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Methods of multi-criteria analysis in technology selection and technology assessment: a systematic literature review

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ABSTRACT
Technology assessment and selection problems have gained importance in recent decades as the used technology often determines the enterprises' competitive advantage. Due to the extensive catalogue of criteria that should be considered and, on the other hand, the extensive catalogue of available technologies and solutions, the decision-making process of choosing a technology becomes a significant challenge for organisations and individuals. This study aims to identify the main research directions and trends in the scientific literature on applying multi-criteria analysis (MCA) in the context of technology assessment and/or technology selection. The author conducted a bibliometric analysis of publications indexed in the Web of Science and Scopus databases. The methodology of this study also included identifying the most productive authors, countries, organisations, and journals and analysing the occurrence and co-occurrence of terms. Final analyses included 380 publications retrieved from the Scopus database and 311 documents retrieved from the Web of Science repository. The analysis of the occurrence of terms and keywords allowed distinguishing two main research directions in using MCA methods in assessing and selecting industrial and health and medicine-related technologies. Some sub-areas have also been distinguished within these two areas: energy and renewable energy technologies, waste management, biomedical and medical technologies, and drug production technologies.

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KEY WORDS
technology selection, technology assessment, multi-criteria analysis, bibliometric analysis

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Introduction

Considering the rapid technology development and its growing impact on the company's competitiveness and performance, selecting an appropriate technology that meets all requirements constitutes a challenging strategic decision problem faced by entrepreneurs and institutions (Kafuku et al., 2019). Assessing or selecting new technologies requires solving conflicts between various competing objectives to pursue environmental quality, economic

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prosperity, technological efficiency, and social equity. Such a task becomes difficult for decision makers. The research field of technology selection (TS) has been rapidly developing over the last few years (Halicka, 2020). It is strictly connected with technology assessment (TA) which allows evaluating alternative technologies in terms of economic potential, innovation level, usability, or environmental impact. Each technology has several characteristics that may be considered its advantages or disadvantages and, thus, many different factors influence the technology selection process (Hamzeh & Xun, 2019). A decision maker, either a company, an organisation, or an individual, presents certain needs and preferences. Technology selection does not rely only on internal factors of the organisation but also considers external factors. Sometimes, the most effective criteria for technology selection are not merely financial, and some other factors, such as political issues or the technology impacts on employment, are also significant (Elahi et al., 2011). Therefore, the final criteria catalogue for technology selection may consist of diverse economic, technological, environmental, and social criteria, representing such aspects as trends, functionality, flexibility, or sustainability. Furthermore, they may be described in qualitative, quantitative, or mixed categories making technology selection a complex multi-criteria problem (Saen, 2006). The technology selection problem is focused on choice (choosing the best option) or ordering (ranking) variants in the descending order of preference. Thus, it may be supported by the methods of multi-criteria analysis (MCA) or methods supporting Multi-Criteria Decision Making (MCDM) (Fang et al., 2020). These methods enable the identification of the problem, formulation of goals, analysis of the alternatives, and generation of information facilitating the final choice. MCA provides procedures, tools, and mathematical and IT methods that allow solving complex decision-making problems, the analysis of which requires considering many and, often, opposing points of view.

Recently, many articles were published addressing the above-described problems. For example, a problem of assessing green technologies with Multi-Criteria Decision Making (Si et al., 2016), TS problem in the automotive industry (Ansari et al., 2016), TS for photovoltaic cells (Fang et al., 2020), evaluation of water supply alternatives with multi-criteria decision-making methods (Savun et al., 2020), renewable energy source technology selection (Long et al., 2021) or the selection of waste-to-energy-based-distributed generation (Alao et al., 2022). A review of several sample studies has led the article's author to conclude that the topic is evolving and is worth exploring. Therefore, this study aims to answer the following research questions:

RQ1: What are the main research directions in applying multi-criteria analysis methods in the field of technology selection and technology assessment?

RQ2: Which countries, authors, institutions, and journals are most productive in this research field?

RQ3: Which multi-criteria analysis (MCA) methods are mostly used in the technology assessment and selection problems?

The study's methodology includes a systematic literature review focused on applying multi-criteria analysis in decision-making processes concerning technology selection and technology assessment. A bibliometric analysis was conducted using tools available in chosen databases to indicate the most productive authors, countries, organisations, and journals (RQ2). Furthermore, text mining analysis and visualisation techniques were used to answer the research questions RQ1 and RQ3. The methodology of the study is presented in detail in Section 2.

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1. Literature review

Technology assessment (TA) is a rapidly evolving research field visible in a growing number of research and publications appearing during the last decades (Halicka, 2020). It was primarily strictly connected with the policy tools supporting policymakers in identifying technological changes and planning future development (Delvenne & Rosskamp, 2021). So, it mainly played a crucial role in technology policy. Over time, it has evolved from a strategic government instrument to an element of business decision-making (Halicka, 2020). Nowadays, technology assessment is used at the organisational level in enterprises and institutions. It aims to reduce the human-inflicted costs of test-and-error learning in people handling new technologies and foresee the potential effects of its application on people, organisations, and the environment. The significance of the problem and its interdisciplinarity is reflected in the development of various approaches, methods, and tools for technology assessment (Chodakowska & Nazarko, 2020b). Many stakeholders and many assessment aspects must be considered in analysing and assessing technology. The criteria that are finally considered are related to the assessment context and are implied by the subject and field of analysis (Chodakowska & Nazarko, 2020a). Technology assessment is an integral part of the technology selection process, which, in turn, focuses on choice (choosing the best option) or ordering (ranking) variants in the descending order of preference. A technology selection (TS) problem is described as identifying the best technology from a set of possible alternatives or options (Singh & Sushil, 1990). Knowing how to solve this problem will help organisations create more competitive offers and solutions and more efficient processes (Hamzeh & Xu, 2019). However, this problem usually appears complex as it encompasses the need to consider such aspects as uncertainties of technical and commercial success, current life-cycle level of the technology, possibilities of its development, environmental impact, etc. and also interactions with the current technologies in the organisation (Houseman et al., 2004; Krishnan & Bhattacharya, 2002; Wang et al., 2014). Technology selection aims "to obtain new know-how, components, and systems which will help the company to make more competitive products and services, more effective processes, and/or create completely new solutions" (Houseman et al., 2004, p. 2). The criteria affecting the technology assessment and selection may be tangible and intangible. Moreover, they might be described as qualitative or quantitative categories and may represent very different aspects of technology, including economic, social, technological or technical, and environmental (Ragavan & Punniyamoorthy, 2003; Muerza et al., 2014; Shen et al., 2010). A catalogue of final criteria is highly dependent on many conditions, like the type of technology, the goal of technology selection, the scale of the selection problem, the sector of the economy it considers, the level of governance, and the complexity of related know-how, etc. Thus, the assessment and selection of technology constitute a complex and multi-criteria problem.

