on performance of an enterprise.

DEMATEL, ANP and VIKOR are mostly used together in performance evaluation in such studies of Lee [126], Liu et al. [127], Lu et al. [128], Lee and Tu [129], Wang et al. [130], and Wang and Tzeng [131]. For instance, Lee [126] proposed a method for merger and acquisition evaluation and presented a case to evaluate the performances of three Taiwanese banks. Liu et al. [127] evaluated sales performances of travel agencies. Lee and Tu [129] discussed the influence relationships and relative weights of the major factors influencing value of company. Wang et al. [130] evaluated and improved six sigma projects for reducing performance gaps in each criterion and dimension. Wang and Tzeng [131] clarified the interrelated relationships of brand marketing and determined the problems or gaps. Chen and Tzeng [132] proposed a hybrid MCDM approach combining BSC and abovementioned three methods to establish an evaluation and relationship model for organization performance.

Fu et al. [133] and Yeh and Hsieh [134] used fuzzy AHP and VIKOR based methods. Fu et al. [133] studied benchmarking analysis in hotel industry. Yeh and Hsieh [134] divided brand equity criteria into five dimensions (product, service quality, sales strategy, the professional sales personnel's ability and corporate image), using 20 indicators and ranked the preferences of five cosmetics chain stores.Bhosale and Kant [135] proposed a hybrid fuzzy AHP-fuzzy VIKOR methodology to select the best knowledge flow practicing organisation. Fu et al. [136] proposed a fuzzy ANP-VIKOR approach to reveal the critical success factors affecting the adoption of inter-organization systems by small and medium enterprises (SME). Liu and Cui [137] made an evaluation of the Baoding industrial clusters' competitiveness based on AHP-VIKOR hybrid method.

Krivka [138] applied SAW, TOPSIS and VIKOR methods for evaluating 68 industries identified according to the 2nd-digit level classification of economic activities by Statistics Lithuania. Ginevičius and Podvezko [139] applied SAW and VIKOR method for evaluation of the usage of information technologies in the countries of eastern and central Europe. Chu et al. [140] aimed to establish the objective and measurable patterns to obtain anticipated achievements of knowledge communities through TOPSIS, VIKOR, and SAW comparison. Fallah et al. [141] applied an extended VIKOR method to calculate Malmquist productivity index for MCDM problem with interval numbers. A numerical example for ten bank branches' performance evaluation is presented. Rostamzadeh et al. [142] analyzed the Malaysian business angels' (BAs) preferences to evaluate and select the city with the highest potential for investment using fuzzy VIKOR method. Tsai and Chang [112] conducted a performance analysis for the top seven tablet PCs using an MCDM approach based on the BOCR perspectives. AHP-GRA, AHP-TOPSIS, AHP-VIKOR, and fuzzy AHP were employed in the performance analysis to compute the weights of the criteria, ranking the tablet PCs' performance and attempting to explain the differences among seven tablet PCs, respectively.

In the context of performance and benchmarking, most papers integrate VIKOR rather than classical and stand-alone model. The integrated approaches are considered as more representative and applicable when carrying out practical and complicated problems. AHP, TOPSIS, ANP, DEMATEL, entropy method and fuzzy based methods are commonly used techniques which are either integrated or compared with VIKOR method, in this subsection.

4.2.2. Human resources

VIKOR applications in human resources management include personnel selection and evaluation. Liu and Wu [143] focused on manager selection using the entropy method for determining weights of the criteria and VIKOR for ranking. The results were also compared with the results of TOPSIS approach. Kabir [144] developed an improved and more effective total quality management consultant selection model through fuzzy VIKOR method. Wan et al. [145] proposed a triangular intuitionistic fuzzy VIKOR approach for personnel selection problem and compared the results with other MCDM methods' results. Cevikcan et al. [146] applied three methods, as fuzzy TOPSIS, fuzzy VIKOR and fuzzy axiomatic design, in a real case nurse selection problem for a hospital. Similarly, Liu et al. [147] proposed an interval 2-tuple linguistic VIKOR method to choose a head nurse in a tertiary care hospital among candidates in a group decision-making environment.

4.2.3. Investment decisions

Investment decisions related papers are concerned with evaluating business investments. The four papers mentioned here are model based papers and present numerical examples on an investment decision. Tan and Chen [148] developed a decision making approach based on VIKOR and Choquet integral in a fuzzy environment where preferences of decision makers with respect to criteria are represented by interval-valued intuitionistic fuzzy sets. Hajiagha et al. [149] considered a fuzzy multi objective decision making problem, where all of its parameters are defined as fuzzy, and a solution inspired by VIKOR method. A numerical example was also provided in an investment problem, and applicability of the proposed method was performed. Rostamzadeh et al. [150] used fuzzy AHP for finding the weights of criteria and sub criteria and VIKOR for final ranking of the companies. Qin et al. [151] extended the VIKOR method based on the prospect theory to accommodate interval type-2 fuzzy circumstances.

4.2.4. Other papers on business management

Other business management applications include various papers for new service development [108], enterprise crisis improvement [109] and a few new method based papers [110,111]. Tsai et al. [108] aimed to employ both AHP and VIKOR methods to analyse efficient managerial strategies for advancing new service development by involving viewpoints of the customer needs and expectations within a financial service context. Hu et al. [109] presented a new enterprise crisis improvement model based on a hybrid MCDM method with DEMATEL technique to construct an influential network relationship map.

Ginevičius et al. [110] evaluated the effect of state aid to enterprises by SAW, TOPSIS, VS, and VIKOR methods. Liao et al. [111] developed a hesitant fuzzy linguistic VIKOR (HFL-VIKOR) method, which is motivated by the traditional VIKOR method. Some numerical examples are provided to demonstrate the advantages and practicality of the method.

4.3. Logistics and supply chain management

Logistics and supply chain management is the second largest main application category like business management with 45 papers. The sub application categories are as follows: facility layout and location, supplier selection, and other papers on logistics and supply chain management. Other categories include some papers for logistics concept selection [152], third-party reverse logistics provider (3PRLP) selection [153], and evaluation of green supply chain management practices [154]. Fig. 7 shows the distribution of the papers in the logistics and supply chain management category according to sub application areas.

4.3.1. Facility layout and location

Facility layout and location has been a well established research area within operations research and management science. In this sub application area, 8 papers applied VIKOR method. Tzeng et al. [155] used an AHP-VIKOR model to rank alternative restaurant locations in Taipei. Su [156] presented a modified VIKOR method and a modified GRA method for reverse logistics applications. Zandi and Roghanian [157] aimed to extend ELECTRE I method based on VIKOR to rank a set of alternatives vs a set of criteria to show the decision makers' preferences. Bashiri et al. [158] proposed a fuzzy VIKOR method to model a hybrid solution to the hub location problem. The results were used by a genetic algorithm solution to successfully solve a number of problem instances. Milosevic and Naunovic [159] presented an evaluation and selection of the most favourable location for a sanitary landfill facility from three alternative locations, by applying VIKOR method. Lee [160] used DEMATEL technique to build an influential network relations map, and then DEMATEL based ANP was expected to obtain the influential weights using the basic concept of ANP. Then, the VIKOR method was used to integrate the performance gaps of criteria and dimensions separately and simultaneously. Mokhtarian et al. [161] proposed interval valued fuzzy VIKOR for selecting a suitable location for digging some pits for municipal wet waste landfill in one of the largest cities of Iran. Çebi and Otay [162] proposed a comprehensive and systematic approach for multi-criteria and multi-stage facility location selection problem using interval type-2 fuzzy TOPSIS method. The proposed method was applied to a region and site selection problem of a cement factory. To analyse the robustness of the method, the results were compared with other MCDM methods' results.

4.3.2. Supplier selection

In this sub application area, while 14 papers considered case studies, 13 papers conducted empirical studies. The studies consider real case applications focus on the supplier selection [163–173], vendor selection [174], green supplier selection [175,176]. Tosun and Akyüz [163] developed TODIM approach for supplier selection problem. The obtained result was compared with the results of TOPSIS and VIKOR based on triangular fuzzy numbers. Alimardani et al. [164] used step-wise weight assessment ratio analysis (SWARA) for determining the importance of each criterion and calculating their weights. Further, VIKOR was applied for evaluating alternatives as well as ranking supplier alternatives from the best to the worst. Parthiban et al. [165] developed a modified VIKOR method for evaluation and selection of sourcing partners. The results were also compared with TOPSIS and ELECTRE's results. Leng et al. [166] proposed an integrated decision support model for Parts machining outsourcing using ontology, constraint-based reasoning, fuzzy VIKOR and game theory in three phases, namely supplier prequalification, ultimate selection and order coordination. Mohammady and Amid [167] presented a hybrid fuzzy AHP and fuzzy VIKOR model for supplier selection in an agile and modular virtual enterprise. Mishra et al. [168] used fuzzy VIKOR method to assess multi-criteria attributes on suppliers' performances and select the best supplier among a group of alternative suppliers. A numerical illustration was given to focus on application's feasibility of the aforesaid methodology. Chen and Wang [169] presented a fuzzy VIKOR based method for the evaluation of supplier/vendor in information system/information technology outsourcing projects. Ayazi et al. [170] proposed a fuzzy MODM model including fuzzy VIKOR for supplier selection and order size determination in a supply chain. Mukherjee et al. [171] proposed a supplier selection model based on fuzzy AHP-VIKOR and a case study was performed in cement industry of India. Aghdaie et al. [172] proposed an integrated model with Cluster analysis, SWARA and VIKOR in supplier clustering and ranking. Hsu et al. [174] proposed a DEMATEL based ANP-VIKOR approach to determine the best vendor for conducting the recycled material. Wu and Liu [173] applied VIKOR with entropy method for the supplier selection problem. The method gave the weights to indicators by incorporating fuzzy TOPSIS. Datta et al. [175] proposed a methodology for green supplier selection using interval-valued fuzzy sets coupled with VIKOR method. A

Fig. 7. Distribution of papers in the logistics and supply chain management category according to sub application areas.

case study was also presented to stimulate the better understanding of the proposed methodology. Akman [176] aimed to determine green/environmental performances of suppliers using fuzzy factor analysis, c-means, and VIKOR.

