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Review

Performance of the decision-making trial and evaluation laboratory

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Abstract: Multiple attribute decision-making (MADM) techniques constitute a practical approach for solving complex problems involving multiple and often conflicting criteria. Decision-making trial and evaluation laboratory (DEMATEL) is a popular MADM technique with both admirers and critics. This study presents a comprehensive review of DEMATEL through bibliometric analysis using the Scopus database. This article examined 3,521 papers published in journals, conferences or books between 1981 and 2023. We examined a few parameters for commenting on the performance of the technique. Among them are research outputs, the network of DEMATEL users, implementation subject areas, research zones, financing opportunities and publication hosts and their impact trends. We conclude from the findings of this study that the DEMATEL is capable of dealing with modern problem-solving in future environments. Although the growth of new MADMs is obvious, based on the gathered data, we forecast that more than 776 documents will be published in 2025 using DEMATEL for problem-solving. This expanding tendency will continue in the future. As distinct MADMs have diverse constraints, foundations, computing complexity and standpoints, which result in different performances, outmoded low-performance MADM techniques must be reported by researchers to continue this paper's objective to minimize ambiguity among decision-makers and practitioners. To facilitate such a comparison in the future, a quantitative performance coefficient was also developed here.

Keywords: decision-making; DEMATEL; performance coefficient; bibliometric analysis; publication trends
Mathematics Subject Classification: 90B50

Abbreviations

No.	Definition	Abbreviation
1	Analytic Hierarchy Process	AHP
2	Analytic Network Process	ANP
3	Coefficient of Performance Index	CoPI
4	Complex Proportional Assessment	COPRAS
5	DEMATEL-based ANP	DANP
6	Documents which received citations	Dc
7	Decision-Making Trial And Evaluation Laboratory	DEMATEL
8	Decision-Making	DM
9	Elimination and Choice Translating Reality	ELECTRE
10	Interpretive Structural Modeling	ISM
11	Multiple Attribute Decision-Making	MADM
12	Multiple Correspondence Analysis	MCA
13	Multiple-Criteria Decision Making	MCDM
14	Multiple-Objective Decision Making	MODM
15	Multi-Objective Optimization by Ratio Analysis	MOORA
16	MOORA plus the full multiplicative form	MULTIMOORA
17	Number of Publications	NP
18	Stepwise Weight Assessment	SAW
19	Stepwise Weight Assessment Ratio Analysis	SWARA
20	Times Cited	TC
21	Times Cited per Year	TCpY
22	Total Documents	TD
23	Technique for Order Preference by Similarity to Ideal Solution	TOPSIS
24	VIekriterijumsko KOmpromisno Rangiranje	VIKOR
25	Visualization of Similarities	VOS
26	Weighted Aggregated Sum Product Assessment	WASPS

1. Introduction

Decision-making (DM) is a part of everyone's daily life, with various personal and corporate choices taken daily [1]. DM, on the other hand, entails the application of experience, inventiveness and insight to satisfy common needs or solve specific problems [2]. When dealing with decision problems with a single criterion, a DM method and techniques are usually simple and intuitive; however, as multiple alternatives or actions with multiple criteria are ranked and measured, the situation becomes extremely complicated, necessitating the use of advanced approaches [1]. The wide diversity of methods for coming to a decision might be confusing and frustrating for those practitioners in need of a solution to a specific problem. Thus, defining a DM technique and reviewing its performance in practice is the reason for this study. A similar strategy might be used to weed out unsuccessful techniques and provide decision makers access to streamlined alternatives that nonetheless deliver best DM performance. According to Aruldoss et al. [3], Many regular decisions will be made based on multiple criteria; thus, one may decide by assigning weights to these various criteria. Identifying the structure of the challenge, as well as the clear assessment of various criteria, is

critical; the authors of [4] stated that to reduce the possibility of conflict about problem definition goals, specifications, and criteria, DM should begin by defining the stakeholder(s) and decision-maker(s) for that decision. A general DM method can then be divided into several other phases to achieve the best possible result [4].

According to Ansah et al. [2] and Almulhim [1], over the last 30 years, one of the most common DM categories has been multiple criteria DM, also known as MCDM, which has been used to solve decision problems with various alternatives and criteria. The word MCDM acts as an umbrella term that describes a variety of systematic methods that intend to take formal account of many requirements in assisting individuals or organizations in exploring critical decisions [1]. Mardani et al. [5] stated that MCDM should be thought of as a catch-all word for all current strategies for assisting individuals with diabetes depending on their needs in cases when more than one conflicting criterion exists. According to Almulhim [1] and Zavadskas et al. [6], as it incorporates mathematical and computational methods to subjectively measure success requirements by decision-makers, MCDM is currently one of the most important and increasingly growing disciplines of management science and operations research. It employs a broad class of operations research models that account for decision issues where there are several criteria for DM [2]. According to Mardani et al. [5], the use of MCDM can be seen as a method/technique for dealing with complicated problems by breaking them down into smaller pieces. Following considerations and judgments on the smaller elements, the fragments are rebuilt so that the decision-makers can see the wider picture.

1.1. Classification of MCDM approaches

There are very few uniform classifications for MCDM; as a result, they can be categorized in a variety of ways, such as the features of the decision space, the model's structure or the solution process [1]. Nonetheless, a few studies have given a general MCDM field classification that contains two divisions, the first of which is focused on different objectives and the second on various alternatives [1,2,6–8], multiple objective DM (MODM) and multiple attribute DM (MADM). Each classification has many techniques, and each with its own set of characteristics [2]. For both MADM and MODM, the decision criteria should be determined before the DM [9].

MADM and MODM differ in that the former focuses on the decision space, while the latter focuses on mathematical programming with MODM functions that often have a continuous decision space [1,8,9]. MADM, on the other hand, focuses on problems with discrete decision areas [1,8,9]. Thus, MADM's primary goal is to rank or classify the alternatives, while MODM's primary goal is to find the approach that meets the objectives [9]. Be that as it may, the expressions MCDM and MADM are sometimes used interchangeably in the literature to refer to the same class of MADM [1]. The MADM is regarded as one of the decision support systems and it has been chosen as the foundation for the DM [2]. The MADM focuses on a decision goal, a set of chosen criteria and decision alternatives that a person wishes to examine during the DM process [2]. MADMs have identified alternatives, and decision-makers only need to analyze and rate the existing alternatives [9]. To evaluate alternatives, a list of criteria is defined, and the alternatives are compared against the list [1].

1.2. Multiple attribute decision making

MADM is important in a variety of fields, including engineering, social and management sciences [10]. According to a 2014 report, there are over 30 recognized MADM methods; however, due to the existing pattern in developing modern, updated and hybrid MADMs, the number would be hundreds.

Nonetheless, the number of MADM methods has not been easily determined, since any method, such as statistical and mathematical methods, that can solve multi-criteria problems is MADM form [9]. From the literature summary that Mardani et al. [11] provided, it can be observed that some MADMs were constructed before 2000 and some were introduced after 2000. Similarly, Mardani et al. [5] managed to categorize MADM methods into two groups: newly invented and classic methods. The DM trial and evaluation laboratory (DEMATEL), analytic hierarchy process (AHP), analytic network process (ANP), technique for order preference by similarity to ideal solution (TOPSIS), stepwise weight assessment (SAW) and elimination and choice translating reality (ELECTRE) are examples of classic methods. Modern MADM approaches include complex proportional assessment (COPRAS), multi-objective optimization by ratio analysis (MOORA), stepwise weight assessment ratio analysis (SWARA), weighted aggregated sum product assessment (WASPS), MOORA plus the full multiplicative form (MULTIMOORA) and a slew of other applied and increasingly developed methods for dealing with real-world issues.

Although there are lots of MADMs that have been introduced until now, in general, an important disadvantage of them is that when applied to the same problem, different MADMs have different limitations, assumptions, premises, levels of computational intensity and viewpoints, resulting in different decision outcomes [12,13]. Hence, outdated MADM techniques should be omitted to avoid confusion among decision-makers. Thus, for this essay we have chosen to focus on DEMATEL from the classic category.