Methods of Multi-Criteria Analysis (MCA) or tools supporting the Multi-Criteria Decision-Making process (MCDM) have been developing in the frame of operations research or mathematical modelling of complex decision problems. In multi-criteria analysis, no ideal or optimal solution can be found. It is a rather compromised solution that matches the decision maker's preferences in the best possible way. One of the most popular multi-criteria decision-making tools is the analytic hierarchy process (AHP), which was proposed and developed by Saaty. It enables the decomposition of a complex decision problem and the creation of a final ranking for a finite set of variants (Saaty, 1980). The method is still being developed and modified (Saaty, 2005). Other most used are SAW, TOPSIS, VIKOR, ELECTRE, and PROMETHEE. Until now, the Simple Additive Weighting (SAW) method is the best known and most frequently used discrete multi-criteria method. Its advantages are simplicity and intuitiveness in modelling the decision maker's preferences through an additive linear function (Tzeng & Huang, 2011). Both VIKOR and TOPSIS methods are based on an aggregating function describing closeness to the ideal solution. The VIKOR method ranks alternatives and determines the solution closest to the ideal solution. The base in the TOPSIS method are two "reference" points called "ideal solution" and "negative-ideal solution". The aggregate index allows for choosing the alternative that is at the "shortest distance" from the ideal solution and the "farthest distance" from the "negative-ideal" solution (Opricovic & Tzeng, 2004). The group of ELECTRE methods is based on the rule of pairwise comparisons. The method employs the concordance and discordance of the criteria and the threshold values to evaluate the scoring schemes between the available alternatives (Effatpanah et al., 2022). PROMETHEE belongs to the family of multi-criteria outranking methods based on the dominance relationship principles and a generalisation of the criterion notion (Brans et al., 1984). More knowledge on multi-criteria methods is available from outputs by Hwang & Yoon (1981), Zanakis et al. (1998), Tzeng & Huang (2011), Arslan (2017) and others.

Some studies review and examine the use of MCA methods or MCDM tools in fields of engineering and management (Mardani et al., 2018), business analytics (Yalcin et al., 2022) or financial decisions (Hallerbach & Spronk, 2003), energy planning (Pohekar & Ramachandran, 2004), the assessment of multi-sector interactions in the emerging offshore Blue Economy (Turschwell et al., 2022), geographical information systems (Carver, 1991), decommissioning of offshore oil and gas facilities (Li & Hu, 2022) or research planning (Loo et al., 1990). This study focuses on a review of the use of multi-criteria analysis methods for technology assessment and selection.

2. Research methods

A systematic literature review and bibliometric analysis are the most popular approaches in scientific research for uncovering emerging trends and identifying authors and institutions most engaged in certain scientific fields or journals that affect the analysed subject the most (Donthu et al., 2021). Many researchers indicate main research directions or areas based on systematic literature review results (in chosen scope) (Glińska & Siemieniako, 2018; Hamzeh & Xun, 2019; Alcácer et al., 2019; Szum, 2021), research gaps (Hajduk, 2017; Winkowska et al., 2019; Szpilko et al., 2020; Ciani et al., 2022; Michalski et al., 2022) or opportunities and directions for further research (Halicka, 2017; Siemieniako et al., 2021; Belezas & Daniel, 2022; Sun et al., 2022). Many useful tools and software were developed (e.g., Gephi or VOSviewer) to analyse a set of database records resulting from searching the scientific repositories. Such software is designed to present the relationships between terms and individual elements (Gudanowska, 2017; Siderska & Jadaa, 2018). Visualisation and clustering of these relationships enable the understanding of how the research field manifests itself and develops over time. Combining results of bibliometric analysis and visualisation techniques is considered a complementary approach to studies aimed at literature review analysis and synthesis (Donthu et al., 2021). Therefore, it has been applied in this study. Considering the convergence of the research questions raised in some papers (Szum, 2021; Szpilko & Ejdys, 2022), an analogous research methodology was adopted in this study.

This study's methodology (Fig. 1) included five main stages: database selection (Stage 1), keyword selection (Stage 2), inclusion criteria selection (Stage 3), data extraction and removal of duplicates (Stage