Thirteen papers in supplier selection sub category presented new VIKOR based methods considering empirical examples. DEMATEL, ANP and VIKOR are integrated [177,178]. Liou and Chuang [178] proposed a new hybrid MCDM model, which addresses the dependent relationships between criteria with the aid of the DEMATEL method to build a relations-structure between criteria. ANP was used to determine the relative weights of each criterion with dependence and feedback. The VIKOR method was then used to prioritize the alternatives. Peng and Tzeng [177] presented two categories of hybrid dynamic MCDM. First, ANP with DEMATEL to yield influential weights of criteria, and combined influential weights with the additive types of VIKOR were used. Second, fuzzy integral was used to assess and improve complex problems.

Fuzzy sets are also applied with VIKOR for supplier selection. Alkhatib et al. [179] compared fuzzy VIKOR with their proposed method which integrates fuzzy DEMATEL and fuzzy TOPSIS. It was aimed to evaluate and select logistics service providers. Kumar et al. [180] proposed consistent fuzzy preference relation (CFPR) and VIKOR method for selection the most appropriate third party logistics (3PL) provider. Büyüközkan and Feyzioglu [181] applied fuzzy VIKOR for rating suppliers' environmental performances. Sanayei et al. [182] proposed a hierarchical MCDM model based on fuzzy sets theory and VIKOR method to deal with the supplier selection. A numerical example was proposed to illustrate an application of the proposed model. You et al. [183] proposed an extended VIKOR method for group multi-criteria supplier selection with interval 2-tuple linguistic information. Three realistic supplier selection examples and comparisons with the existing approaches were presented. It was concluded that the proposed method is more suitable and effective to handle the supplier selection problem under vague, uncertain and incomplete information environment. Wang et al. [184] applied normal intuitionistic fuzzy numbers to MCDM problems, and meanwhile some new aggregation operators were proposed, including normal intuitionistic fuzzy weighted arithmetic averaging operator, normal intuitionistic fuzzy weighted geometric averaging operator, normal intuitionistic fuzzy-induced ordered weighted averaging operator, normal intuitionistic fuzzy-induced ordered weighted geometric averaging operator and normal intuitionistic fuzzy-induced generalized ordered weighted averaging operator. The proposed method was compared with the existing methods. Lu and Tang [185] aimed to build up an evaluating system for auto parts suppliers using VIKOR method based on intuitionistic fuzzy numbers. Jiang and Yao [186] proposed a hybrid MCDM method based on fuzzy AHP and the interval valued intuitionistic fuzzy (IVIF)-VIKOR to select supplier under an incomplete and uncertain information environment.

There are also some new methods for supplier selection using VIKOR method. Shemshadi et al. [187] proposed an extended VIKOR for a supplier selection problem while the objective weights were determined based on Shannon entropy. Geng and Liu [188] considered SERVQUAL and VIKOR approaches to evaluate the service suppliers. Hsu et al. [189] utilized ANP to determine the relative weights of each criterion and applied VIKOR to evaluate carbon performance of suppliers and compromise solution under each of the evaluation criteria.

4.3.3. Other papers on logistics and supply chain management

Other papers consider various problems related to algorithms comparison, city logistics concept, acquisition of manipulative transport, key factors for procurement and selection of global manufacturing and logistics system in this sub application area. Sasikumar and Haq [153] used a fuzzy MCDM model based on VIKOR method for the selection of the best 3PRLP. Tzeng and Huang [190] proposed a DEMATEL technique based novel MCDM method with ANP, GRA as well as VIKOR for selecting and re-configuring the aspired global manufacturing and logistics system. Samantra et al. [191] proposed an interval-valued fuzzy VIKOR method to facilitate in designing effective product recovery policy depending on various criteria. Tadic et al. [152] developed a novel hybrid MCDM model that combines fuzzy DEMATEL, fuzzy ANP and fuzzy VIKOR methods. The model provides support to decision makers in selecting the city logistics concept, which is successfully performed for Belgrade. Fu et al. [192] examined the factors that influence the adoption of RFID in the logistics industry in Taiwan, and objectively identified the key factors (KFs) for a successful adoption using a hybrid fuzzy AHP-VIKOR approach. Chithambaranathan et al. [193] proposed a Grey based hybrid model for evaluating environmental performance of service supply chains via integrating grey based method with ELECTRE and VIKOR approaches. Pamucar and Cirovic [194] presented an application of a new DEMATEL-multi-attributive border approximation area comparison model in the process of making investment decisions on the acquisition of manipulative transport (Forklifts) in logistics centres. Sarrafha et al. [195] implemented VIKOR method to compare the algorithms (multi-objective biogeography based optimization, multi-objective simulated annealing algorithm and non-dominated sorting genetic algorithm) in terms of multi-objectives metrics. Chen [196] integrated DEMATEL, ANP and VIKOR methods for hybrid dynamic MCDM method to explore the key factors for the internal control of procurement circulation. Rostamzadeh et al. [154] applied a fuzzy VIKOR method to evaluate green supply chain management indicators.

4.4. Natural resources and environmental management

With 29 papers, natural resources and environmental management is the third largest main application category like structural, construction and transportation engineering. We determined five sub application areas as follows: water management, waste management, land management and geology, forestry management and other papers on natural resources and environmental management. Other categories include some papers for new service development [108], enterprise crisis improvement [109] and a few new methods based papers [110,111]. Fig. 8 shows the distribution of the papers in the natural resources and environmental management category according to sub application areas.

Fig. 8. Distribution of papers in the natural resources and environmental management category according to sub application areas.

4.4.1. Water management

Water requirement increases by the reason of continuous growth in demand and water allocation in the river basin as a complex management problem, with conditions that may promote conflicts. Conflict over the management of a shared water resource arises mostly because of differing objectives among different interest groups. Conflict resolution is considered as an MCDM problem in water management [197]. In this sub application area, the specific application areas which are solved using VIKOR are watershed vulnerability, basin environmental vulnerability, reservoir watershed, flood management and water quality. Opricovic [197] applied VIKOR to plan water resources with noncommensurable and conflicting criteria including economic, environmental, social, and cultural features. Chang [198] applied AHP for determining the weights of seven criteria for assessing basin environmental vulnerability. The weighted method and VIKOR are integrated to evaluate the environmental vulnerability of major basins in Taiwan. Kim and Chung [199] assessed vulnerability of the water supply regarding to climate change and variability in the South Korean provinces for the present and future, with a fuzzy VIKOR approach. Chang and Lin [200] proposed a VIKOR based method to evaluate the design of the water quality monitoring network in the Taipei water resource domain.

Hashemi et al. [201] introduced VIKOR method based on Atanassov's intuitionistic fuzzy sets under multiple criteria in real-life situations. The performance of the proposed method is illustrated via a case of water resources management problem. Opricovic and Tzeng [202] developed a multi criteria genetic algorithm to solve scheduling optimization problem. The approach was originated from VIKOR. A numerical example in water resources engineering was presented. Chang and Hsu [203] proposed VIKOR based MCDM method for prioritizing land-use restraint strategies in the Tseng-Wen reservoir watershed. It was concluded that subdivisions close to the outlet or reservoir area should have the priority of land-use restrictions. Chang and Hsu [204] employed a modified VIKOR method for Tseng-Wen reservoir watershed in southern Taiwan with regard to the spatial variability of its environmental characteristics. Chitsaz and Banihabib [205] applied a practical framework to prioritize the flood risk management alternatives for Gorganrood River in Iran. A comparative study is also conducted between different MCDM methods. Sabzi and King [206] presented a numerical comparison of six MCDM techniques on flood management multi-criteria systems. Opricovic and Tzeng [20] proposed an extended version of VIKOR with a stability analysis determining the weight stability intervals, and trade-offs analysis. The extended method was compared with TOPSIS, PROMETHEE, and ELECTRE. A numerical example about potential dam site selection for reservoirs to provide hydropower was given. Kim et al. [207] quantified the environmental feasibility scores of ten alternative dam construction sites based on VIKOR method. Opricovic [208] proposed a fuzzy VIKOR method to water resources planning. The development of a reservoir system was studied for the storage of surface flows of the Mlava River and its tributaries for regional water supply. A comparative analysis of results by fuzzy VIKOR and few different approaches were also presented. Tscheikner-Gratl et al. [209] investigated the integrated rehabilitation of infrastructure networks of a small municipality (13,100 inhabitants) using a VIKOR based MCDM approach. Kim and Chung [210] proposed a robust prioritization framework for climate change adaptation strategies under uncertain climate change scenarios, using VIKOR method together with the Shannon entropy-based weights.

4.4.2. Waste management

In this sub application area, the papers consider waste treatment or disposal [211,212] and waste location selection [213–215] are proposed. Liu et al. [216] presented a new MCDM technique based on fuzzy set theory and VIKOR method for evaluating health-care waste disposal methods. Liu et al. [211] proposed a novel hybrid MCDM model by integrating the 2-tuple DEMATEL technique and fuzzy MULTIMOORA method for selection of health-care waste treatment alternatives. The obtained results were compared with fuzzy VIKOR and fuzzy TOPSIS. Martin-Utrillas et al. [212] proposed a hybrid AHP-Delphi-VIKOR method for selection of the optimal process of leachate treatment in waste treatment and valorisation plants or landfills.

Liu et al. [213] extended VIKOR method based on trapezoidal fuzzy numbers. The proposed method was applied to determine the priority ranking of site alternatives in municipal solid waste management. Liu et al. [214] extended VIKOR method based on interval 2-tuple linguistic fuzzy numbers and applied it to determine the priority ranking of site alternatives in municipal solid waste management. Kabir [215] focused on selection of the hazardous industrial waste transportation firm through fuzzy VIKOR method.