1.3. Decision-making trial and evaluation laboratory

Duval, Fontela and Gabus introduced the DEMATEL in 1974 at the Battelle Memorial Institute, Geneva Research Centre, to visualize the form of dynamic causal interactions using matrices or digraphs [14–17]. DEMATEL is based on graph theory which includes the use of matrices to convert interrelationships into cause-and-effect units [14,17–20]. Ali et al. [21] described that the procedures for conducting DEMATEL can be summarized as shown in Figure 1. The DEMATEL's formulation phases can be summarized as follows, as based on a few past successful practices [20,21]:

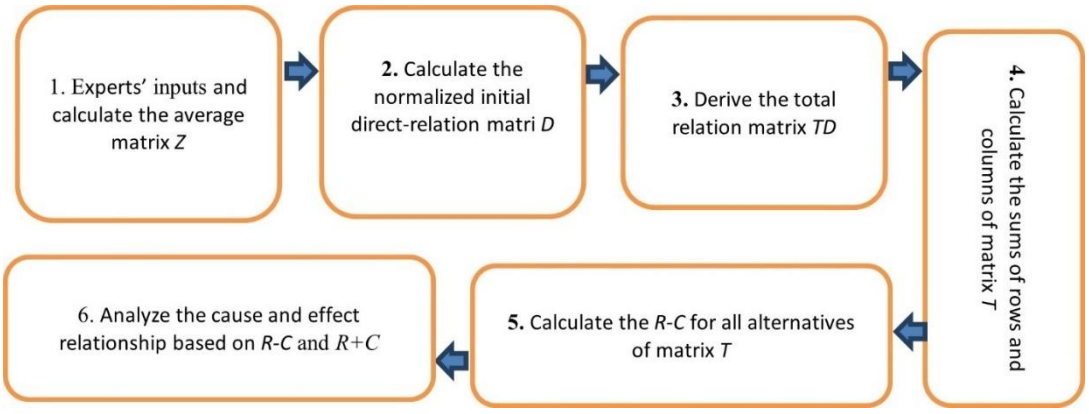

Figure 1. DEMATEL steps [21].

Step 1: Experts' inputs and calculating the average matrix *Z*.

For this study, consider a set of *m* experts and *n* parameters as a sample. Experts will be given a list of variables organized into sets of *i* and *j*. They will then be asked to show the estimated degree of influence that the factors have on one another (pair-wise comparison); that is, how factor *i* influences

factor j. The recommendation can be made on a scale of 0 to 4; 0 denotes no influence, 1 denotes medium influence, 2 denotes moderate influence, 3 denotes strong influence and 4 denotes extremely strong influence. Nonetheless, this measure is only used as an example; otherwise, the performance scale can be based on the researcher's preferences. The amount to which the expert's perception of factor i affects factor j is indicated by X_{ij}. For each expert, an n x n non-negative matrix is created as $X^k = X_{ij}^k$, in which k is the number of experts participating in the evaluation procedure with $1 \leq k \leq m$. The mathematical terminology is as follows in Eq 1:

$$X = \begin{bmatrix} 0 & x_{12} & \cdots & x_{1n} \\ x_{21} & 0 & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \ldots & 0 \end{bmatrix}. \tag{1}$$

Thus, we would get X^1, X^2, X^3, ..., X^m as the answer matrix acquired from the experts. Every element of the matrix is designated as X_{ij} representing the amount of impact that parameter i has on parameter j. It is necessary to gain an average understanding of the experts' inputs. This may be obtained by computing the matrix average, also known as the original direct-relation matrix. Matrix $Z = Z_{ij}$, based on Eq 2, may be used to represent this matrix:

$$Z_{ij} = \frac{1}{m}\sum_{i=1}^{m} x_{ij}^k. \tag{2}$$

Step 2: Normalizing the initial direct-relation matrix D.

The average matrix Z is used to obtain the normalized direct-relation matrix D in the second step. This is achieved by dividing each element by the average matrix's largest row sum, Z. The total direct effect of the factor with the greatest direct impact on the other parameters is given in Eq 3:

$$\max_{0 \leq x \leq 1} \sum_{j=1}^{n} z_{ji}. \tag{3}$$

Each node in this normalized direct-relation matrix D has a value between [0,1]. Eqs 4 and 5 demonstrate the computation to generate the matrix.

$$\mathrm{D} = \frac{Z}{s}, \tag{4}$$

where,

$$S = \max_{0 \leq x \leq 1} \sum_{j=1}^{n} z_{ji}. \tag{5}$$

Step 3: Finding the total relation matrix T.

The third step will be to determine the total or direct/indirect relationship between each system factor pair. According to the assumptions, the matrix of indirect influence converges to the null matrix, as seen in Eq 6:

$$\lim_{k \to \infty} D^k = 0. \tag{6}$$

When 0 is the null matrix and I is an $n \times n$ identity matrix, the following Eq 7 holds.

$$\lim_{k \to \infty} (I + D + D^2 + \cdots + D^K) = (I - D)^{-1}. \tag{7}$$

The matrix of total relation T will be defined with Eq 8:

$$T = D(1 - D)^{-1}. \tag{8}$$

Step 4: Calculating the sums of rows and columns of matrix T.

The vectors R and C denote the sums of the rows and columns, respectively, in the matrix of total influence T. Let vector R be $n \times 1$ and vector C be $1 \times n$. As a result, the number of rows, i.e., Eq 9, and columns, i.e., Eq 10, will be calculated.

$$R = [R_i]_{n\times 1}(\sum_{j=1}^{n} t_{ij})_{nx1}, \tag{9}$$

$$C = [C_j]_{n\times 1}(\sum_{j=1}^{n} t_{ij})_{nx1}. \tag{10}$$

Set R_i as the sum of the ith row in matrix T. The value of R_i presents the total given affects (both indirectly and directly), that factor i has on other factors. Set C_j as the sum of the jth column in matrix T. The value of C_j indicates the total received affects (both indirectly and directly), that other factors have on factor j.

Step 5: Calculate the R-C for all alternatives of matrix T.

When i=j, the subtraction (R_i-C_j) for each factor indicates the net indirect and direct interrelationship that factor i contributes to the system and it is given in Eq 11:

$$(R_i - C_j) = \sum_{j=1}^{n} t_{ji} - \sum_{k=1}^{n} t_{ik}. \tag{11}$$

If (R_i–C_j) is positive, the influence factor i is a net cause, while if (R_i–C_j) is negative, factor i is a net receiver (effect).

Hence, according to Lytras [22], Chen et al. [23], Wu [24] and Dedasht et al. [25] the final results of DEMATEL are in two groups:

(i) Cause group:

The measured (R_i–C_j) value represents the "severity of impact." This category includes all complete matrix factors of positive (R_i–C_j). These variables may have direct and/or indirect effects on the other components of the device. The trigger category factors will be prioritized depending on the outcome of (R_i–C_j); the higher the value of (R_i–C_j), the greater the effect on other factors. On the other hand, the component with the closest (R_i–C_j) to zero has a smaller effect on the system's other variables.

(ii) Effect group:

This category includes all total matrix factors of negative (R_i–C_j). These factors may be influenced by other device factors via direct and/or indirect relations. The factors in the effect group are prioritized based on their estimated (R_i–C_j); the factor with the lowest (R_i–C_j) has the most effect performs in the scheme. On the other hand, the element with the closest (R_i–C_j) to zero receives the least effect from the system's other influences.

1.4. DEMATEL performance

Some scholars do not trust the classic DEMTEL, such as Liu et al. [26], who called it "unreasonable and unfair". Some other researchers encourage the use of DEMATEL, for one, by saying that DEMATEL deserves a great deal of attention from contemporary users. Hence, it would be important to see how this classic DEMATEL, among other classic MADM competitor techniques, in an environment where the above-defined modern MADM category is also rapidly producing new competitors.

To answer this question, as a statistical instrument, bibliometrics is capable of commenting on DEMATEL's performance by exploring the existing reports [27–29]. Bibliometric analysis of scholarly outputs allows one to quantitatively investigate a particular study field by understanding its structure, characteristics and patterns [30]. It is also superior at predicting knowledge-based performance [29].

Therefore, here, the authors are reporting their bibliometric study to answer their research question.

2. Data and method

Regarding literature analysis approaches, a bibliometric study was chosen to comment on DEMATEL performance. For a bibliometric study, there are two main scientific databases: Web of Science (WoS) and Scopus. To choose the proper database for this research, the data were retrieved and compared based on search inquiries from both databases. There were 499 additional documents from the Scopus database relative to WoS. Therefore, the data were collected on 28 September, 2022, from the Scopus database. It was predictable as in general, Scopus has broad coverage as compared to WoS [31].