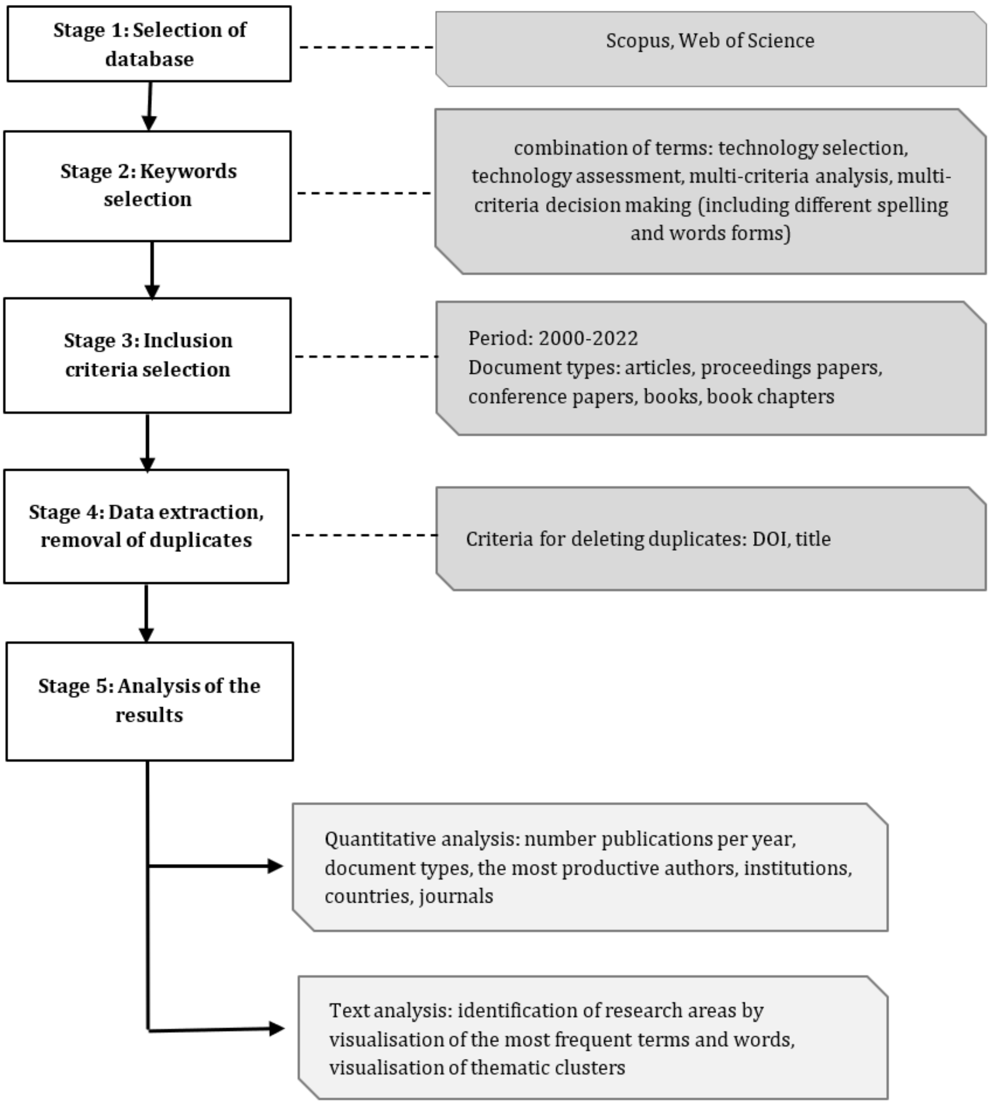

Fig. 1. Methodology of the study

Tab. 1. Search results

Step	Scopus	Web of Science
searching query	TITLE-ABS-KEY („MULTI-CRITERIA DECISION MAKING" AND „TECHNOLOG* ASSES*") OR TITLE-ABS-KEY (mcdm AND „TECHNOLOG* SELECT*") OR TITLE-ABS-KEY (mcdm AND „TECHNOLOG* ASSESS*") OR TITLE-ABS-KEY („MULTI-CRITERIA DECISION MAKING" AND „TECHNOLOG* SELECT**") OR TITLE-ABS-KEY („TECHNOLOG* ASSES*" AND „MULTI CRITERIA") OR TITLE-ABS-KEY („TECHNOLOG* SELECT*" AND „MULTI CRITERIA") OR TITLE-ABS-KEY (MCA AND „TECHNOLOG* ASSES*") OR TITLE-ABS-KEY (MCA AND „TECHNOLOG* SELECT*")	ALL=(((„TECHNOLOG* ASSES*" AND („MULTI-CRITERIA" OR „MULTI CRITERIA")) OR („TECHNOLOG* SELECT*" AND („MULTI-CRITERIA" OR „MULTI ARTERIA")) OR (MCA AND („TECHNOLOG* SELECT*" OR „TECHNOLOG*ASSES*")) OR („MULTI-CRITERIA DECISION MAKING" AND „TECHNOLOGY ASSES*") OR („MULTI-CRITERIA DECISION MAKING" AND „TECHNOLOGY SELECT*") OR (MCDM AND („TECHNOLOGY SELECT*" OR „TECHNOLOGY ASSES*"))))
Number of articles before inclusion criteria	392	321
Number of articles after inclusion criteria and removal of duplicates	380	311

4), and analysis of the results (Stage 5). The last stage of the methodology consisted of two steps: quantitative analysis of obtained results (in terms of the number of publications per year, document types, most productive authors, institutions, countries, and journals) and qualitative analysis based on text mining techniques aimed at identification of most frequently explored areas of research. The first stage was the database selection. Scopus and Web of Science were chosen mainly due to the author's free access to these repositories. However, both databases are popular in bibliometric studies, and their content is relatively wide, both in the scope of scientific thematic and in the number of publications indexed. Therefore, they appeared representative in terms of bibliometric analysis results. Database searches were performed using the following keywords in various forms and configurations: technology selection, technology assessment, multi-criteria analysis, and multi-criteria decision making. Thus, a set of publications obtained as a query phrase result was exactly and closely related to the analysed scientific field. In the next stage, the set was limited in terms of publication date (period: 2000–2022) and document types (articles and conference papers or proceedings, books, and book chapters). The search result is shown in Table 1. The search was performed in early 2022. As both databases are updated daily, a perfect replication of the search results may not be possible.

A detailed query formulated in each database is shown in the first row of Table 1. After including the selection criteria and removing duplicates, a set of 380 papers was used for further analyses from the Scopus database. A set of 311 papers was extracted from the Web of Science database. These sets were used to show the publication trends over the years and identify the most productive authors, institutions, countries, and journals. Finally, a text analysis was performed to visualise the most frequently occurring terms and words. This allowed identifying thematic clusters, which indicated the main research directions in applying and adapting multi-criteria analysis for technology selection and assessment.

3. Research results

The last 20 years of applying multi-criteria analysis to technology selection and assessment problems show a growing trend in the number of published papers (Fig. 2). The most significant increase may be noticed after 2010 — from only 5–10 in 2010 to almost 40–50 in 2021.

The publication increase index illustrates the dynamic of increase. It can be calculated as the ratio of the number of publications in a given year to the number of publications in the previous year or as a ratio to the one basic year. Considering the last ten years (from 2012 to 2021), there is a substantial dynamic visible in the growth of the number of publications in the analysed research field. Growth may be seen almost every year (columns A and B, Table 2, the value of the index greater than 1 indicates growth), and during the last ten years, the number of publica-

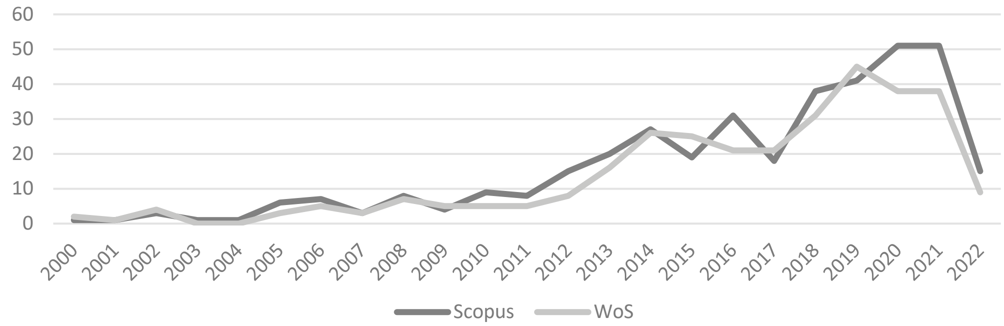

Fig. 2. Number of publications per year

tions increased six to seven times in relation to 2011 (columns C and D, Table 2). It shows rising interest in this research field, particularly in recent years, so the subject of applying multi-criteria analysis for technology assessment and/or technology selections appears to be an emerging research field. This is also confirmed by the structure of the analysed set of extracted documents in terms of type (Fig. 3). Most of them are articles (65 % among Scopus results, 76 % in WoS results) and conference proceedings or conference materials (23 % and 16 %, respectively). Few books have been published so far, typical of emerging research fields.

In the Web of Science database, each document is described with the Web of Science Category, which represents the main addressed research field. The largest part of examined documents (almost 15 %) was assigned to the Health Care Science Services category. The next three groups, almost equal in size (about 12–12.5 % of analysed documents), constitute papers classified as Environmental Sciences, Green Sustainable Science Technology, and Energy Fuel. About 11 % of publications were related to Health Policy Services and over 10 % to Operations Research Management Science. In the Scopus database, documents are assigned to the subject area. Within extracted documents, the subject area of almost 20 % was classified as Engineering, 12 % as Medicine, 11.5 % as Computer Science, 10.5 % as Business, Management and Accounting, 10 % as Environmental Studies, and over 8 % as Energy.