4.4.3. Land management and geology

Land use management, post-earthquake region assessment and mine location selection are some of the problems related to papers in this sub application area. Opricovic and Tzeng [217] proposed a fuzzy multi criteria model for analysing land-use strategies to reduce the future social and economic costs in areas with the post-earthquake regional planning problem in central Taiwan. Opricovic and Tzeng [218] proposed a VIKOR based model for analysing the post-earthquake reconstruction problem in Central Taiwan, including the restoration concerning the safety and serviceable operation of "lifeline" systems, such as electricity, water, and transportation networks, immediately after a severe earthquake. Pricovic [219] developed a fuzzy VIKOR based methodology for the post-earthquake regional planning problem in central Taiwan. Hudej et al. [220] presented the PROMETHEE, ELECTRE, AHP and VIKOR, as multi-model multi-criteria selection method for new shaft location selection of Velenje coal mine. Azimi et al. [221] proposed an integrated ANP and VIKOR model for prioritizing the Iranian mining sector strategies.

4.4.4. Forestry and natural reserves

There is only one study about forestry management using VIKOR method. Kaya and Kahraman [222] proposed an integrated VIKOR–AHP methodology to make a selection among the alternative forestation areas in Istanbul. The weights of the selection criteria are determined by fuzzy AHP. It is concluded that Ömerli watershed is the most appropriate forestation district in Istanbul.

4.4.5. Other papers on natural resources and environmental management

Hashemi et al. [223] extended VIKOR method based on an interval-valued intuitionistic fuzzy environment for reservoir flood control operation. Peng [224] proposed an approach which integrates the results of 6 MCDM methods to provide regional earthquake vulnerability assessment of 31Chinese regions.

4.5. Structural, construction and transportation engineering

With 29 papers, structural, construction and transportation engineering is the third largest main application category like natural resources and environmental management. We have determined two sub application areas as follows: structural and construction engineering and transportation engineering.

4.5.1. Structural and construction engineering

Structural and construction engineering include some papers for project selection [225], project manager selection [226], contractor selection [227,228]. Ebrahimnejad et al. [225] integrated fuzzy ANP and fuzzy VIKOR for the project selection in the construction industry. Mohammadi et al. [226] applied a hybrid QFD and cybernetic ANP model to select project manager in construction industry. The results were also compared with VIKOR method's results. San Cristóbal [227] applied VIKOR and TOPSIS methods for the selection of contractors for construction projects. Vahdani et al. [228] proposed a new compromise solution based on VIKOR method for contractor selection problem. The proposed method can deal with the situations in which fuzzy and crisp evaluations are simultaneously required.

There are some papers about building, desing and redevelopment using VIKOR method. Ginevičius et al. [229] compared wall insulation scenario using SAW, TOPSIS, GV, VIKOR and COPRAS methods. Antucheviciene et al. [230] performed ranking of building redevelopment alternatives by using fuzzified COPRAS, TOPSIS and VIKOR methods. It was concluded that the priority order of the redevelopment alternatives of buildings was not always the same in a particular region. Zavadskas and Antuchevičiene [231] analysed the problem of derelict buildings' redevelopment by using VIKOR and TOPSIS methods. Antucheviciene and Zavadskas [232] presented a VIKOR based MCDM study. In their study, redevelopment problems relating to derelict buildings in Lithuanian rural areas were analysed by the proposed techniques. Formisano and Mazzolani [233] selected the optimal solution for both seismic retrofitting of existing RC buildings and super-elevation of existing masonry constructions using TOPSIS, ELECTRE and VIKOR methods. Kosoric et al. [234] adopted a MCDM method in the evaluation of the design alternatives for building integration of photovoltaics (PV) using a PV demonstration site in Singapore. Mela et al. [235] compared six different MCDM methods for building design. Martin-Utrillas et al. [236] developed a model based on Delphi, AHP and VIKOR methods for optimal infrastructure selection.

Caterino et al. [237] investigated the applicability and effectiveness of different MCDM methods for the seismic retrofit of structures. Zolfani et al. [238] used SWARA method to evaluate criteria and, then VIKOR method was applied to evaluate, rank and select the optimal method for mechanical longitudinal ventilation of tunnel pollutants. Vučijak et al. [239] described the application of a multi criteria optimization in selecting the best alternative for choosing a tunnel security door. Mandal et al. [240] developed a fuzzy VIKOR based methodology for human error identification and risk prioritization to overhead crane operations. Safari et al. [241] proposed a fuzzy VIKOR based method for prioritization of enterprise architecture risk factors. Mousavi [242] developed a fuzzy stochastic VIKOR approach. The developed approach is used to select and rank the important risks in a highway project in Iran. Ahmadi et al. [243] presented a methodology which is based on AHP-enhanced TOPSIS, VIKOR and benefit-cost ratio for selection of a maintenance strategy to assure the consistency and effectiveness of maintenance decisions. Tosic et al. [244] aimed to determine the optimal choice of aggregate type and transport scenario in concrete production, employing VIKOR taking into account technical, economic and environmental limits and constraints.

4.5.2. Transportation engineering

In this sub application area, service quality evaluation and public transportation evaluation are presented using VIKOR method. For example, Liou et al. [245] applied a modified VIKOR method to improve service quality among domestic airlines in Taiwan. Kuo and Liang [246] combined VIKOR and GRA methods based on fuzzy sets for evaluating service quality of Northeast-Asian international airports by conducting customer surveys. Kuo [247] presented an effective approach based on combining VIKOR, GRA, and interval valued fuzzy sets to evaluate service quality of Chinese cross-strait passenger airlines via customer surveys. Kuo and Liang [248] presented an interval-valued fuzzy VIKOR method for evaluating the performances of three major intercity bus companies. Liao and Xu [249] extended the classical VIKOR method to accommodate hesitant fuzzy circumstances. They presented an empirical study for the evaluation and ranking of the service quality among domestic airlines. Celik et al. [250] applied SERVQUAL and VIKOR based on interval type-2 fuzzy sets for evaluating customer satisfaction in rail transit of Istanbul, Turkey.

Public transportation buses are also evaluated [251,252]. Tzeng et al. [251] proposed a multi-criteria analysis of alternative-fuel buses for public transportation. AHP was applied to determine the relative weights of evaluation criteria. TOPSIS and VIKOR are compared and applied to determine the best compromise alternative fuel mode. Aydin and Kahraman [252] considered the problem of bus selection for public transportation using fuzzy AHP and fuzzy VIKOR for Ankara, the capital city of Turkey. Liu et al. [253] addressed a novel method of hybrid MCDM, including DEMATEL, DEMATEL based ANP and VIKOR, to present the best improvement schemes in the connection service to the urban airport in Taipei.

4.6. Information technology

Information technology category is divided into five sub categories. The sub categories are: network selection, software evaluation, e-commerce and m-commerce, website evaluation and other papers on information technology. Information technology is the fifth largest main application category in the reviewed papers with 27 papers. Fig. 9 shows the distribution of the papers in the information technology category according to sub application areas.

4.6.1. Software evaluation

Software evaluations are used in evaluating software performances and knowledge management effectiveness. Büyüközkan and Ruan [254] extended the fuzzy VIKOR method for measuring the performance of enterprise resource planning software products. Büyüközkan et al. [255] applied a fuzzy VIKOR based approach to identify the most appropriate knowledge management tool for improving the effectiveness of an organization. Liao and Xu [256]

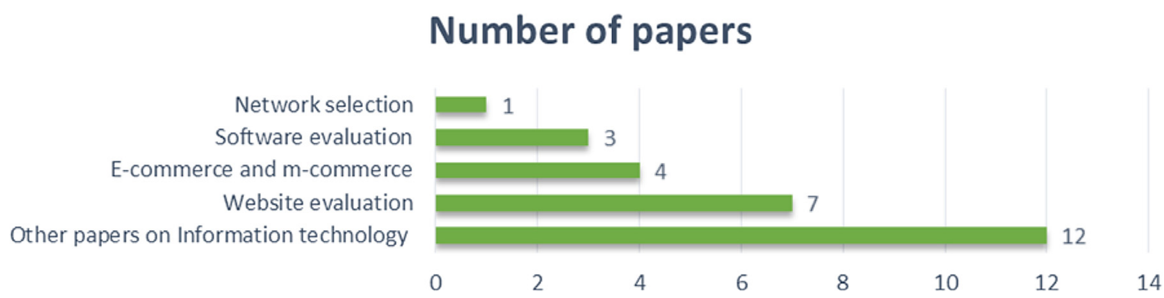

Fig. 9. Distribution of papers in the information technology category according to sub application areas.

developed the cosine distance-based hesitant fuzzy linguistic TOPSIS method and the cosine-distance-based hesitant fuzzy linguistic VIKOR method.

4.6.2. *Network selection*

There is only one paper in this sub category, network evaluation, which was studied by Mehbodniya et al. [257] in order to select the best target network via a fuzzy VIKOR ranking algorithm.

4.6.3. *E-commerce and m-commerce*

Various assessments of e-commerce and m-commerce systems and technologies are presented in this sub category. Hu et al. [258] developed a new hybrid fuzzy MCDM model using the fuzzy DEMATEL and the fuzzy DEMATEL based ANP methods to construct the fuzzy influential network relationship map and determining the fuzzy influential weights by fuzzy DEMATEL based ANP. Then, they combined the fuzzy influential weights with the fuzzy VIKOR method to explore and improve m-commerce adoption with uncertain information in a fuzzy environment to create the best improvement plan. Chou and Cheng [259] combined the fuzzy ANP and fuzzy VIKOR for evaluating website quality of the top-four certified public accountant firms in Taiwan. Chang et al. [260] applied fuzzy AHP to calculate the weights of the e-book business models. VIKOR, GRA and TOPSIS were utilized to rank the three alternatives. Chiu et al. [261] developed a new hybrid model, combining the DEMATEL, ANP, and VIKOR methods for assessing and improving strategies to reduce the gaps in customer satisfaction caused by interdependence and feedback problems among dimensions and criteria to achieve the aspiration level.