The only DEMATEL literature search that the authors found was written by Si et al. [32]. Despite its limitations, they used its searching protocol but in an improved form. The work by Si et al. [32] studied 509 articles, though the improved protocol received 3,521 publications for analysis. Si et al. [32] worked with a closed time domain to search from the year 2006 to 2016, but we left the domain open from the first indexed publication until the search day (28 September, 2022). Si et al. [32] grouped the indexed publications by searching one keyword, "DEMATEL", in their abstract, title or keywords into a classical DEMATEL and others (such as a fuzzy or gray DEMATEL and DEMATEL-based ANP). We have argued that a single keyword could not capture enough evidence. We have included not only DEMATEL but also the "trial and evaluation laboratory" that is partially covering the full term of DEMATEL and can capture those papers referring to it. Sometimes "decision making trial and evaluation laboratory" is also known in different forms, such as "decision-making trial and evaluation laboratory", "decision trial and evaluation laboratory" or "decision analyses trial and evaluation laboratory" etc.). Si et al. [32] filtered the search result to a single category of journal articles. We argue that many conference papers or book chapters should be included to present a better picture of DEMATEL implementation performance. Hence, this study covered not only journals but also conferences and book chapters. We exclude review works, erratum letters, notes and retracted publications as we argue that these types of publications are less likely to report a new experience of implementation of the technique.

From our search, there were 3,604 documents on the Scopus database for all document types. The articles, conference papers and book chapters consist of 97.70% of the total documents. The search was limited to articles, conference papers and book chapter document types. Therefore, the total number of documents reached 3,521. There were 83 documents that were excluded from the main search inquiry, i.e., Review (39), Conference Review (25), Erratum (6), Retracted (6), Note (2), Letter (2), Book (1), Data Paper (1) and Editorial (1). The search strategy based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 flow diagram [33] is shown in Figure 2. Finally, the exported data from Scopus included comprehensive and detailed data on the publication year, author, sources, institutions and keywords. The collected data were analyzed by using the "visualization of similarities" (VOS) VoSviewer software [34], the R-tool of the bibliometrix-package that was specifically designed for quantitative bibliometrics research [35] and ScienceScape (https://medialab.github.io/sciencescape/), which is an online science visualization software developed by Mathieu Jacomy at the Sciences-Po Medialab (https://medialab.sciencespo.fr/). ScienceScape allows users to obtain their desired visual charts by uploading data from WoS or Scopus.

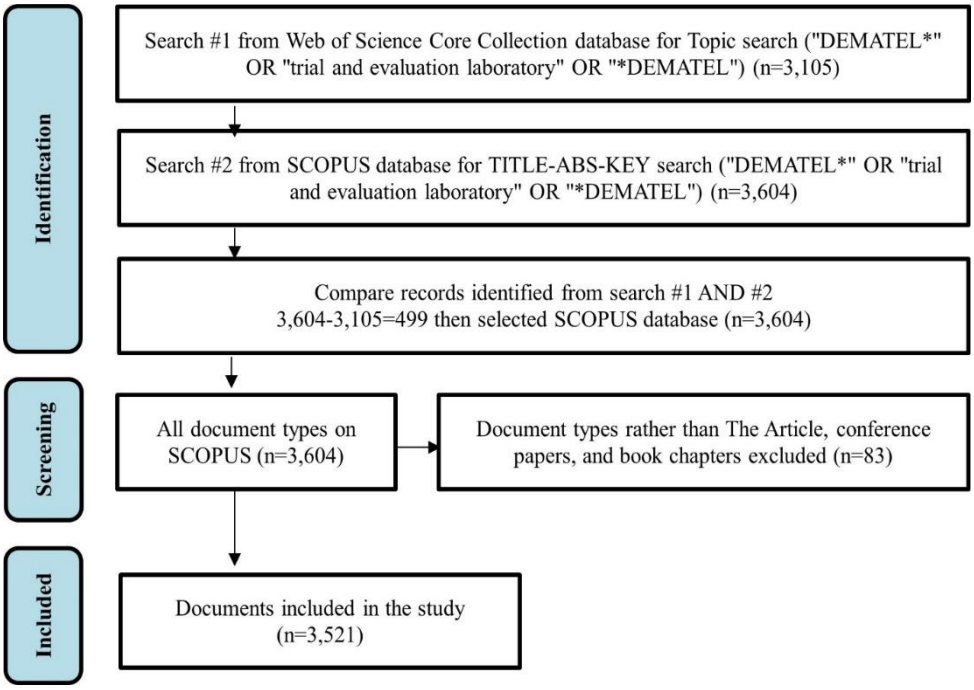

Figure 2. Search strategy flow diagram.

3. Results

The annual distribution of the "DEMATEL" data set of 3521 documents is illustrated in Figure 3, The publication line declined in the year 2021 because the current year data were not completed yet. The year 2023 is not available yet, but four documents were published in advance in the Scopus database. The development of publications could be divided into three periods/phases. The first phase started from 1981–2005, which reflected the fact that "DEMATEL" was in its infancy stage and the number of publications per year was less than two. The first journal paper recorded in the Scopus database was published in 1981, entitled "An attempt of multivariate data analysis and DEMATEL to develop the academic intelligent system" written by Kawata [36] in the Japanese language.

In the second phase (2006–2012), the publications grew steadily from six to 113. The third phase began in 2013 when the publication fluctuated but the trend shows even sharper growth. This pattern, which shows that the number of researchers is constantly increasing, is evidence of the advancement of the topic and its capability for being in more fields [37].The publication's output trends show that the "DEMATEL" research area will remain thriving in the next few years. Even with the aim of linear regression analysis and based on data from Phase 3, it is predicted that more than 776 DEMAETL-related articles will be published in 2025 with a 92% confidence interval. The most relevant authors who have above 50 publications were Tzeng (150), Yüksel (75), Dinçer (74) and Tseng (64).

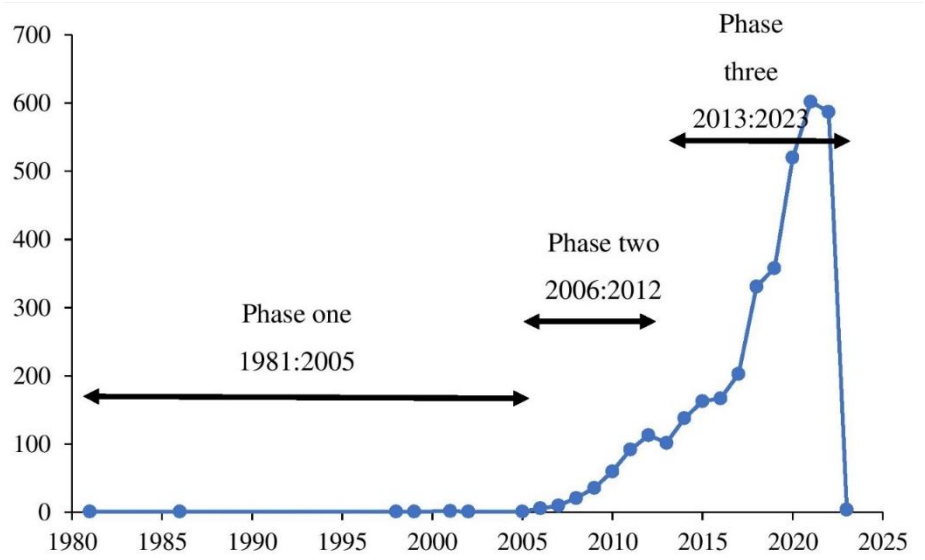

Figure 3. Publication outputs of "DEMATEL" data set from 1981–2023.

3.1. Citation and networking

Table 1 illustrates the descriptive statistics of the "DEMATEL" data set; 3,521 documents from 1,178 sources were published during the time spanning 1 January, 1951 to September 28, 2022. Given that, in recent years, more subject areas have expressed an interest in covering DEMATEL-related publications, not only in the total time span, but also in every phase; engineering and computer science were the top topic areas covered, as shown by the Scopus analysis tool.