The summary presenting the most productive authors, countries, organisations, and journals is revealed in Table 3. The average citation count was calculated specifically for the search results using both databases' tools. For example, 57 publications in Scopus came from the USA, and their total citation number was 946, giving 16.6 citations per paper on average. The most productive authors (eight publications) in the field of multi-criteria analysis methods applied for technology selection or assessment are Büyüközkan Gulcin, a researcher from Galatasaray University (the most productive institution) in Turkey (second most productive country) and Streimik-

Tab. 2. Indexes illustrating the increase of publications in the last ten years

Year	Index of increase in the number of publications (previous year=100)		Index of increase in the number of publications (2011 year=100)	
	Scopus (A)	WoS (B)	Scopus (C)	WoS (D)
2012	1.9	1.6	1.9	1.6
2013	1.3	2.0	2.5	3.2
2014	1.4	1.6	3.4	5.2
2015	0.7	1.0	2.4	5.0
2016	1.6	0.8	3.9	4.2
2017	0.6	1.0	2.3	4.2
2018	2.1	1.5	4.8	6.2
2019	1.1	1.5	5.1	9.0
2020	1.2	0.8	6.4	7.6
2021	1.0	1.0	6.4	7.6

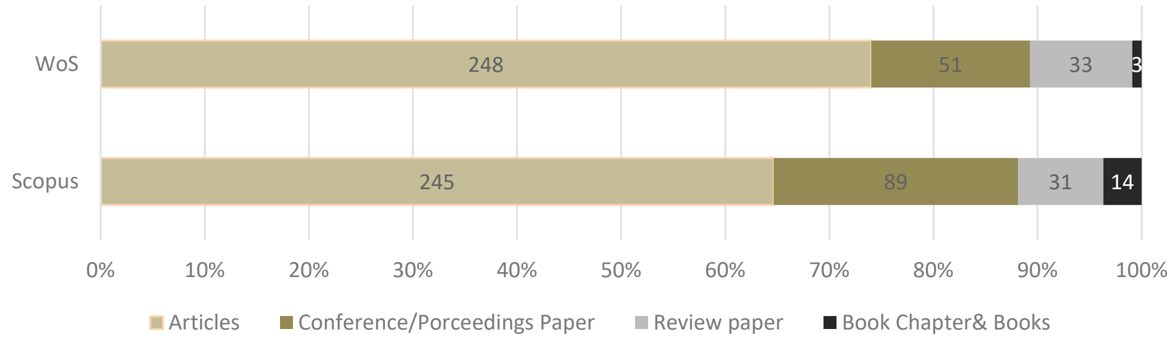

Fig. 3. The structure of search results in terms of document types

iene Dalia from the Lithuanian Energy Institute in Kaunas, Lithuania. It should be noted that Streimikiene's average citation rate is much higher than Büyüközkan's. The articles co-authored by Büyüközkan with the highest citation rate are (1) "Cloud computing technology selection based on interval-valued intuitionistic fuzzy MCDM methods" from 2018, with 46 citations in the Scopus database, and (2) "Selection of sustainable urban transportation alternatives using an integrated intuitionistic fuzzy Choquet integral approach" from 2018, with 45 citations in the Web of Science database. The most cited paper co-authored by Streimikiene is "Intuitionistic fuzzy MULTIMOORA approach for multi-criteria assessment of the energy storage technologies" from 2019, with 92 citations in Scopus and 83 citations in Web of Science.

The other authors with a similar or slightly smaller number of publications were Göçer Fethullah (Kahramanmaras Sutcu Imam University, Turkey), Kahraman Ceng (Istanbul Technical UniversityTurkey), Kalo Zoltan (Eotvos Lorand University, Budapest, Hungary), and Oztaysi Basar (Istanbul Technical University, Turkey). But the author with the highest average citation rate is Oztaysi (50.5 in Scopus and 46.8 in WoS). The countries with the highest number of publications are the United States of America, Turkey, and the United Kingdom. It should be noted that publications from the United Kingdom are the most highly cited (Scopus: 27.9, WoS: 37.6).

Among the most productive organisations are Galatasaray University, Islamic Azad University, Istanbul Technical University, University of Tehran, University of Twente, and Warsaw University of Technology. The most cited are studies from the University of Twente, Netherlands (the average citation rate of 35 in Scopus and 26.9 in WoS).

Among the top ten most productive journals, the International Journal of Technology Assessment in Health Care ranked first (12 publications in Scopus, 15 in WoS). This was followed by the Journal of Cleaner Production with 14 publications in Scopus and 12 in WoS and the International Journal of Production Research with 9 and 11 publications, respectively. However, the journal Energy, published by Elsevier, achieved the highest average number of citations in each database (Scopus: 96.8, WoS: 84.8). In comparison with other journals in the ranking, it had by far the highest average number of citations in Scopus and Web of Science databases.

The total number of citations of publications on multi-criteria analysis or multi-criteria decision making in the context of technology selection or technology assessment was 6002 for Web of Science and 6140 for Scopus. The top ten publications included two articles published in Energy (Elsevier). The most cited publication (Scopus: 264, WoS: 228) was the article by Afgan and Carvalho (2002) entitled "Multi-criteria assessment of new and renewable energy power plants". Next in the ranking list was the article "R&D project evaluation: An integrated DEA and balanced scorecard approach" by Eilat, Golany and Shtub (2008), which has 212 citations in Scopus and 160 in WoS, and "Evaluation methodologies for technology selection" by Chan, Chan and Tang (2000) which was cited 159 times in Scopus and 132 in WoS (Table 4).

Search results were analysed in the next step with different text analysis tools. The author first conducted several analyses to reveal the main research directions in the field of MCA methods applied for TA and TS, the files with the results obtained from both databases were explored separately, and maps of the frequency of terms were produced. Then, the results were merged, and a keyword co-occurrence

Tab. 3. Most productive authors, countries, organisations and journals

No.	Item	Number of publications		Average citation count	
		Scopus	WoS	Scopus	WoS
	Authors				
1.	Büyüközkan, G.	8	8	8.9	11.9
2.	Streimikiene, D.	7	8	43.1	37.0
3.	Göçer, F.	5	6	14.8	15.2
4.	Kahraman, C.	8	6	23.25	36.7
5.	Kalo, Z.	4	6	6.3	2.3
6.	Oztaysi, B.	6	6	50.5	46.8
7.	Ijzerman, M. J.	4	5	46.0	34.6
8.	Farshidi, S.	5	3	10.4	10.7
9.	Jansen, S.	5	3	10.4	10.7
10.	Marsh, K.	3	4	20.7	46.5
	Countries				
1.	USA	57	43	16.6	21.4
2.	Turkey	45	39	12.8	23.1
3.	United Kingdom	32	24	27.9	37.6
4.	Germany	30	23	19.1	21.2
5.	China	28	27	17.9	26.0
6.	Iran	28	24	11.5	10.8
7.	Italy	27	21	17.4	20.3
8.	Netherlands	25	25	23.7	21.4
9.	Canada	21	19	27.2	30.9
10.	India	18	16	17.5	17.8
	Organisations				
1.	Galatasaray University	15	13	15.6	20.9
2.	Islamic Azad University	5	10	20.6	18.9
3.	Istanbul Technical University	15	10	25.4	30.8
4.	University of Tehran	8	7	14.6	14.0
5.	University of Twente	7	7	35.0	26.9
6.	Warsaw University of Technology	8	7	8.5	6.5
	Journals				
1.	International Journal of Technology Assessment in Health Care	12	15	31.8	23.9
2.	Journal of Cleaner Production	14	12	21.1	20.5
3.	International Journal of Production Research	9	10	29.6	27
4.	Cost Effectiveness and Resource Allocation	9	5	11.0	4.8
5.	Expert Review of Pharmacoeconomics and Outcomes Research	5	7	12.0	15.0
6.	Sustainability	8	6	8.6	6.5
7.	Energies	6	6	15.0	14.2
8.	Energy	6	6	96.8	84.8
9.	Expert Systems with Applications	5	5	32.2	27.6
10.	Renewable and Sustainable Energy Reviews	5	5	41.6	35.0