4.6.4. *Website evaluation*

Website evaluation studies are proposed in various contexts. Researchers and practitioners aim to determine the important factors for evaluating online service and marketing. Seven papers are reviewed under this sub category. Tsai et al. [262] and Tsai et al. [263] used DEMATEL, ANP and the modified VIKOR methods to rank the performance of web-based marketing of the airline industry and Taiwanese national park websites, respectively. Burmaoglu and Kazancoglu [264] applied fuzzy AHP to determine the criteria weights and fuzzy VIKOR to select e-government websites among a group of selected EU countries. Wu et al. [265] obtained the importance weights of criteria using fuzzy AHP and applied the VIKOR method to evaluate commercial activities on Facebook for global brands. Büyüközkan et al. [266] proposed a quality evaluation model based on the fuzzy VIKOR to measure the e-learning Web sites' performances. Chen et al. [267] analysed websites of benchmark companies with DEMATEL, ANP and VIKOR. Lu et al. [268] evaluated the mobile banking services of user behaviour for achieving aspiration level in criteria using integrated DEMATEL, ANP, and VIKOR methods.

4.6.5. *Other papers on information technology*

Other papers consider various problems related to information security management system improvement, change management for information services centres, customer satisfaction of mobile services, vehicle telematics service system improvement and some empirical studies in this sub application area. Ou Yang et al. [269] proposed a VIKOR method for improving information security management system. Nakhoda and Givi [270] proposed a change management framework for Iranian information services centres. Fuzzy SAW, fuzzy TOPSIS and fuzzy VIKOR were applied to select the most suitable change management model. Kang and Park [271] developed a new framework for the measurement of customer satisfaction in mobile services by combining VIKOR and sentiment analysis. Lin [272] applied a novel MCDM model integrating DEMATEL, PCA, ANP, and VIKOR for vehicle telematics service system improvement. Hu et al. [273] proposed a smart phone improvement for promoting the product value to satisfy the customers' needs with a hybrid MCDM model, which combines DEMATEL based ANP and VIKOR.

Yang et al. [274] proposed a combined VIKOR, DEMATEL and ANP to solve a problem of conflicting criteria that shows dependence and feedback. An empirical application of evaluating the risk controls was applied to present the proposed method. Salman et al. [275] proposed a new mapping between channel quality indicator and modulation, and coding scheme to address energy efficiency and spectral efficiency trade-off with the use of VIKOR and TOPSIS. Chen and Chen [276] adopted a hybrid fuzzy MCDM model based on fuzzy AHP and VIKOR to complete the construction of a novel aviatic innovation system. Azad and Sharma [277] applied VIKOR method to evaluate an energy-efficient clustering scheme for cluster heads. Kou et al. [278] and Kou et al. [279] studied the evaluation of classification and clustering algorithms done by MCDM-based approaches. Hung et al. [280] proposed an ANP-DEMATEL-VIKOR based MCDM approach to solve knowledge management (KM) adoption problem, and ranked the gaps of the KM aspects. It was concluded that the KM gaps within the service industry were higher than the gaps within the IC (Integrated Circuit) and banking industries. The findings also showed that the criteria for weighting in different industry sectors were quite different; and the adoption strategies for different industry sectors should be considered separately according to the SME industry sectors.

4.7. *Policy, social and education*

In policy, social and education main category, VIKOR method is used for various problems related to entrepreneurship policy in education, e-learning, performance evaluation of education centres, higher education system evaluation and policy and social topics. Tsai et al. [281] combined the ANP method and the modified VIKOR method for evaluating current entrepreneurship policies. Mazdeh et al. [282] proposed a framework to evaluate the entrepreneurship intensity of Iranian state universities. A hybrid multi method framework consisting of Delphi, ANP, and VIKOR was proposed. Su et al. [283] integrated fuzzy DEMATEL, fuzzy ANP and fuzzy VIKOR for cloud e-learning service strategies to improve e-learning innovation performance.

Pekkaya [284] applied VIKOR, PROMETHEE and TOPSIS methods for career preference in one of the Turkish universities. Fu et al. [285] combined fuzzy AHP and VIKOR for training institutions to allocate their resources appropriately by focusing on the critical success factors. Chen and Tzeng [286] proposed a novel MCDM consisting of DEMATEL, ANP and VIKOR for evaluating, comparing, and improving the effectiveness of competence indicators in the various publications for teaching materials in primary school based on different viewpoints. Ranjan et al. [287] developed a MCDM framework by integrating DEMATEL, entropy and VIKOR for performance evaluation and ranking of 16 engineering departments in an Indian university. Wu et al. [288] studied analysing the intellectual capital of universities based on indicators of innovation capital using fuzzy AHP-VIKOR hybrid approach. Wu et al. [289] presented a performance evaluation model for education centres in universities based on the BSC, DEMATEL, ANP and VIKOR. Zolfani and Ghadikolaei [290] presented a performance evaluation model of private universities in Iran based on BSC, DEMATEL, ANP and VIKOR. Park et al. [291] proposed an extended VIKOR method for dynamic intuitionistic fuzzy MCDM in university faculty evaluation.

Chen and Chen [292] aimed to provide a clear and valid way for the higher education system to enhance the innovation level and performance by confirming the creative-oriented personality. They calculated the weighting evaluation creativity dimensions and criteria with fuzzy AHP and then the most creative personality was selected by VIKOR. Chen and Chen [293] applied VIKOR method to select critical creativity strategies that were developed by the Taipei County government for the higher education system to implement creativity improvement and enhancement. Wu et al. [294] aimed to (i) weight the performance evaluation indices for higher education based on the official performance evaluation structure and (ii) rank 12 private universities as a case study using AHP and VIKOR methods.

Liu et al. [295] proposed a hybrid MCDM method, including DEMATEL, ANP and VIKOR to suggest an optimal improvement plan for Taiwan tourism policy. Chou et al. [296] applied the VIKOR and entropy method to evaluate the performances of women in the science and technology.

4.8. Energy management

Here, two sub application areas are determined; large scale energy management and HVAC systems, and small scale energy management. Most of the papers study energy policy on large scale management (10 papers vs 4 papers).

4.8.1. Large scale energy management

Energy planning is a strategic operation for governments or policy makers. Most papers are concerned with renewable energy selection. Kaya and Kahraman [297] aimed at determining the best renewable energy alternative for Istanbul by using a hybrid VIKOR-AHP methodology and selecting among alternative energy production sites in Istanbul by the same methodology. San Cristóbal [298] applied VIKOR for selection of a renewable energy project corresponding to the renewable energy plan launched by the Spanish government. Weighting the importances of different criteria is performed by AHP. It is concluded that the biomass plant option (Co-combustion in a conventional power plant) is the best choice, followed by the Wind power and Solar Thermo-electric alternatives. Dai et al. [299] proposed a multi-criteria renewable energy planning decision-making model based on VIKOR to achieve the optimal choice of a renewable energy planning. The model is applied for the renewable energy planning decision making in one of the provinces in China. Quijano H et al. [300] developed an integrated simulation platform as a tool to promote and develop renewable energy plans under sustainability criteria in order to increment the participation of renewable technologies in the national "energy mix". They presented an application to Colombia as a case study. To obtain an appropriate mix of renewable sources that could be introduced in the national energy mix, VIKOR method is used. Yazdani-Chamzini et al. [301] integrated COPRAS-AHP methodology to select the best renewable energy project. In order to validate the output of the proposed model, it is compared with five MCDM tools. Sharma et al. [302] aimed to rank viable energy resources for India by a fuzzy decision making approach.

There are also different applications for large scale energy management. For example, Vučijak et al. [303] presented a VIKOR method for applicability of sustainable hydropower. Sakthivel et al. [304] used ANP to determine the relative weights of the criteria, whereas TOPSIS and VIKOR were used for obtaining the final ranking of the best biodiesel blend. Three well-known decision-making methods, namely TOPSIS, VIKOR, and LINMAP were used in risk evaluation of mega projects in power industry [305]. Sun et al. [359] proposed a hybrid VIKOR method for power system restoration.

4.8.2. HVAC systems and small scale energy management

VIKOR applications in HVAC systems and small scale energy management include solar water heating and insulation options for warmth of buildings. Golic et al. [306] proposed a VIKOR based method for selecting the optimal solar water heating systems (SWHS) to solve the integration of SWHS through the refurbishment of residential buildings in one suburban area of Belgrade. Furundzic et al. [307] used VIKOR method for a comprehensive evaluation of design options, and selection of optimal integrated solar thermal collector regarding the conflicting criteria: energy performance, economic, ecological, functional and aesthetic aspects. Civic and Vucijak [308] aimed to optimize the insulation of the walls in buildings taking into the account several criteria. A case of the buildings in Sarajevo is performed and the best one is selected by VIKOR method. Ray [309] aimed to solve the multi-response optimization problem and to select optimum process parameters of green Electrical Discharge Machining (EDM) using an integrated methodology comprising of entropy and GRA. The proposed methodology is compared with the fuzzy TOPSIS and Taguchi-VIKOR methodologies.

4.9. Financial management

Two sub-categories were defined for the financial management category. There are total of twelve papers about financial management.

4.9.1. Portfolio and investment management

Portfolio and investment management consist of 3 empirical papers. Baležentis et al. [310] applied fuzzy VIKOR, fuzzy TOPSIS, and fuzzy ARAS methods for assessing and comparing of Lithuanian economic sectors on the basis of financial ratios. Ho et al. [311] and Shen et al. [312] proposed an integrated DEMATEL, ANP, and VIKOR approach. Ho et al. [311] explored portfolio selection based on capital asset pricing model. Shen et al. [312] aimed to solve a glamor stock selection problem based on fundamental analysis.