From Table 1, the average citation per document was 18.23, which is considered very high as compared to the engineering field (6.92) [30]. There is an alternative source for comparing the average citation per document, which is Incites Essential Science Indicators (https://esi.clarivate.com/). According to Incites, the average citation per document for All Fields, Computer Science, Economics & Business and Engineering are 13.83, 9.01, 10.33, and 9.94, respectively. Therefore, the average citation per document for this study (18.23) is much higher than that for the other fields of research, which indicates that DEMATEL is a hot and trendy topic of research. Moreover, the international co-authorships index "DEMATEL" data set from 1981–2023, increased from zero to 5.32% and 24.19% during the respectively three phases. However, the co-authors per document increased from Phase one (2.5) to Phase three (3.37), which indicates that the recent publications in the "DEMATEL" research area are more collaborative.

China (with 1,040 publications), Taiwan (735), India (564), Iran (471), Turkey (318), the United Kingdom (159), the USA (131), Malaysia (114), Australia (85) and Indonesia (60) are top 10 countries with the highest number of publications in the "DEMATEL" research area. Although geographically, the eastern part of the world appears to have more DEMATEL users, Figure 4 is evidence of the worldwide expansion of the DEMATEL application network. With reference to Figure 4, China has the strongest relationship with the United Kingdom, USA and Turkey with 60, 54 and 51 common documents, respectively. India with the United Kingdom also has 51 documents in common. The growth of the involvement of DEMATEL in collaborative studies is shown via a comparison of co-authorship countries in Phases two and three in Figure 5. Figure 6 shows the co-authorship networks.

Table 1. Main information about the data.

Description	Results for 1981–2023	Results for 1981–2005	Results for 2006–2012	Results for 2013–2023
Sources (Journals, Books, etc.)	1,178	8	179	1,060
Documents	3,521	8	338	3,175
Annual growth rate %	3.36	0	63.11	NA
Average citations per document	18.23	28.62	45.63	15.28
References	161,595	24	8,217	154,323
Keywords index	10,168	45	2,071	9,118
Author's keywords	7,661	36	844	7,113
Single-authored documents	251	1	40	210
Co-authors per documents	3.31	2.5	2.77	3.37
International co-authorships %	22.32	0	5.32	24.19
Article	2,822	6	191	2,625
Book chapter	73	0	2	71
Conference paper	626	2	145	479

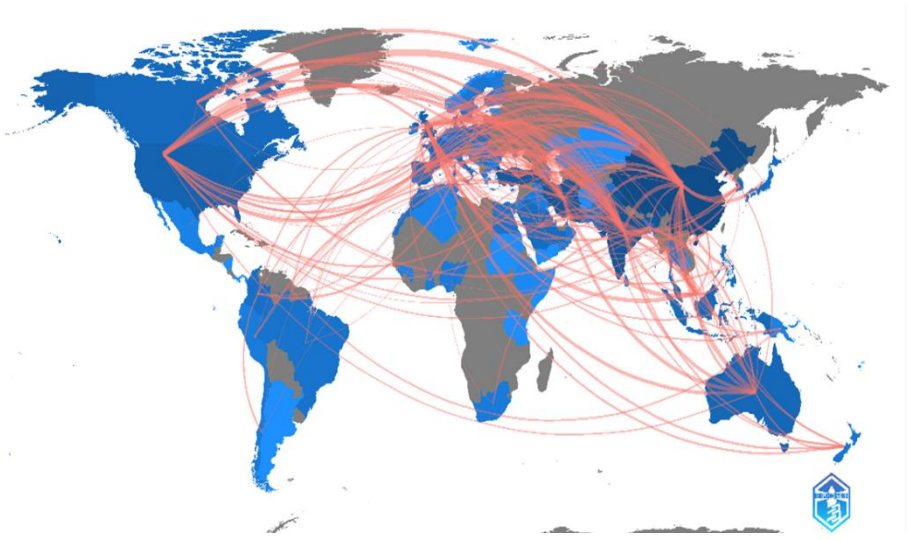

Figure 4. Country collaboration map of "DEMATEL" data set from 1981-2023; the gray area means zero documents, and the blue shade from light to dark represents one to 1,040 publications (China).

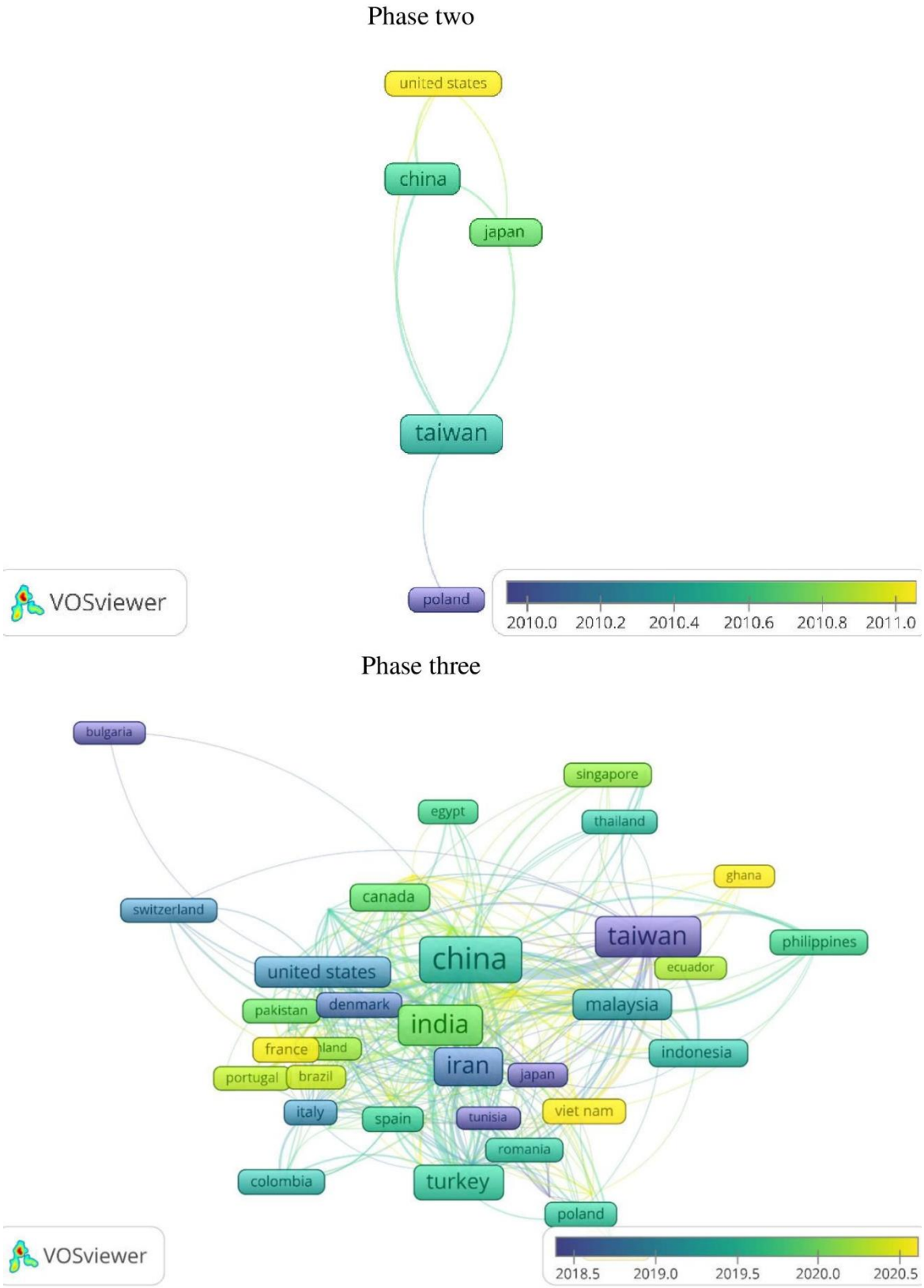

Figure 5. Co-authorship countries in the "DEMATEL" network.