Tab. 4. Most cited publications

No.	Author(s), year	Title	Source	Citation count	
				Scopus	WoS
1.	(Afgan & Carvalho, 2002)	Multi-criteria assessment of new and renewable energy power plants	Energy 27(8), pp. 739–755	264	228
2.	(Eilat et al., 2008)	R&D project evaluation: An integrated DEA and balanced scorecard approach	Omega-International Journal of Management Science 36 (5), pp. 895–912	212	160
3.	(Chan et al., 2000)	Evaluation methodologies for technology selection	Journal of Materials Processing Technology 107 (1-3), pp. 330–337	159	132
4.	(Marsh, K. et al., 2014)	Assessing the Value of Healthcare Interventions Using Multi-Criteria Decision Analysis: A Review of the Literature	Pharmacoeconomics 32 (4), pp. 345–365	155	140
5.	(Oztaysi, 2014)	A decision model for information technology selection using AHP integrated TOPSIS-Grey: The case of content management systems	Knowledge-Based Systems 70, pp. 44–54	132	113
6.	(Scott et al., 2012)	A review of multi-criteria decision-making methods for bioenergy systems	Energy 42(1), pp. 146–156	132	116
7.	(Choudhury et al., 2006)	Consensus-based intelligent group decision-making model for the selection of advanced technology	Decision Support Systems 42(3), pp. 1776–1799	131	107
8.	(Si et al., 2016)	Assessment of building-integrated green technologies: A review and case study on applications of Multi-Criteria Decision Making (MCDM) method	Sustainable Cities and Society 27, pp. 106–115	123	115
9.	(Xiao, 2018)	A novel multi-criteria decision making method for assessing health-care waste treatment technologies based on D numbers	Engineering Applications of Artificial Intelligence 71, pp. 216–225	122	119
10.	(Peterseim et al., 2013)	Concentrated solar power hybrid plants, which technologies are best suited for hybridisation?	Renewable Energy 57, pp. 520–532	120	101
11.	(Onar et al., 2015)	Multi-expert wind energy technology selection using interval-valued intuitionistic fuzzy sets	Energy 90, pp. 274–285	114	106
12.	(Danner et al., 2011)	Integrating patients' views into health technology assessment: Analytic hierarchy process (AHP) as a method to elicit patient preferences	International Journal of Technology Assessment in Health Care 27(4), pp. 369–375	111	96
13.	(Karsak & Ahiska, 2005)	Practical common weight multi-criteria decision-making approach with an improved discriminating power for technology selection	International Journal of Production Research 43(8), pp. 1537–1554	110	102

map was generated. These three analyses led to similar conclusions and allowed identifying mostly discussed and explored research areas within the analysed topic.

The map of the most frequently occurring terms based on the text of documents extracted from the WoS database was generated with VoSViewer. Fig. 4 shows the most common words in abstracts and titles