4.9.2. Other papers on financial management

Some issues considered in the papers in this category are: banking performance, financial risk prediction, financial feature analysis, and business performance evaluation of companies. For example, Shen and Tzeng [313], Wu et al. [314], Afful-Dadzie et al. [315], and Chang and Tsai [316] evaluated financial performances of banks. Shen and Tzeng [313] integrated DEMATEL and ANP for evaluating financial performance criteria. The VIKOR was applied to rank banks with respect to 2011 and 2012 data. Wu et al. [314] considered four perspectives of balanced scorecard as a framework for establishing performance evaluation criteria. Fuzzy AHP was used to obtain the fuzzy weights of the criteria. SAW, TOPSIS, and VIKOR were respectively applied to evaluate the banking performance based on the weight of each criterion. Afful-Dadzie et al. [315] proposed fuzzy TOPSIS for ranking African development banks and then the obtained result was compared with the results of VIKOR and AHP. Chang and Tsai [316] employed AHP and VIKOR analytical methods in the performance analysis for computing the weights of the criteria, ranking the banking performance. Hsu [317] and Lin et al. [318] also evaluated financial performances of private companies. Hsu [317] used grey clustering analysis and GRA for dividing companies into risk groups as low, moderate and high-risk. Then, VIKOR was applied for business performance evaluation and sorting of each grouping for optoelectronics companies in Taiwan. Lin et al. [318] utilized VIKOR method to analyse 100 publicly issued companies using five important financial features.

In these sub application areas, there are some papers for developing new approaches using VIKOR method. Peng et al. [319] developed a two-step approach to evaluate classification algorithms for financial risk prediction. Performance of classification algorithms were used to measure performance scores. TOPSIS, PROMETHEE, and VIKOR were applied to provide a final ranking of classifiers. Lee and Yang [320] aimed to explore the unexplained portion of the pricing model of convertible bonds by adopting DEMATEL, ANP, and VIKOR. Hsu and Pai [321] employed a multiple feature selection technique and translated the structure selection problem into an MCDM task using various classification criteria to evaluate the Support vector machine (SVM) classifiers.

4.10. Health, safety and medicine

In the health, safety and medicine main category, 6 papers are reviewed. They consider various problems related to quality evaluation of hospitals and risk prioritization within empirical examples. Chang [322] proposed a fuzzy VIKOR based framework to provide a rational, scientific and systematic process for evaluating the hospital service quality under 33 evaluation criteria in Taiwan. It was concluded that the service quality of private hospitals was better than of the public hospitals because the private hospitals were rarely subsidized by governmental agencies. It was suggested that the private hospitals had to fend themselves to retain existing patients or attract new patients to ensue sustainable survival. Lu et al. [323] proposed a hybrid method that combines DEMATEL, DEMATEL based ANP, and VIKOR to evaluate the factors that influence the adoption of RFID. It was applied to the adoption of RFID in Taiwan's healthcare industry. It was concluded that technology integration is the most influential criterion and the strongest driver in the adoption of RFID of Taiwan's healthcare industry. Zeng et al. [324] proposed an improved VIKOR method with enhanced accuracy VIKOR to make it suitable for such data in medical field.

Papers regarding risk prioritization within empirical examples are as follows: Liu et al. [325] proposed an extended VIKOR method under fuzzy environment in risk evaluation of failure mode and effects analysis. A numerical example was also provided in the study. Liu et al. [326] proposed a fuzzy digraph and matrix approach in risk evaluation of failure mode and effects analysis. A numerical example and the comparison results with other MCDM methods were also provided in the paper. Liu et al. [327] applied an integrated fuzzy AHP and entropy method for risk factor weighting in their proposed approach. The risk priorities of the identified failure modes were obtained based on fuzzy VIKOR method.

4.11. Chemical and biochemical engineering

In the chemical and biochemical engineering main category, 4 papers are reviewed. They studied various problems related to bioethanol production, determination of optimal conditions for ceramics and multi response process optimizations. Ren et al. [328] aimed to (i) combine the life cycle sustainability assessment framework and the AHP-VIKOR based MCDM methodology for sustainability assessment and (ii) determine the most sustainable scenario for bioethanol production in China. Salmasnia et al. [329] suggested a robust posterior preference articulation approach based on a non-dominated sorting genetic algorithm (NSGA-II) to optimise multiple responses. In order to minimise the variation in deviation of responses from targets, the maximum and sum of the deviations were taken into consideration. Vats and Vaish [330] used AHP and VIKOR to determine the optimal sintering temperature for $K_{0.5}Na_{0.5}NbO_3$ ceramics. The weights of these physical properties for KNN are calculated using the modified digital logic method. Tong et al. [331] employed the VIKOR method to optimise the multi response process. The proposed method considered both the mean and the variation of quality losses associated with multiple responses. Two case studies of plasma-enhanced chemical vapor deposition and copper chemical mechanical polishing were given to show the effectiveness of the proposed method.

4.12. Agriculture

There is only one paper relating with agriculture category. Aktan and Samut [332] analysed the agricultural performance of the provinces of Turkey for 2009 according to the agricultural performance criteria using fuzzy AHP and VIKOR.

4.13. Other areas and non-specific applications

Applications that do not fit into any of other 12 categories are given in this last category. Some examples are non-specific applications including cinema service quality performance evaluation, conservation development, mine equipment selection, insurance company performance evaluation, trustee evaluation and VIKOR-based models with non-specific application. Hsu [333] integrated fuzzy AHP and fuzzy VIKOR for evaluating the performance of cinema service quality. Pourebrahim et al. [334] applied an integrated VIKOR-fuzzy AHP method to make a selection among alternatives for conservation development in a coastal area. Bazzazi et al. [335] applied AHP and fuzzy VIKOR for surface mine equipment selection problems. Vahdani et al. [336] proposed a method based on interval-valued triangular fuzzy ANP, IVF-TOPSIS and IVF-VIKOR methods. A numerical example on performance assessment of the property responsibility insurance companies was also provided. Ashtiani and Azgomi [337] developed a fuzzy AHP-fuzzy VIKOR based trustee evaluation model. Fallahpour and Moghassem [338] presented a new MCDM technique based on VIKOR to select the suitable drawing frame parameters for 30Ne rotor spun yarn intended to be used for weft knitting process.

Sixteen papers in this main category have VIKOR-based models with non-specific applications. Opricovic [339] developed fuzzy VIKOR approach using triangular fuzzy numbers. Chang [340] proposed a new calculation method for utility and regret functions of VIKOR. Li et al. [341] introduced a group assessment approach based on a cloud model and VIKOR method. Wei and Zhang [342] developed an extended VIKOR method to deal with the correlative MCDM problem under a hesitant fuzzy environment. Park et al. [343] proposed an extended VIKOR method under an interval-valued intuitionistic fuzzy environment, used the different distances to calculate the particular measure of closeness of each alternative to the interval-valued intuitionistic PIS, and used the extended VIKOR method to rank and select the optimal alternative. The results of the proposed method were compared with the results of the extended TOPSIS method. Zhang and Wei [344] developed an extended VIKOR and TOPSIS method to solve the MCDM problems with hesitant fuzzy sets. A numerical example was illustrated as an application of the extended VIKOR method, and the result were compared with the TOPSIS method's results. Sayadi et al. [345] extended the VIKOR method for decision making problems with interval numbers. A numerical example illustrates and clarifies the main results developed in this paper. Xu et al. [346] and Xu [347] established a model based on the collective interval-valued intuitionistic fuzzy decision matrix and VIKOR method with interval-valued intuitionistic fuzzy assessments and partially known weight information. A numerical example was used to illustrate the applicability of the proposed approach. Li [348] proposed a new methodology called the relative ratio (RR) for the MADM problems. Comparisons of the RR method with the TOPSIS as well as the VIKOR were presented via a numerical example. Li and Zhao [349] proposed a VIKOR method based on prospect theory in which probabilities and the attribute value are both grey numbers. Yazici and Kahraman [350] proposed a new VIKOR method based on interval type two fuzzy sets.

Pai et al. [351] proposed a new decision-making method based on linguistic information and intersection concepts that include TOPSIS, ELECTRE, PROMETHEE and VIKOR. Kosareva and Krylovas [352] aimed to apply the types of intuitionistic fuzzy numbers and the exponent values of the generalized weighted averaging operator having the least error probabilities considering alternatives' ranking. Opricovic and Tzeng [17] illustrated a comparative analysis of VIKOR and TOPSIS by considering their aggregating function, normalization effects (linear vs vector). Zhao et al. [353] proposed and extended fuzzy VIKOR method under the interval-valued intuitionistic fuzzy environment. Heydari et al. [354] extended the VIKOR method to solve multi-objective large-scale non-linear programming problems with block angular structure. Ju and Wang [355] proposed a new method to solve multi-criteria group decision making problems in which both the criteria values and criteria weights took the form of linguistic information based on the classical VIKOR method. Peng et al. [356] proposed a fusion approach to produce a weighted compatible MCDM ranking of multiclass classification algorithms. It was concluded that MCDM methods were useful tools for evaluating multiclass classification algorithms and the fusion approach was capable of identifying a compromised solution when different MCDM methods generated conflicting rankings. Peng et al. [357] proposed a method based on intuitionistic fuzzy VIKOR in optimization of multi response problems. Ginevicius and Podvezko [358] made a comparative analysis among SAW and more sophisticated techniques. Peng et al. [91] proposed a method based on intuitionistic fuzzy VIKOR in optimization of multi response problems.

Regarding the future of the theory of VIKOR method; (1) fuzzy extensions related studies can be developed. Recently, intuitionistic fuzzy sets, type-2 fuzzy sets and hesitant fuzzy sets are preferred to have the capability of handling more uncertainty, and hence, to produce more accurate and robust results. (2) As one of the basic fundamentals of VIKOR method is using an aggregation function in MCDM/FMCDM problems, and any new aggregation function can be utilized in VIKOR related studies for further researches. Induced aggregation operators [55] and normal intuitionistic fuzzy-induced generalized aggregation operators [184] are integrated into VIKOR method since they are able to reflect the complex attitudinal character of the decision maker and they provide much more complete information for decision making. Maximal entropy ordered weighted averaging, maximal entropy ordered weighted geometric averaging and additive aggregation approaches can be combined with VIKOR in order to gain a new way on aggregation functions based VIKOR approaches. (3) In MCDM problems, some criterion values can be formed by stochastic variables. Therefore, stochastic MCDM has a valuable research area as well. While Mousavi et al. [242] developed fuzzy stochastic VIKOR approach to address uncertainty in the elements of hierarchy by utilizing Monte Carlo simulations, Li and Zhao [349] proposed a VIKOR method based on prospect theory in which probabilities and the attribute value are both grey numbers. For future directions on this topic, an approach based on the idea of the VIKOR method can be developed to obtain the ranking result of alternatives using stochastic dominance degrees.