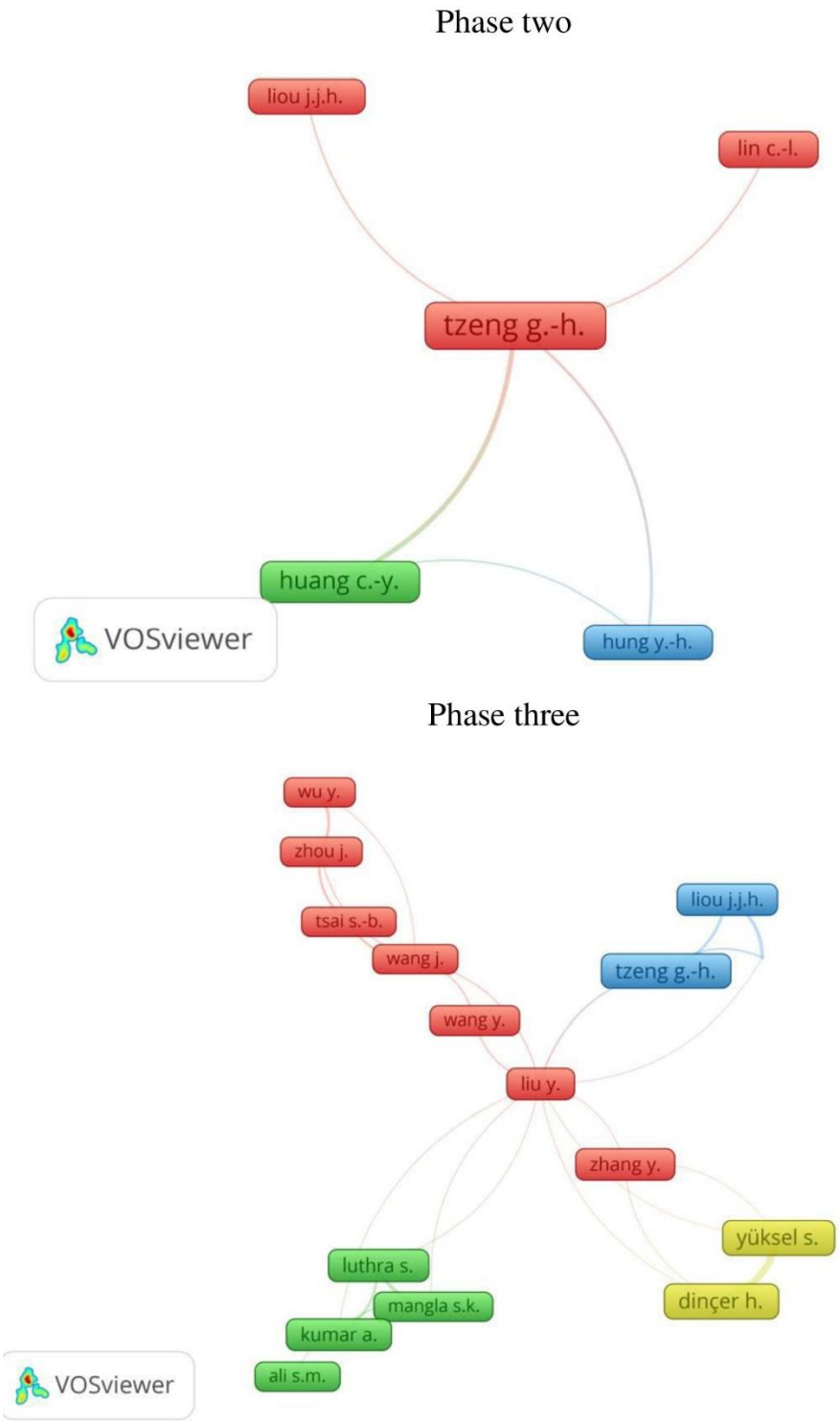

Figure 6. Co-authorship networks.

3.2. Keywords analysis

Keyword analysis was employed to identify and explore leading and emerging topics in the "DEMATEL" research area. There were 7,661 author keywords in the 3,521 documents. The Keyword analysis explains the expansion of the DEMATEL application as the number of keywords was growing

phase by phase. Although none of the top author keywords were repeated in Phase one, Figure 7 illustrates the top author keywords trends in the "DEMATEL" research area. The data were obtained from ScienceScape (https://medialab.github.io/sciencescape) and cleaned manually in an Excel sheet. The data cleaning process was merging similar words in the data set like "multi-criteria decision making", "multiple criteria decision making" and "MCDM". The incomplete year 2023 data were excluded. There were 338 author keywords in Phase two, and 3,175 in Phase three. The top five identified keywords in Phase two were "DEMATEL", which grew from two in 2006 (2, 2006) to 67 in the year 2012 (67, 2012), "Analytic Network Process" (ANP), which grew from (1, 2006) to (15, 2012), "MCDM", which grew from zero to 14, "VIekriterijumsko KOmpromisno Rangiranje" (VIKOR), which grew from zero to nine, and "fuzzy DEMATEL", which grew from zero to five. The top 10 identified author keywords in Phase three were DEMATEL, "fuzzy DEMATEL", "MCDM", "Sustainability", "Covid-19", "Analytic Network Process", "Interpretive Structural Modeling" (ISM), "Circular Economy", "Sustainable Development" and "Industry 4.0". The DEMATEL had the fastest growth among the top 10 author keywords, which grew from 55 in the year 2013 to 239 in the year 2022.

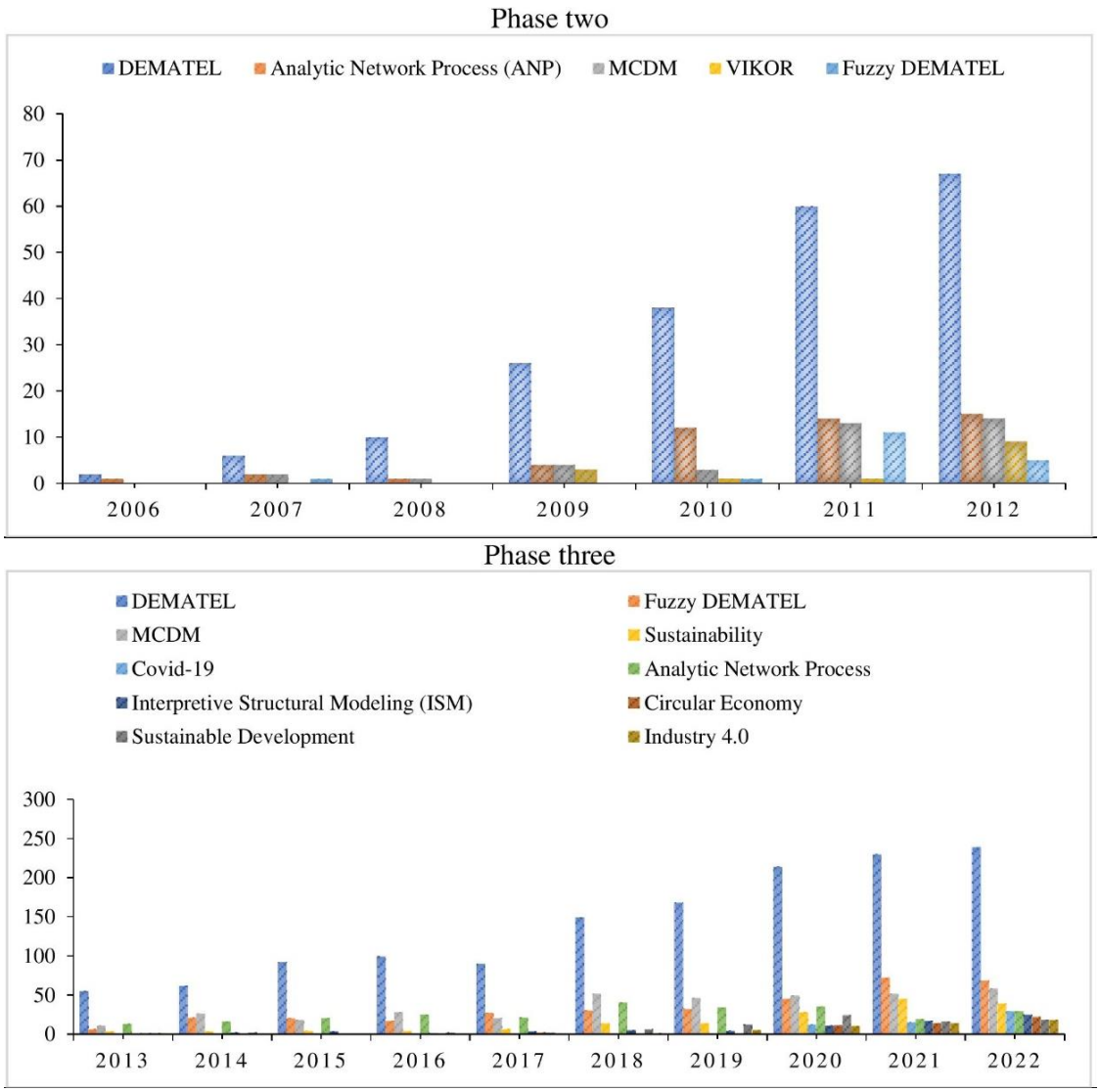

Figure 7. Top author keyword trends in the "DEMATEL" research area.