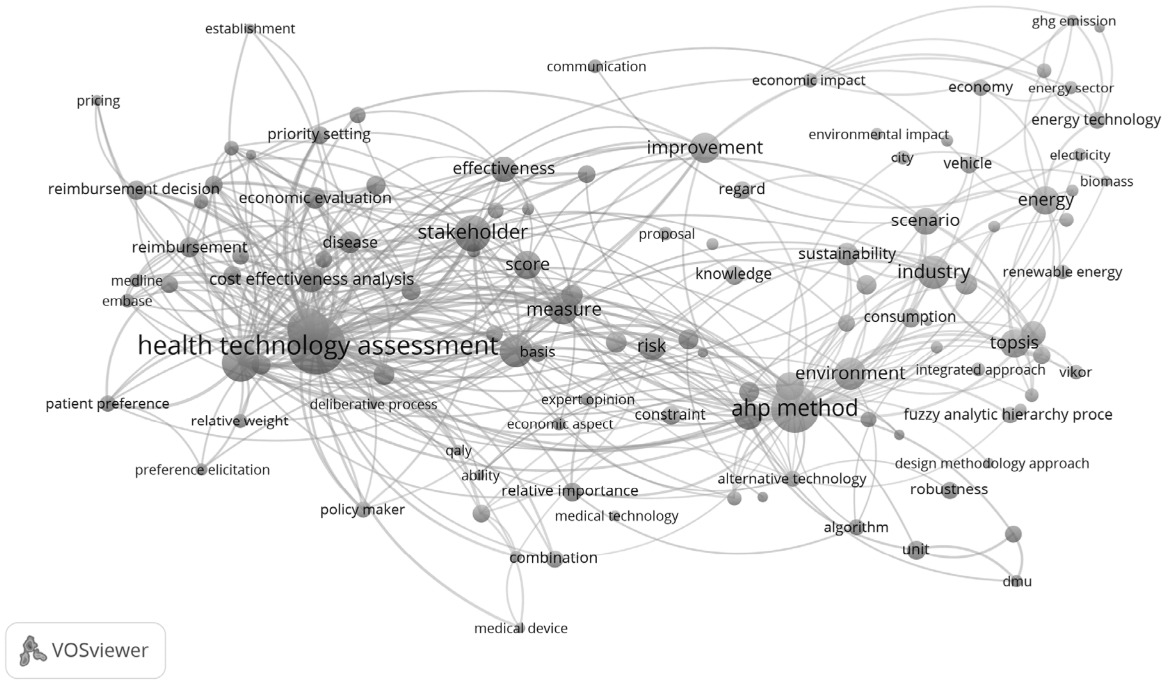

Fig. 4. Most frequent terms in documents extracted from the WoS search

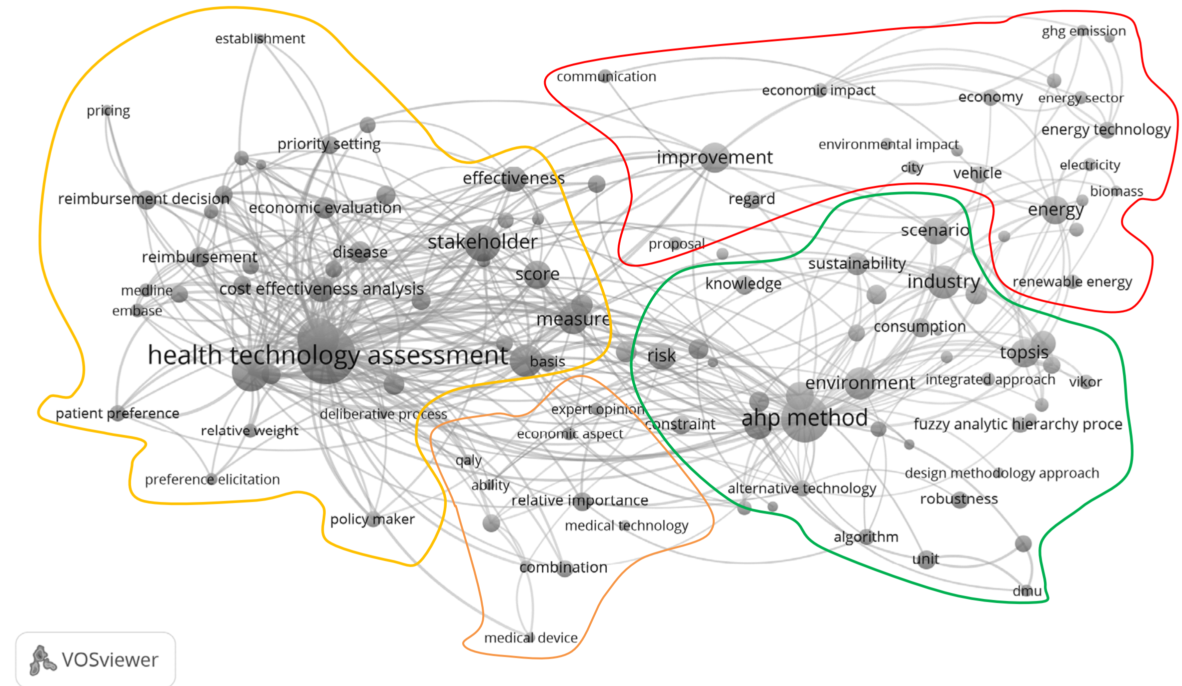

Fig. 5. Thematic clusters on MCA methods applied in technology selection or assessment

of extracted documents. To better understand the visualisations, it should be explained that the size of a caption (or circles) reflects the number of documents in which the term was found. The distance between two terms explains an estimated indication of the relatedness of the terms. The relatedness of terms was determined based on co-occurrences, so the larger the number of documents in which two terms were both found, the stronger the relationship between them (van Eck & Waltman, 2017). It may be observed that health technologies were the most popular subject of assessment and selection with the MCA methods. Also, the terms industry, energy, environment, AHP and TOPSIS are drawn in big circles, demonstrating that these topics were among the most frequently raised.

The main trends in adapting MCA methods for technology selection and assessment may be identified based on the map. The most related terms (shown by the densest network of connections) are enveloped with a yellow line in Fig. 5. These words seem to concern health and healthcare technologies in general. This area contains terms health technology assessment, disease, reimbursement decision, patient preference, effectiveness, stakeholder, and establishment or policymakers.

Terms circled by an orange line are also related to healthcare technology, but they seem to focus more on technical aspects of health technologies (medical device, medical technology), and the density of connections is lower. Words inside a green envelopment represent documents that address the use of different MCA methods for industry technologies considering environmental issues and the sustainable impact of such technologies. The area marked with a red line contains words that seem to relate to research in energy technologies, mainly in the context of its economic and environmental impacts and in the scope of improvements. Also, words like renewable energy, GHG emission, vehicle, and biomass occurred near each other, which means a frequent appearance in the same documents.

Next, the results of the search conducted in the Scopus database were processed using the Statistica software and the Wordart tool. In Statistica, the text mining techniques allow calculating the frequency of

Tab. 5. Most frequently occurring terms in documents extracted from the Scopus database

Word / Phrase	Count	Number of documents
health technology	390	90
energy	140	41
fuzzy	107	45
treatment	94	39
economic	93	63
optimization	85	8
development	84	51
environmental	70	54
systems	70	39
AHP	69	36
hierarchy	58	46
clinical	51	20
sustainability	50	26
waste	46	21
cost	44	32
social	42	32
policy	38	27
renewable	33	16
risk	32	18
sensitivity	30	23

Source: elaborated by the author using Statistica software.

word occurrence. The list of words with the highest number of occurrences is presented in Table 5.

Then, after cleaning the list and removing words that have no meaning, verbs, adverbs, etc., the word cloud was created using the Word Art tool. Table 5 gives a list of top common words. The whole list of terms generated by the Statistica text mining tool was used to create the cloud of words (Fig. 6).

Terms that appear in the word cloud seem to point to similar topics as the WoS map (Fig. 5). The word cloud shows graphically the importance (in this case, the frequency) of the terms, which may be evaluated by the size of the word. It does not, though, carry any information about the relationship between terms. Some conclusions may be drawn based on the relationship of the word size. For example, health technology is almost the same size as energy. Judging from the number in Table 5, energy issues may be much less frequently raised than health technology concerns. However, considering other terms' occurrence, in the cloud visualisation, both terms were considered equally important. Noteworthy, as far as methods are concerned, there is a particular noticeable interest in the AHP method and in using fuzzy logic. Other relatively frequently appearing words that may suggest key research directions are sustain-

Fig. 6. Word cloud representing the most frequently occurring terms regarding MCA methods applied in TS and/or TA

Source: elaborated by the author based on Scopus search results.

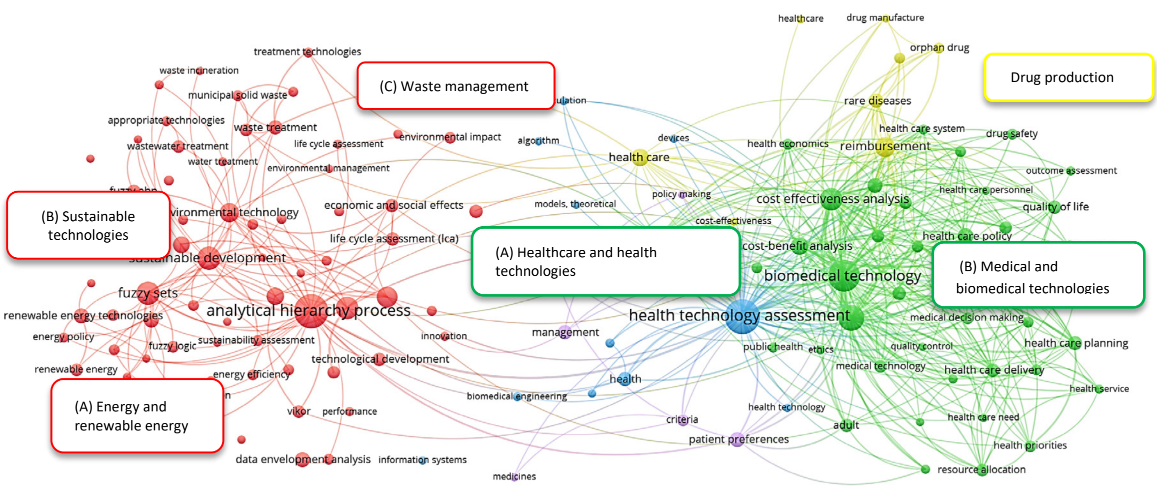

Fig. 7. Keyword co-occurrence map

Source: elaborated by the author based on merged Scopus and WoS search results.

ability/sustainable development, environmental problems, and renewable energy. In this map, new areas may be discovered, i.e., small-sized words like water, wind, wastewater, waste, supply, transport, and automotive. It provides a guideline for new kinds of topics brought into the scientists' consideration. They are relatively rarely discussed in comparison to the most popular topics, e.g., energy or healthcare technologies but may constitute an emerging research field.