It is shown that research on VIKOR method is already a fertile source to focus on. VIKOR can be applied to new areas especially agriculture, chemical and biochemical engineering, health, safety and medicine, policy making, social and education. For instance, cropping system evaluation, agricultural land-use prioritization and sustainability should be added in the potential application areas of VIKOR. In chemical and biochemical engineering area, hazard evaluation and risk assessment of chemical substances, identification of bacteria, assessment of processes for the use in hydrogen production, optimizing pulping process, and selecting chemical processes should be considered as new application areas of VIKOR. Researchers on policy making, social and education should be directed to the areas of technology selection policies in public planning, assessing residential quality and choosing social policies by VIKOR method. There is also a lack of user friendly software packages developed for VIKOR methodology.

5. Discussion

This section presents a distribution of VIKOR papers by the following points of view: (1) publication year, (2) publication journal, (3) country of origin, (4) main application area and application type, (5) main application area and approach type and (6) version of fuzzy numbers.

5.1. Distribution of papers by publication year

The followed classification depends on whether the paper uses a unique VIKOR method or two or more MCDM methods in combination. The 343 papers are handled to model the evolution of approaches to VIKOR methods in time, by adjusting the distribution of the number of studies during the period of 2000–2015 through a regression analysis which is determined with 95% confidence level. The year 2015 was also included in the analysis. Thereby, after classifying the studies according to three categories as single, hybrid and total, the data compiled are fitted through polynomial regression models separately, as shown in Fig. 10. This type of adjustment presents the most balanced ratio between percentage of explained model and the number of parameters needed. From Fig. 10, it can be easily inferenced that after 2009 there is an important increase in the production of papers based on these three categories. The hybrid methods are used more than single ones, recently. Indeed, the hybrid methods appeared as a solution to some of the shortcomings of the traditional approaches when they are used individually. In all studies, the trend becomes even more pronounced with a higher R^2 value (97%), indicating that the VIKOR related papers have increasingly better reception within the literature.

5.2. Distribution of papers by published journal

Papers related to the VIKOR method are published in a total of 160 journals. Table 4 shows the journals in descending order with respect to the number of published articles. The journal with most publications is "Expert Systems with Applications" ($n = 33$; %10). The journals which placed in the first five ranking are: "Materials

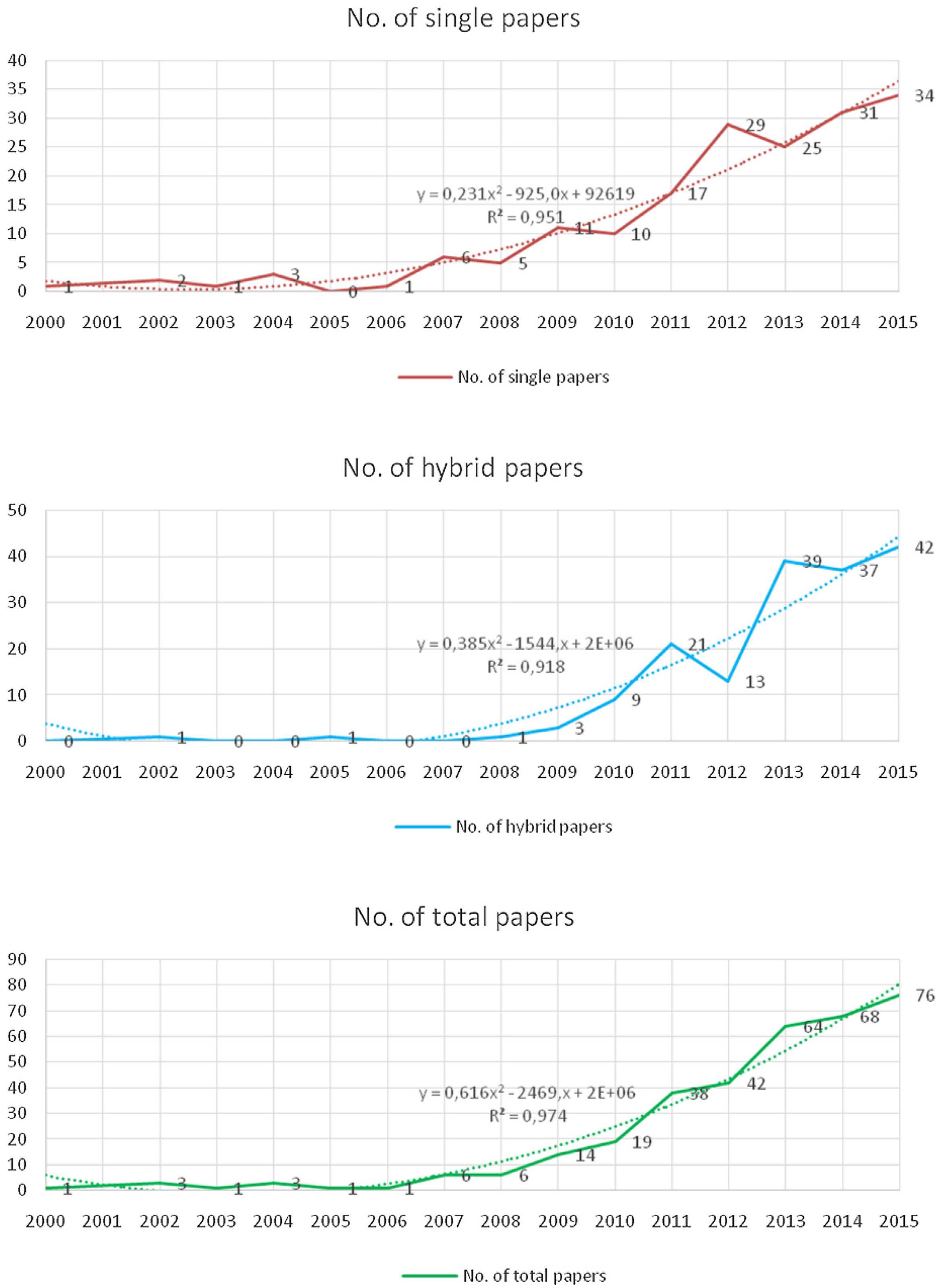

Fig. 10. Distribution of papers by publication year respect to categories single, hybrid and total.

& Design", "Applied Mathematical Modelling", "Technological and Economic Development of Economy" and "The International Journal of Advanced Manufacturing Technology". Most of the journals published only one, two or three articles.

5.3. Distribution of papers by country of origin

The literature review is, also, classified by the country of origin for each study, resulting in 12 portions and presented in Fig. 11. Taiwan accounts for 83 (24%) of all papers related to the VIKOR

Table 4
Distribution of papers in terms of published journal.

Publication journal	#	%
Expert Systems with Applications	33	9.62
Materials and Design	22	6.41
Applied Mathematical Modelling	11	3.21
Technological and Economic Development of Economy	11	3.21
The International Journal of Advanced Manufacturing Technology	11	3.21
International Journal of Information Technology & Decision Making	8	2.33
Applied Soft Computing	7	2.04
Applied Mechanics and Materials	6	1.75
International Journal of Production Research	6	1.75
Journal of Business Economics and Management	6	1.75
Journal of Intelligent & Fuzzy Systems	6	1.75
Quality & Quantity	6	1.75
Computers & Industrial Engineering	5	1.46
The Service Industries Journal	5	1.46
Advanced Materials Research	4	1.17
Knowledge-Based Systems	4	1.17
Water Resources Management	4	1.17
3 articles from each of 13 journals	39	11.37
2 articles from each of 19 journals	38	11.08
1 articles from each of 111 journals	111	32.36

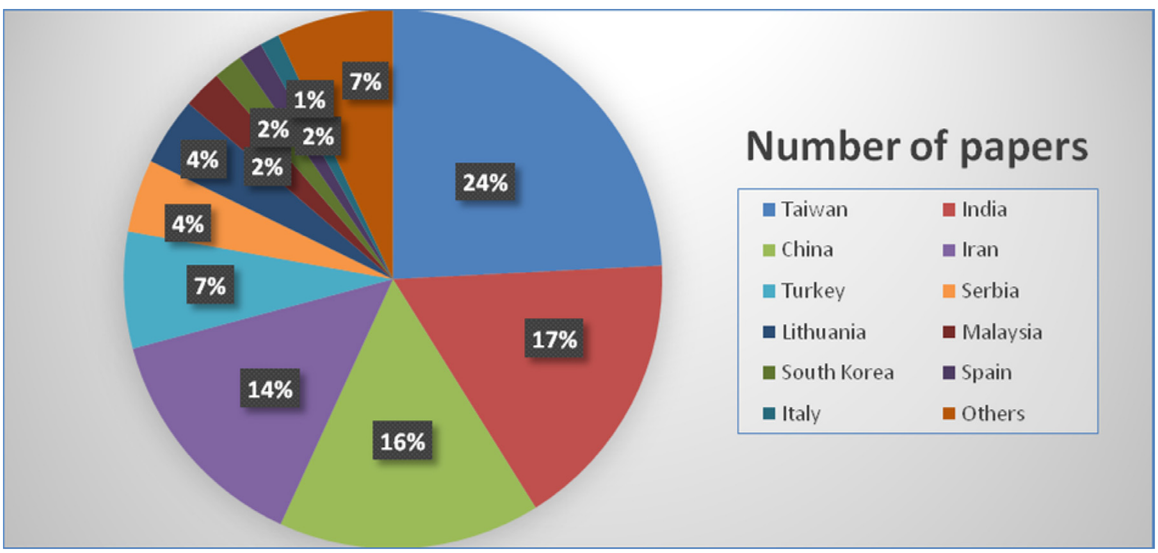

Fig. 11. Distribution of papers by country of origin.

method. India, China, Iran, and Turkey are also prolific in the usage of VIKOR method (17%, 16%, 14% and 7% respectively). The remaining countries have a rather testimonial presence (Serbia, Lithuania, Malaysia, South Korea, Spain, and Italy) with 15(4%), 14(4%), 8(2%), 6(2%), 5(2%) and 4(1%), respectively. The other countries include Bosnia and Herzegovina ($n=3$), Canada ($n=3$), Japan ($n=3$), USA ($n=3$), Singapore ($n=2$), UK ($n=2$), Austria ($n=1$), Colombia ($n=1$), Czech Republic ($n=1$), Finland ($n=1$), Germany ($n=1$), Ireland ($n=1$), Slovenia ($n=1$), and Sweden ($n=1$).