The emerging keywords are shown in Figure 8 overlay views of the top 50 "author's keywords" co-occurrence network. This shows the capability of the DEMATEL to be a hybrid with fuzzy sets (a theory that focuses on certainty issues in advanced forms [38]) as well as its initial simple version, Gray theory and/or other MCDMs (such as ANP, VIKOR and TOPSIS). It also presents the successful application of DEMATEL in trending fields ranging from ISM and blockchain, to sustainability, industrial revolution 4.0 and circular economy.

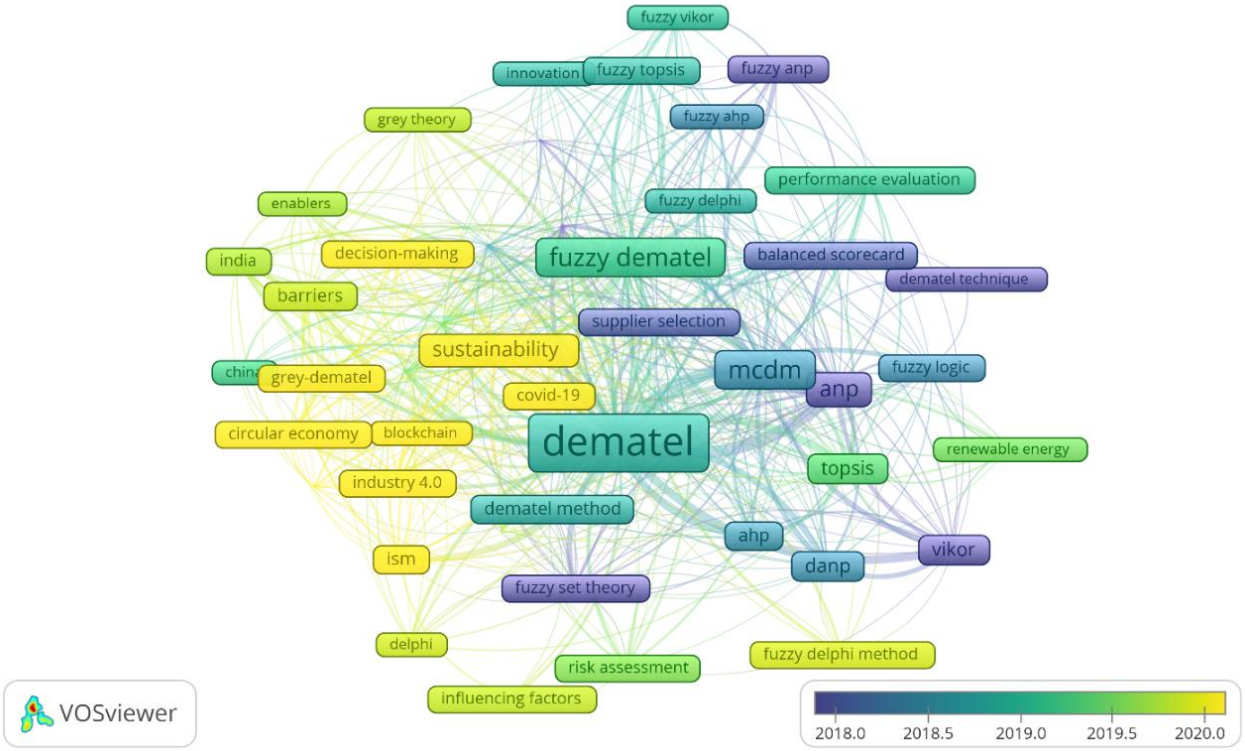

Figure 8. Overlay view of top 50 "Author's keywords" co-occurrence network.

3.3. Most prolific sources

Source analysis helps to identify the distribution of core journals in the research area. The data in Table 1 show 3,521 documents published in 1,178 sources (journals, books, etc). Table 2 ranks the top 10 sources by the h-index value. The original h-index was formulated for the measurement of researcher impact. However, it is used for journal evaluations as well. The h-index 52 in Table 2 for the "Journal of Cleaner Production" indicates that the journal has at least 52 publications and each of them received a minimum of 52 citations.

The "Expert Systems with Applications" journal has received 10,123 citations (ranked number one according to its citations); it historically has the record of being the most consistent DEMATEL publishing journal starting from 2007. Figure 9 shows the top 10 journals' growth based on the number of publications in the "DEMATEL" research area from 1981–2023.

There was not any publication before 2006 in the top 10 journals. The top three journals with the highest number of documents were Sustainability (Switzerland), Journal of Cleaner Production and Expert Systems with Applications, with 143, 138, and 77 publications respectively.

Table 2. Top 10 journals on impact in the "DEMATEL" research area from 1981–2023.

Source	H-index	NP	NP-Rank	TC	TC-Rank	PY-start	Q_s	Q_p
Journal of Cleaner Production	52	133	1	7490	2	2013	Q_1	Q_1
Expert Systems with Applications	51	73	3	10123	1	2007	Q_1	Q_1
Sustainability (Switzerland)	25	120	2	1879	4	2014	Q_2	Q_2
Computers and Industrial Engineering	22	35	4	1682	5	2012	Q_1	Q_1
Resources, Conservation and Recycling	20	27	6	1586	6	2012	Q_1	Q_1
Applied Soft Computing Journal	17	19	14	1213	7	2011	Q_1	Q_1
Benchmarking	15	30	5	468	18	2015	Q_1	Q_1
International Journal of Production Economics	14	20	13	2160	3	2012	Q_1	Q_1
International Journal of Production research	13	16	22	874	11	2014	Q_1	Q_1
Sustainable Production and Consumption	13	15	28	589	13	2016	Q_1	Q_1

*Note: (TC=Times cited, and NP=Number of publications, Qs=Journal quartile according to Scimago journal ranking when the first DEMATEL paper was published, Qp=Journal presentes quartile according to Scimago journal ranking).

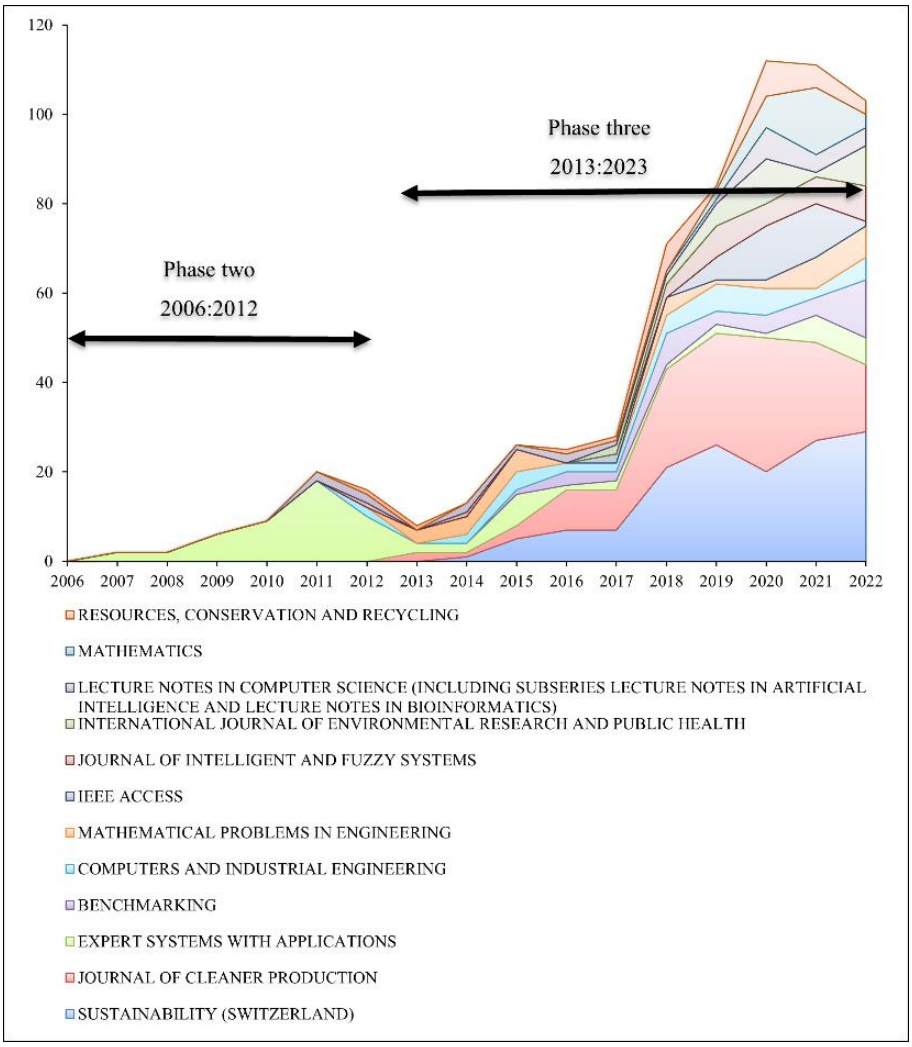

Figure 9. Top 10 journals with growth in the "DEMATEL" research area from 1981–2023.