The last step of text analysis was a visualisation of keyword occurrence and co-occurrence. The map was generated based on the file containing merged results from both databases. The map (Fig. 7) was created after removing general keywords (like article, questionnaire, or names of countries) and phrases used in the search query and using a thesaurus for phrases of similar or identical meaning. Clustering keywords gives more general insight into research directions in the analysed scientific field.

In this map, colours indicate associations, and the line size informs about the co-occurrence frequency (the thicker the line between terms, the more frequently they appear in one document). Research topic emerging by clustering keywords shows two main groups of the topic raised in scientific papers: industrial technology (red cluster) and healthcare/medical technologies (green cluster) assessment and/or selection. Within industrial technologies, the cluster can be divided into three subareas: (A) energy and renewable energy technologies, (B) sustainable technologies, and (C) waste management. The green cluster may be split into two themes: (A) healthcare and health technologies and (B) medical and biomedical technologies. Furthermore, one smaller cluster (yellow) can be pointed out with fewer connections and minor co-occurrence, gathering terms related to drug production.

4. Discussion of the results

The research field of technology assessment and selection with multi-criteria analysis does not seem extensive now as for this analysis, the set of publications retrieved from both databases contained around 300 documents in each set. So, it is a rather narrow field of research with a rapidly growing body of literature. Between 2012 and 2021, the number of articles and other documents published each year grew several times. In 2021, the number of publications was 6 to 7 times higher than in 2012. It demonstrates the rapidly increasing interest in the academic environment in this research field.

One of the main findings of this study is the identification of thematic clusters representing current directions of the research in the field of MCA methods applied in TA and TS problems. This is targeted toward the first research question, RQ1 "What are the main research directions in applying multi-criteria analysis methods in the field of technology selection and technology assessment?". First, it should be noted that, in general, a vast majority of the studies propose a certain MCA method, a combination of methods, a modification of methods, a few-step methodology, or more advanced solutions based on MCA methods (e.g., computer programs or decision support systems) for assessment or selection of technology of a certain type or destination. Using the MCA method allows building the ranking of alternatives and then choosing the best option. A part of the studies focuses on criteria choice and weighting, or preferences and priority setting (e.g., Kaur et al., 2019; Freire et al., 2019, Castro et al., 2018; Mobinizadeh et al., 2016; Daniels, 2018; Isoke & van Dijk, 2014; Husereau et al., 2010), namely, concentrate on adjusting the method to the particular technology, sector or problem. But primarily, it is the assessment or selection of the best alternative which is the main aim of the studies. And the key thematic groups in which the TA and TS problem-solving are supported with the MCA method are described by the clusters created based on keyword occurrence and co-occurrence.

The biggest thematic cluster considers the assessment and selection of healthcare and health technologies, within which a subarea of medical and biomedical technology selections was distinguished. Health Technology Assessment (HTA) is a well-established research field (Oortwijn & Klein, 2019). Within the search results, documents related to healthcare technologies or health constitute almost 30 % in WoS and around 14 % in Scopus. There are many developed HTA models or methodologies (Karatas et al., 2018; Improta et al., 2018; Santos & Garcia, 2010; Lasorsa et al., 2019). A considerable part of studies focuses on patient preferences (Marsh, Caro, Hamed, Zaiser, 2017; van Overbeeke et al., 2021; Mühlbacher & Juhnke, 2016; Hummel et al., 2012; Danner et al., 2011; Badia et al., 2019), or other stakeholders (hospital employees, managers, etc.) of the healthcare system (Wahlster et al., 2015; Karrer et al., 2021; Tal et al., 2019). There are also papers analysing and evaluating the application of Multi-Criteria Decision-Making (MCDM) tools in HTA (Kelley et al., 2018; Marsh et al., 2018; DiStefano & Krubiner, 2020; Schmitz et al., 2016). As far as medical and biomedical technologies are concerned, the following technologies were the subject of assessment or selection with multi-criteria decision-making tools: medical device assessment (Nur et al., 2020; Rogalewicz & Jurickova, 2014;), selection of various medical devices and equipment (Ivlev et al., 2015; Jurickova & Kraina, 2014; Hilgerink et al., 2011; Villegas et al., 2020), including devices for individual patient use in hospitals (Martelli, 2016) or innovative sterile medical devices (Boudard et al., 2016), and also, such niche subject like an assessment of optoelectronic biosensors for oncology (Improta et al., 2019).

A smaller area, also related to this scientific field, seems to be related to drug production. This cluster had words like drug manufacture, orphan drug, drug safety, and rare disease. Various investigators have proposed orphan drugs and rare disease-specific MCA approaches by considering criteria specific to rare diseases. Often, orphan-drug technologies are assessed from the perspective of patient, public, or government preferences (Badia et al., 2019; van Overbeeke et al., 2019; Kwon et al., 2017; Laba et al., 2020; Kolasa et al., 2018). There are also several studies focusing on the review in the assessment of rare disease therapies or orphan drugs from the literature's perspective (Baran-Kooiker et al., 2018; Zelei et al., 2021) or a more practical perspective, such as the evaluation and review of case studies (Blonda et al., 2021; Baran-Kooiker et al., 2019; Farghaly et al., 2021).

The second biggest thematic cluster covers industrial technologies assessment and selection. Although there is a part of studies focused on MCA in manufacturing or technologies (Beyaz & Yildirim, 2019; Büyüközkan & Göçer, 2020; Schneberger et al., 2019), most articles may be associated with one of three distinguished subareas: (a) energy and renewable energy technologies, (b) sustainable technologies, and (c) waste management technology. Analysing search results in terms of categories (in WoS) or the subject area (Scopus), over 8 % in Scopus and around 12% in Web of Science were evidently or partly related to the energy and renewable energy technologies. The most explored subjects are technology selection of solar and photovoltaic systems (Fang et al., 2020; Dat et al., 2014; Ghasempour et al., 2019; Yimen & Dagbasi, 2019; Sellak et al., 2017; Ma et al., 2013), renewable energy storage (Liu & Du, 2020; Zhang et al., 2019; Qie et al., 2021) wind energy technologies (Onar et al., 2015; Narayanamoorthy, 2012) or hybrid renewable technology solutions (Ali et al., 2020; Peterseim et al., 2013). Within the second subarea, sustainable technologies, there are studies on choosing the best alternative industrial technology selection problems considering the sustainability perspective in general (Ibanez-Forez et al., 2014; Gil-de-Castro et al., 2009; Jin & Gambatese, 2020; Ren & Lützen, 2015) or some particular issues like greenhouse gas emission (Streimikiene et al., 2013; Streimikiene & Balezentiene, 2012), transportation technologies (Štreimikiene, 2013; Oztaysi et al., 2017) or sustainable supply chain technologies (Khatri & Srivastava, 2016; Buyukozkan & Gocer, 2019). Waste management technology assessment and/or selection is another identified subarea. A substantial part of the studies concerns wastewater treatment technology selection (Ilangkumaran et al., 2013; Fetanat et al., 2021; Aydiner et al., 2016; Sadr et al., 2013; Meerholz & Brent, 2013; Salamirad et al., 2021) with the use of MCA methods. Some authors address problems of waste disposal technology selection (Jiang et al., 2015; Govind Kharat et al., 2019), biowaste treatment technology (Mpanang'ombe et al., 2018) or food waste technology (Chadderton et al., 2017). Many studies address interdisciplinary subjects, for example, sustainable waste disposal management (Torkayesh et al., 2021; Kharat et al., 2020). Consequently, industrial technology assessment and selection represent the main direction of research, covering, in particular, the three above-mentioned areas.