5.4. Distribution of papers by main application area and application type

Regarding to the main application area, "Design, mechanical engineering and manufacturing" constitutes nearly a quarter of the total papers. 25% of total papers ($n=87$) are concentrated in this application area (Fig. 12). They focus on specific problems such as material selection, robot selection, new product design, and machine tool selection. Another the most studied application areas are "Logistics and supply chain management", "Business management" by 13% of total papers ($n=45$). "Natural resources and environmental management" and "Structural, construction and transportation engineering" are probably in the most delicate disciplines. Other application areas such as "Energy management, Information technology, Policy, social and education, Financial management, Chemical and biochemical engineering, Health, safety and medicine, Agriculture" are also rarely selected by the authors in terms of applying VIKOR. 48% of total papers ($n=165$) present empirical study without focusing on a real world applications.

5.5. Distribution of papers by main application area and approach type

Regarding the distribution of papers by main application area and approach type (single/hybrid), Fig. 13 shows that among single approaches, the main category of "Design, mechanical engineering and manufacturing" is appeared as the most applied area ($n=57$). Among hybrid methods, "Business management" is the most preferred area for researchers ($n=31$).

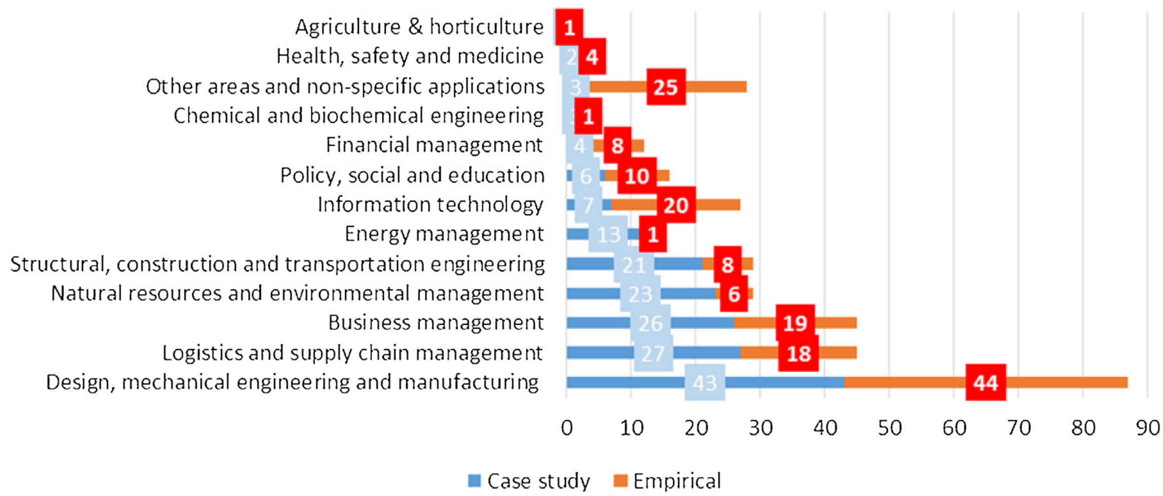

Fig. 12. Distribution of papers by main application area and application type.

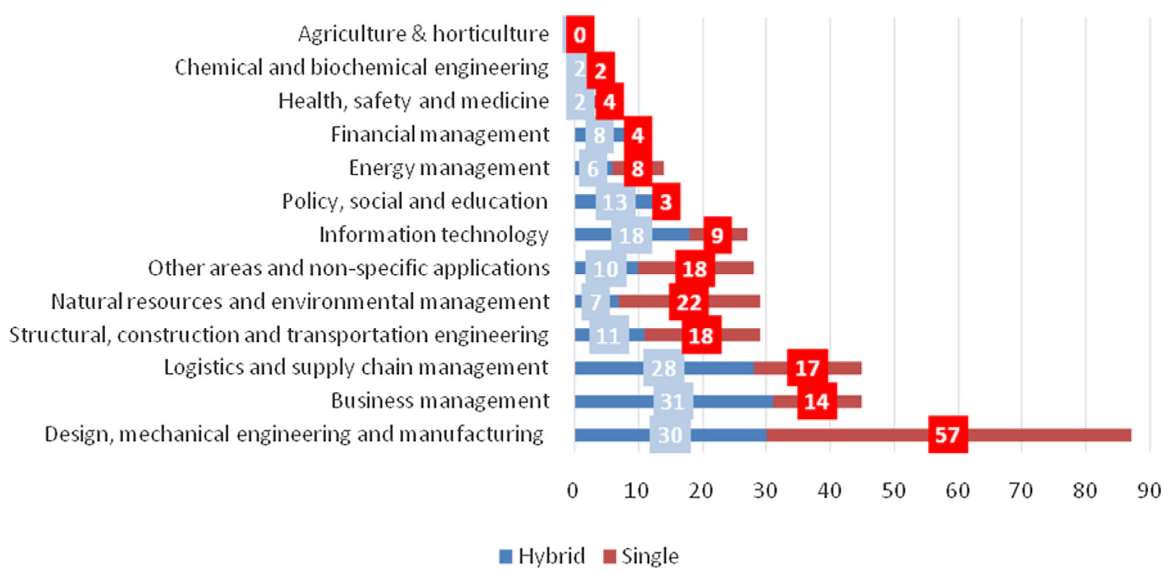

Fig. 13. Distribution of papers by main application area and approach type.

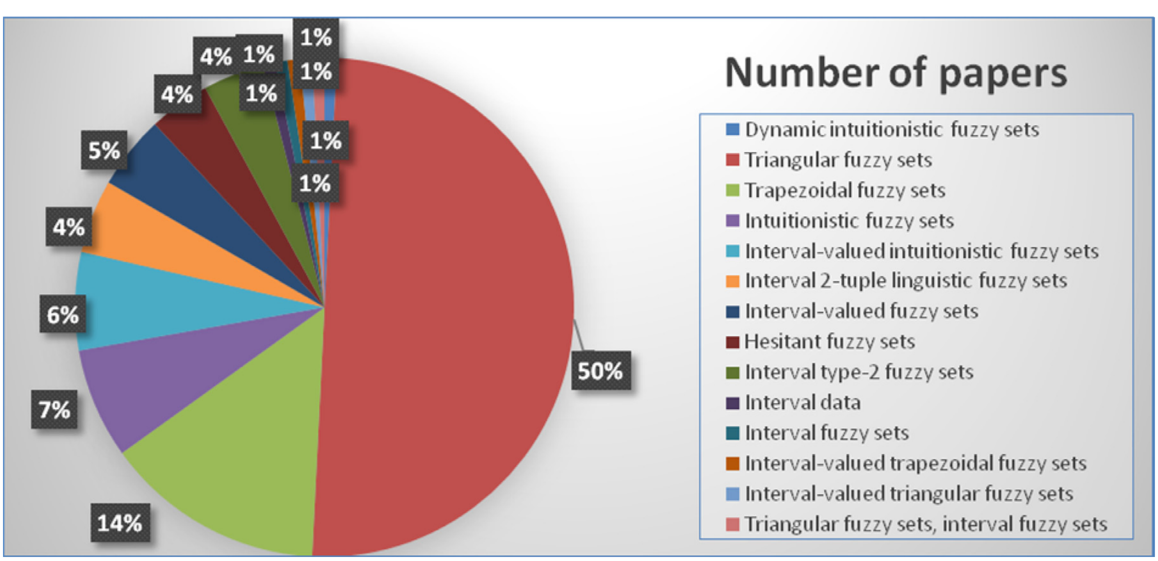

Fig. 14. Distribution of papers by version of fuzzy sets.

Table 5
Summary of VIKOR method extensions in each main application area.

VIKOR method extensions	Agriculture & horticulture	Business management	Chemical and biochemical engineering	Design, mechanical engineering and manufacturing	Energy management	Financial management	Health, safety and medicine	Information technology	Logistics and supply chain management	Natural resources and environmental management	Other areas and non-specific applications	Policy, social and education	Structural, construction and transportation engineering	Total
FVIKOR		4		10	1	2	2	3	8	5	1		4	40
DEMATEL + ANP + VIKOR		7		4		4	1	7	4			2	1	30
FAHP + VIKOR	1	7		4		1		5	2		3	3		26
AHP + VIKOR		4	2	6	1	1			1			1	2	18
FAHP + FVIKOR		2		3	1				1	2	1		1	11
Entropy + VIKOR		1		1	1				1	1		1		6
I2TLVIKOR		1		2					1	1	1			6
IFVIKOR				1					2	1	1	1		6
IVFVIKOR				2					3				1	6
ANP + VIKOR					1				1	1		2		5
IVIFVIKOR										1	4			5
ANP + DEMATEL + BSC + VIKOR		1										2		3
SWARA + VIKOR									2				1	3
Taguchi + IFVIKOR				1							2			3
AHP + Entropy + VIKOR				2										2
Entropy + IFVIKOR		1			1									2
FGRA + FVIKOR				1									1	2
HFLVIKOR		1						1						2
HFVIKOR											1		1	2
IT2FVIKOR				1							1			2
QFD + VIKOR				2										2
Taguchi + VIKOR			1	1										2
Others		10		14	2	2	2	7	17	6	5	2	6	73
Total		1	39	3	55	8	10	5	23	43	18	20	14	257

Abbreviations: I2TLVIKOR = Interval 2-tuple linguistic VIKOR, IFVIKOR = Intuitionistic fuzzy VIKOR, IVFVIKOR = Interval-valued fuzzy VIKOR, IVIFVIKOR = Interval-valued intuitionistic fuzzy VIKOR, HFLVIKOR = Hesitant fuzzy linguistic VIKOR, HFVIKOR = Hesitant fuzzy VIKOR, IT2FVIKOR = Interval type-2 fuzzy VIKOR.