3.4. Auxiliary assessment

In this section, the top 30 documents, as illustrated in Table 3, were qualitatively analyzed. Evaluating top-cited papers' content helps to analyze the most significant research topics within the study areas. The data were analyzed by using Bibliometrix software and the threshold of 29 times cited per year (TCpY) was employed to retrieve the top-qualified documents.

Table 3. Top 37 documents with highest times cited per year (TCpY).

Paper	Total Citations	TCpY	Phase
[43]	229	114.50	3
[44]	266	88.67	3
[45]	239	79.67	3
[46]	683	62.09	2
[47]	839	52.44	2
[48]	244	48.80	3
[49]	195	48.75	3
[50]	380	47.50	3
[51]	139	46.33	3
[52]	741	46.31	2
[53]	135	45.00	3
[54]	221	44.20	3
[55]	438	43.80	3
[56]	131	43.67	3
[57]	251	41.83	3
[58]	413	41.30	3
[59]	119	39.67	3
[60]	310	38.75	3
[61]	73	36.50	3
[62]	437	36.42	2
[63]	105	35.00	3
[64]	278	34.75	3
[65]	69	34.50	3
[66]	136	34.00	3
[67]	98	32.67	3
[68]	130	32.50	3
[69]	192	32.00	3
[70]	94	31.33	3
[71]	405	31.15	2
[72]	154	30.80	3

*Note: Total citations calculated from the day of publication to 28 September, 2022

The top 30 were the most frequently cited papers per year reviewed, and the common key research directions were extracted. Among them, none were published in Phase one, but there were only five publications from Phase two and other publications from Phase three show the growth of the quality

outcome via DEMATEL contributions, as well as the capacity of recent publications. Similarly, in the top 100 most frequently cited per year (TCpY), 12 were from Phase two and the remaining 88 resulted in phase three. While in the top 100 most frequently cited papers, 40 were from Phase two and the remaining 60 resulted in Phase three. The older papers have more chances of getting citations. Therefore, the number of Phase two papers rose in the total citation rankings. Among the top 10 highly cited papers, only the Wu [39] paper from Phase two received 423 citations (28.20 TCpY), which did not meet the criteria of 29 times cited per year.

Additionally, from the reported funds in the articles, the significant growth from 0 funds in Phase one to 35 funds in Phase two, and from 1,281 funds in Phase three is disclosed in the statistics, demonstrating the DEMATEL contribution to fund raising research projects. Finally, our findings show that more journals are publishing DEMATEL-related papers. DEMATEL-enabled projects obtain more funding now. This was also witnessed as the number of high-impact publications increased in new phases, and it is expected that the scientific community would see even more numbers in the future.

The R-tool of the Bibliometrix package allows use of the conceptual structure function to perform multiple correspondence analysis (MCA) to map a conceptual structure of the DEMATEL for identifying clusters of documents that express common concepts. Figure 10 maps the top 30 author keywords of documents relevant to DEMATEL.

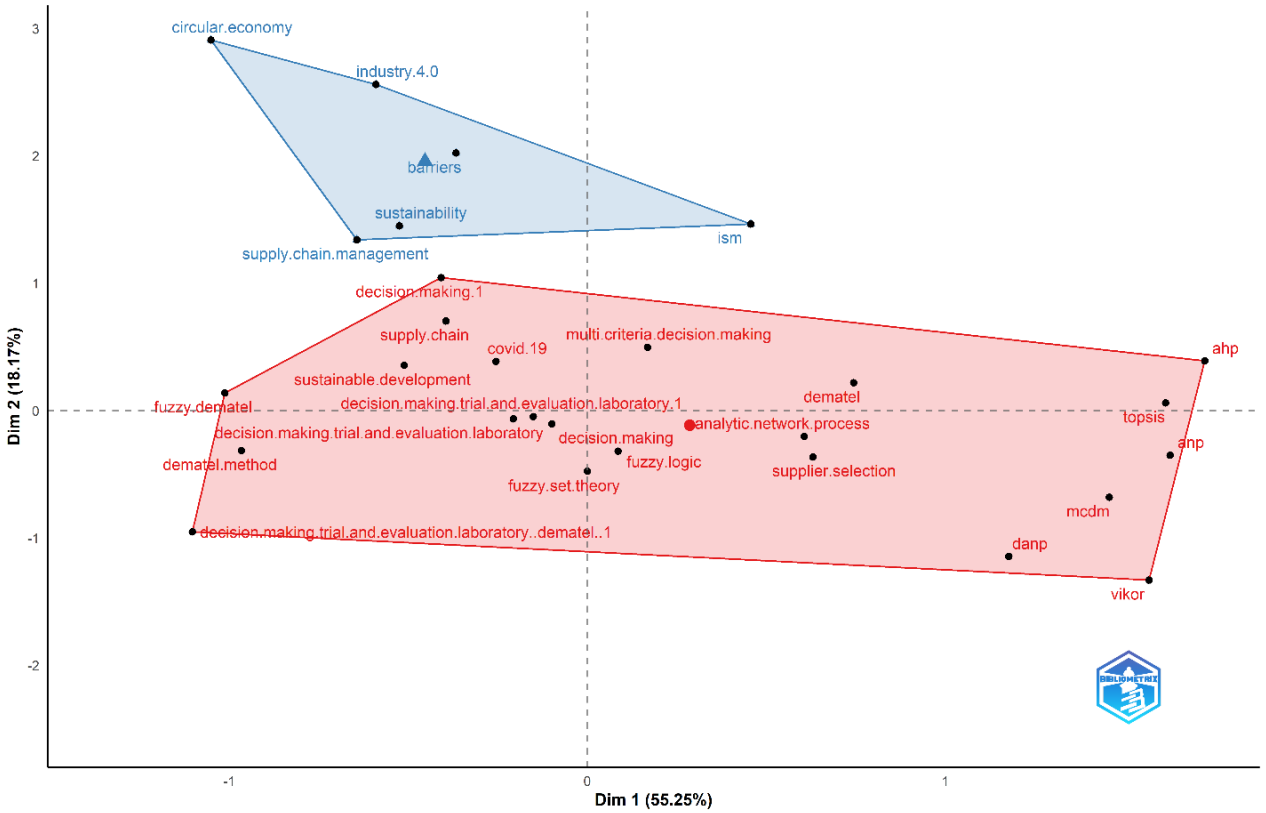

Figure 10. Conceptual structure map based on author keywords.

Two distinct clusters of red and blue, shown in Figure 10, represent the subdomain of DEMATEL. Dim. 1 and Dim. 2 indicate the average position of the documents included in each keyword, and the midpoint of the map represents the center of the research area [40,41]. In the conceptual structure map, the keywords of each document are connected through a single network. This co-word network

structure helps readers to understand the subjects covered by the research fields and identify the research fronts [42].

On one hand, the red cluster is the largest and consists of MCDM, TOPSIS, ANP, DEMATEL-based ANP (DANP), AHP, VICOR, fuzzy set theory, fuzzy DEMATEL and supplier selection. This cluster revolves primarily around the various methods and techniques that are utilized with DEMATEL. On the other hand, the blue cluster consists of circular economy, industry 4.0, barriers, ISM and sustainability. This primarily refers to the new trend of applications in the literature via the DEMATEL contribution. Yet, both clusters contain keywords related to supply chain management, indicating that the DEMATEL technique was also commonly used in this field of study.