As far as RQ2 is concerned, namely "Which countries, authors, institutions, and journals are most productive in this research field?", a large part of the previous section contains the answer to this research question.

Regarding RQ3, "Which multi-criteria analysis (MCA) methods are mostly used in the technology assessment and selection problem?", an answer can be given by the analysis of a map that visualises the most frequently occurring words. An obvious leader in the MCA method used for TA and/or TS is the Analytical Hierarchy Process (AHP method), represented by one of the biggest circles or captions in visualisations (Fig. 4–7). Also, TOPSIS and VIKOR methods appeared on the maps. TOPSIS was proposed inter alia in the assessment of concentrated solar power technologies (Cavallaro et al., 2019), selection of sustainable urban transportation alternatives (Buyukozkan et al., 2018), healthcare waste treatment technology selection (Lu et al., 2016) or in the selection of waste-to-energy technologies for distributed electricity generation (Alao et al., 2020). Vinodh, Nagaraj, and Girubha show that VIKOR is an appropriate technique to provide effective solutions for supplier selection, concept selection, and planning (Vinodh et al., 2015). The method was also used in the selection of healthcare waste treatment technology (Ada & Delice, 2019). Renewable energy technologies, for example, a solar photovoltaic microgrid system, have also been analysed and selected by the VIKOR method (Ighravwe & Mashao, 2019). These three methods are relatively the most frequently used for TS and TA problems.

There are also studies proposing other MCDM methods to assess or select a technology, but these studies are less common, and for that reason, they did not get on the map. For example, using PROMETHEE II was evaluated and recommended for advanced manufacturing technology selection (Kolli & Parsaei, 1992). And for less recognised problems, like selecting proper technologies for power smart grid systems, a simple SAW method was successfully used (Montazeri et al., 2017). A MULTIMOORA approach was proposed by Zhang and others for the assessment of energy storage technologies (Zhang et al., 2019). It should also be noted that authors often proposed integrated approaches combining classic MCA tools with other methods or the use of several methods in one study or problem for comparing the results. Although Data Envelopment Analysis (DEA) is not a classic multi-criteria method, it is proposed as an integrated approach to improve discrimination power for technology selection (Karsak & Ahiska, 2005). Stojanovic et al. (2015) proposed a combination of AHP, which is used to study the structure of the TS process and to determine the importance and impact of specific criteria in the selection process, and the ELECTRE method, used for creating the final ranking of alternative technologies. Other authors advised combining two or more methods of analysis that may be complementary or give comparable results. This way, Tzeng, Lin, and Opricovic (2005) first applied AHP to determine the relative weights of evaluation criteria. Then, they compared TOPSIS and VIKOR and applied them to determine the best compromise alternative fuel mode. In another study, analysing the selection of a power plant running on renewable energy sources, the authors proposed an integrated approach of complementing outcomes of SWOT analysis with PROMETHEE ranking results. The authors believed that such a combination facilitates the formulation of the basis of future renewable energy policies more objectively (Özkale et al., 2016). An interesting case of desalination technology selection was conducted by researchers from India. In this study, TOPSIS and PROMETHEE-2 were used, and both methods resulted in the same ranking pattern. However, TOPSIS gave the results quicker than PROMETHEE-2. So, in a case with most calculation data being quantitative, the authors recommended using TOPSIS over PROMETHEE-2 (Vivekh et al., 2015). Discussing the MCA methods used for technology assessment and selection, it is noteworthy that fuzzy sets or fuzzy logic are often applied to evaluate different criteria affecting the alternative technologies (Elahi et al., 2011; Onar et al., 2015; Long et al., 2021; Mall & Anbanandam, 2022). A multi-criteria analysis often involves expert opinions to assess criteria weights or to set the priorities and preferences. The problems are usually complex, making it difficult to clearly and precisely give opinions or assessments in numbers. Therefore, fuzzy sets are recommended to capture fuzzy and uncertain cognitive information (Long et al., 2021). It helps to deal with the vagueness of human thought and judgments like "approximately between $xxx and $yyy", "about $80", "very low", "medium", etc. (Chan et al., 2000).

Conclusions

This paper presented a systematic literature review focused on the identification of main directions in research relating to the use of multi-criteria analysis in the field of technology assessment and selection. Two main directions of adapting MCA methods in these decision-making processes were identified: assessing and selecting industrial technologies and health or medical-related technologies. Within industrial technologies, energy and renewable energy technologies have particular attention in academic studies. Within health and medical technologies, despite the major advantage of studies on healthcare-related technologies, biomedical and medical technologies constitute a substantial part of studies. Also, the assessment and selection of technologies for drug production seem to emerge as a separate and relatively frequently addressed issue. The identified areas of up-to-date research are the main contribution of this study from a scientific point of view. Also, authors, journals, organisations, and countries that contribute the most in this research field were indicated.

The study has obvious limitations. The main limitation is the choice of databases, which was determined by the author's free access. On the other hand, these repositories are often selected by other researchers for bibliometric analysis, so the results are comparable to the work of other authors. The second limitation is the formulation of the database query. Modifying the query slightly may produce a different result. To reduce this limitation, the author made several simulations with a slightly different configuration of the keywords in the query, and the difference in the results was 10 %–20 %, so the search results can be considered somewhat stable. Moreover, using the same query in a future study would give results that can be compared.

The results of this study raised many questions for the future research, e.g., a study could be interesting in identifying a catalogue of critical technology characteristics and crucial criteria in the technology selection process in the case of certain sectors or certain areas (e.g., for engineering technologies, renewable energy production, etc.), identifying patterns in using certain MCA methods in a particular sector, investigation of preferences of decision makers in different sectors or areas in the context of technology assessment, the evaluation of the actual usefulness of the MCA results in decision-making processes of technology selection, investigation of the application of the newest MCA methods in technology assessment and selection problems. The study suggests that many MCA methods are successfully used in the waste management field or biomedical technologies. These also seem an interesting field for future research.

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