5.6. Distribution of papers in terms of version of fuzzy sets

Fig. 14 gives the distribution of VIKOR based papers, which use VIKOR with various versions of fuzzy sets. 57% of all papers ($n = 198$) use crisp numbers and 43% of all papers ($n = 145$) use fuzzy sets in applying VIKOR. Regarding the papers which use at least one version of fuzzy sets in the related applications, 43% of them ($n = 63$, in 343 papers) prefer triangular fuzzy numbers. The following most preferred fuzzy number versions are as follows: Trapezoidal fuzzy sets ($n = 18$, 5%), Intuitionistic fuzzy sets ($n = 9$, 3%), Interval-valued intuitionistic fuzzy sets ($n = 8$, 2%), Interval 2-tuple linguistic fuzzy sets ($n = 6$, 2%), and Interval-valued fuzzy sets ($n = 6$, 2%).

Different versions of VIKOR based on fuzzy sets are developed for considering uncertainities and vagueness in MCDM problems. Hesitant fuzzy sets [111,249,256,342,344], interval 2-tuple linguistic fuzzy sets [56,66,147,183,355], Interval fuzzy sets [302], Interval type-2 fuzzy sets [68,151,162,250,350], interval-valued fuzzy sets [60,102,161,175,247,248], interval-valued intuitionistic fuzzy sets [141,148,186,223,291,346,347,353], interval-valued trapezoidal fuzzy sets [60], interval-valued triangular fuzzy sets [102], intuitionistic fuzzy sets [64,145,184,185,191,201,352,356,357], trapezoidal fuzzy sets [22,25,33,57,59,69–71,78,103,123,133,166,177,182,187,240], and 63 papers with triangular fuzzy sets are proposed for developing extensions of VIKOR and applied to different application areas.

5.7. Distribution of papers by VIKOR method extensions

In this section we summarized the extension of VIKOR method. For each main application area, the number of VIKOR method extensions are summarized and presented in Table 5. From the summary of these integrated methods, the following important findings can be extracted: (1) The VIKOR integrated methods (VIKOR method extensions) play a dominant role among all reviewed papers with a rate of 75% ($n = 257/343$). The remaining ($n = 86$) uses VIKOR as a single method in the application domain. (2) 95 of the reported methods use several VIKOR integrated methods. Methods which are used in at least two studies with respect to the application area are presented, whilst the rest are counted in “Others” in Table 5. (3) Of the 95 VIKOR integrated methods, fuzzy VIKOR (FVIKOR) has been the most-applied with 12% ($n = 40$), followed by DEMATEL + ANP + VIKOR with 9% ($n = 30$), FAHP + VIKOR with 8% ($n = 26$), AHP + VIKOR with 5% ($n = 18$), FAHP + FVIKOR with 3% ($n = 11$), Entropy + VIKOR, I2TLVIKOR, IFVIKOR, and IVFVIKOR with 2% ($n = 6$) per each, ANP + VIKOR, and IVIFVIKOR with 1% ($n = 5$) per each, ANP + DEMATEL + BSC + VIKOR, SWARA + VIKOR, and Taguchi + IFVIKOR with 1% ($n = 3$) per each, AHP + Entropy + VIKOR, Entropy + IFVIKOR, FGRA + FVIKOR, HFLVIKOR, HFVIKOR, IT2FVIKOR, QFD + VIKOR, and Taguchi + VIKOR with 1% ($n = 2$) per each. (4) Comparing to other main application areas, FVIKOR is mostly preferred in design, mechanical engineering and manufacturing, while DEMATEL + ANP + VIKOR integrated methods are preferred in information technology area. (5) FVIKOR method is applied to almost all application areas exluding agriculture & horticulture, chemical & biochemical engineering and policy, social & education, while DEMATEL + ANP + VIKOR, FAHP + VIKOR and AHP + VIKOR integrated methods are applied to eight of the thirteen main application areas.

Furthermore, VIKOR method is compared with other MCDM methods for evaluating its performance, including TOPSIS, FTOPSIS, ELECTRE, SAW, PROMETHEE, COPRAS, AHP, GRA, HFTOPSIS, PROMETHEE II, COPRAS-G, IFTOPSIS IVFTOPSIS, ELECTRE II, FAHP, EVAMIX, EXPROM2, MOORA, OCRA, ARAS, FARAS, TODIM, etc. The aim of comparing papers (190 papers) is to define the ranking differences between VIKOR and other MCDM methods. Table 6 presents the number and percentage distribution of techniques compared with VIKOR. The VIKOR related papers are mostly compared with TOPSIS method with %34.7 ($n = 66$) followed by, FTOPSIS, ELECTRE, SAW and PROMETHEE methods.

Table 6
Summary of compared methods vs VIKOR.

Compared method	#	%
TOPSIS	66	34.7
FTOPSIS	14	7.4
ELECTRE	14	7.4
SAW	12	6.3
PROMETHEE	10	5.3
COPRAS	7	3.7
AHP	6	3.2
GRA	6	3.2
HFTOPSIS	3	1.6
PROMETHEE II	3	1.6
COPRAS-G	3	1.6
IFTOPSIS	2	1.1
IVFTOPSIS	2	1.1
ELECTRE II	2	1.1
FAHP	2	1.1
EVAMIX	2	1.1
EXPROM2	2	1.1
MOORA	2	1.1
OCRA	2	1.1
ARAS	2	1.1
FARAS	2	1.1
TODIM	2	1.1
OTHERS	24	12.6

5.8. Overall assessment on existing approaches, main challenges and open problems

Unlike ELECTRE, which is an outranking MCDM method, VIKOR is a compromised ranking method. VIKOR cannot provide an opportunity to improve the current state of the method to an improved one. On the other hand, researchers endeavor on developing new ELECTRE methods. The outranking MCDM methods (e.g. ELECTRE, PROMETHEE) are usually proposed to aid decision making process in selecting among alternatives while considering the conflicting criteria. The alternatives are compared with each other with respect to each criterion. On the other hand, methods, such as AHP, make a pair wise comparison of the criteria to determine the relative importance. The development direction of AHP and similar methods that are based on pair-wise comparison manner can be to the integration of some new concepts. In the literature, various versions of fuzzy sets concept are frequently and easily adopted to AHP, ANP and etc. When a comprehensive insight is ensured regarding VIKOR method, it can be extended considering fuzzy extensions related studies, development of any new aggregation functions and stochastic nature of MCDM concept. Although several approaches have been integrated with the traditional VIKOR, others have not been investigated. Fuzzy extensions are at the forefront of all extensions. They make the traditional VIKOR more representative and workable in handling practical and theoretical problems. However, up to now, little attention has been paid to the traditional VIKOR dealing with hesitant, intuitionistic, interval type-2 and stochastic fuzzy MCDM problems. On the other hand, intuitionistic stochastic VIKOR, interval-valued intuitionistic stochastic VIKOR and other stochastic VIKOR extensions are not yet proposed for real-world MCDM problems.

In this review, we present some new directions for future studies on applications of VIKOR. Materials researchers commonly applied crisp data instead of fuzzy sets and its extensions. Hence, various material selection problems can be dealt with the progress in fuzzy set theory with VIKOR. Like the material selection problem, integration of interval type-2 fuzzy sets, hesitant fuzzy sets and intuitionistic fuzzy sets with VIKOR can be addressed as a future research for both robot selection and NPD problems. VIKOR and its fuzzy extensions can be applied to agriculture and agrifood industry where only one paper is proposed using VIKOR.

6. Conclusions

In this paper, a representative and comprehensive review of 343 journal articles on VIKOR applications is presented. Recently, VIKOR related studies have gained popularity in various MCDM problems due to its ability on the compromise ranking performance by comparing the measure of closeness to the ideal alternative. These papers were classified under 13 main application areas and a number of sub application areas. In addition, all papers were classified by publication year, published journal, country of origin, main application area and application type, main application area and approach type and version of fuzzy numbers used.

It should be acknowledged that the current review study has some limitations. The first limitation is that the data of 343 papers are gathered from scholarly journals of 16 databases. We do not include conference proceeding papers, master's thesis, doctoral dissertations, and book chapters in this VIKOR literature review. Secondly, some papers may be excluded from the review since we did not consider those papers from the journals which are not published in the searched 16 library databases. Third potential limitation is concerned with the languages of the papers. In other words, we did not include any papers written in a language other than English.

A number of significant points with respect to VIKOR applications can be derived from this literature review study. The vast majority of the studies are undertaken in Taiwan, India, China, and Iran. While VIKOR methodology is frequently used in the "Design, mechanical engineering and manufacturing" main application area, it is the least popular in "Agriculture" main application area. Material selection is the most popular sub application area with 37 papers applied for VIKOR. "Expert Systems with Applications" is the most preferred journal with 33 VIKOR based papers among others. VIKOR is not more than 17 years old, but it continues to be a popular method in several application areas. The trend becomes even more pronounced with a higher R^2 value (97%), indicating that the VIKOR related papers have increasingly better reception within the literature. The single methods are used more than hybrid ones and there is a steady state increase in the number of papers after 2009. 63% of all papers consider crisp numbers in applying VIKOR in the related applications. Regarding the papers which use any version of fuzzy sets in the related applications, half of them prefer triangular fuzzy numbers.

We expect and observe that, in the future, the number of applications and approaches related with VIKOR method will raise in the MCDM literature.

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