Bibliometrics could provide an in-depth framework for subjective evaluations and comparisons. In contrast to the subjective viewpoint, an objective evaluation tool can also help to reach a better conclusion. Hence, in this work, to measure the performance of published documents in the area of DEMATEL, a coefficient of performance index (CoPI) was developed. CoPI, as shown in Eq 12, is a ratio of the number of documents which received citations (Dc) to the total documents (TD) minus Dc.

$$CoPI = \frac{Dc}{TD-Dc} \tag{12}$$

There were 2,701 documents which received at least one citation out of 3,521 documents. Therefore, the CoPI for DEMATEL was $3.29 = \frac{2701}{3521-2701}$. This index is comparable to other studies that calculates the same measure for other methods/keywords.

DEMATEL and ISM (Interpretive Structural Modelling) are the two main DM techniques used in MCDM to investigate the complex relationship between decision criteria [73]. Figure 11 from the Scopus archive depicts that, while ISM had more users in 2006 and remained more popular for years, from 2020 it had lost its lead and DEMATEL had surpassed it.

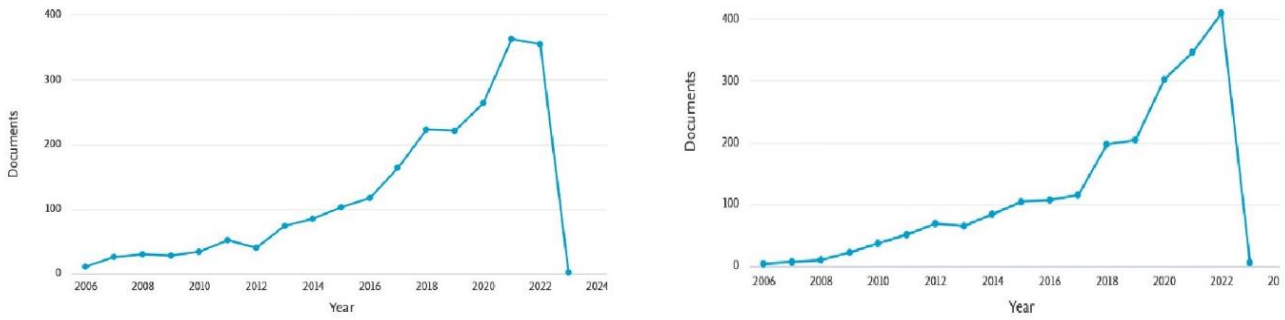

Figure 11. DEMATEL vs ISM.

The literature on DEMATEL includes both theoretical and practical works. However, the majority of attention has been focused on how the DEMATEL is used in practice rather than how the model itself can be upgraded. DEMATEL has been applied in a number of areas, including business and organizational management, decision making, strategic planning, risk assessment, marketing research, medical decision making and crisis management. The papers regarding DEMATEL are generally a mix of theoretical and application-oriented papers. However, this article is a more application-oriented paper. Over the years, the use and application of DEMATEL has grown steadily in various domains, such as business, medicine and engineering. Additionally, researchers have begun to combine the

DEMATEL technique with other multi-criteria decision-making approaches, such as the analytic hierarchy process and the fuzzy analytic hierarchy process. This article can be used as a reference to understand the structure and dynamics of the technique and its potential applications. Moreover, it can serve as an aid to assess the potential of DEMATEL-based approaches in the future.

4. Conclusions

In this article, we explained the DEMATEL from the classic category of MADMs. Considering the spawning of new MADMs in recent years, we attempted to comment on the performance of the classic DEMATEL. For that, we compared previous applications of this technique in three phases and time periods. This study utilized 3,521 documents collected from Scopus databases. Although there might be some documents on other databases, which were not included in this study, our data predict that the number of DEMATEL applications will rise rapidly. According to our data, publications utilizing DEMATEL have a higher average citation per document when compared to the ranges.

We have also seen DEMATEL users expanding their networks; thus new contributors are joining one team phase after the other. Moreover, a developing trend has also been observed via subject areas using this technique. In support of this article's findings, the existing literature presents the following: as one of the most effective classic DM techniques, DEMATEL is well-suited for the extraction of interdependent relationships and the intensities of interdependencies among complex system elements [15]. This is consistent with another paper [18] that says that the DEMATEL technique is widely accepted as one of the best for analyzing the cause-and-effect relationships among decision alternatives and/or chosen criteria. DEMATEL employs expert expertise to gain a better understanding of the relations between variables based on the causes and effects learned via different factors [15]. Si et al. [20] stated that DEMATEL is well hybridizable with other MADMs, as this article also revealed that there are several MADMs combined with the DEMATEL in the literature. The approach may indeed recognize indirect, direct and interdependent effects within each complex component and rank them according to DM strategies, all while signaling the potential for progress [14,18,20]. In the DEMATEL structure, each factor's ranking may acquire an increase or decrease due to indirect relations [19]. As a result, this approach is valuable for enhancing the understanding of complex problems and leading to the identification of more feasible solutions through the use of these systems [15,18]. We also concluded from the findings that DEMATEL is usable even in our current complex decisions.

This research set DEMATEL against similar classic MADMs; Si et al. [20] also concluded similarly, because there are several advantages of using this method. For instance, it analyzes the reciprocal effects (both direct and indirect effects) of different variables and comprehends the dynamic cause-and-effect interaction in the DM problem. It is capable of generating an image of the interrelationships between variables and allowing the decision-maker to identify which parameters have reciprocal effects on one another. It may also be used to determine crucial evaluation parameters and compute the weights of assessment criteria, in addition to rating alternatives. Other advantages of the DEMATEL are as follows: feedback can fully be applied in application [15,18]; the interrelationship between criteria in complicated problems will be determined [74]; criteria can be ranked according to relationship type and the value of mutual influences [75]; the importance and value of using the entire factor set in place of particular parameters will be assessed and established [74].

Furthermore, both direct and indirect dependencies between unpredictable attributes can be revealed [74]. This technique can be used in a variety of ways to manage dynamic interactions between complex system components [32].

Another similar study by Koca and Yıldırım [74] also found the performed bibliometric analysis

of studies on the DEMATEL method, though the authors used only 1963 documents for the analysis. Koca and Yıldırım's work [74] also used bibliometrics, though the outcome is different because the referenced database and the research goal were designed differently. They intended to provide a general picture of DEMATEL evolution, but this study was primarily concerned with judging the technique's performance in relation to its application. Koca and Yıldırım have also observed the increase in reported studies with aid of DEMATEL; similarly our findings also show that more journals are publishing DEMATEL-related papers. We in addition, observed that DEMATEL-enabled projects obtain more funding now. This was witnessed as the number of high-impact publications increased in new phases, and it is expected that the scientific community would see even more numbers in the future.

Overall, this article answered questions including (1) Is there a discernible pattern of growth or decline in the number of articles utilizing the DEMATEL technique over time? (2) According to the evidence from past publications, who are the most frequent adopters of the DEMATEL techniques? (3) With whom are the majority of these DEMATEL users collaborating? (4) How did the DEMATEL-linked articles nourish the overall performance of the scientific establishment? (5) What sort of interest has different areas shown in establishing ties to this technique? (6) What platforms are more beneficial in promoting the technique? (7) In light of the aforementioned lookups, what role did the time play? In addition to a new approach being used in bibliometrics assessments and comparisons, a CoPI was proposed to standardize comparisons. Moreover, this article has the potential to serve as a useful guide for researchers who wish to use DEMATEL in their research because of the detailed discussion of the technique's steps.

As a whole, this article provides evidence to comment on the performance of the classic DEMATEL technique and its applicability to address different challenges and ongoing problems. Yet, in the future, the number of DEMATEL-based approaches and its scientific contributions may again be assessed to keep the users updated on the technique capability when problems on hand become more complex. Furthermore, the development of more efficient algorithms, such as 'hybrid algorithms', through which the DEMATEL can be upgraded with other DM technique's could also be a useful endeavor to improve the techniques performance. This study showed that DEMATEL is able to remain among the DM tools for the time being; correspondingly, the authors invite additional research to remark on the performance of other MADMs to eliminate outdated techniques from practice.

Conflict of interest

The authors have no conflicts of interest.

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