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Use of multicriteria decision aid methods in the context of sustainable innovations: bibliometrics, applications and trends

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Abstract
Sustainable innovation has gained prominence in recent years, due to the demands imposed by global competition, social pressures and the needs of consumers and the environment. Decision-making processes about sustainable innovation are complex and often require auxiliary instruments to reduce uncertainties. Multicriteria decision aid (MCDA) methods can be a useful tool to make these kinds of decisions more assertive. This article presents the main discussions and theoretical approaches through bibliometrics on the application of MCDA methods in the context of sustainable innovations. We used the R package Bibliometrix library to organize the data of the publications and perform the processing for the generated analyzes. The bibliometric analysis provided an overview about the use of MCDA in sustainable innovations (MIS) and it presents citation analysis; identification of central authors through co-citation analysis; main topics, conceptual structure and thematic evolution of the literature by co-word analysis. As main results, we identified the main trends in MIS: there has been a substantial increase in publications on this theme, and the most explored focuses are "product development, production and distribution" and "environmental or social impact assessment" and there is an opportunity to further explore the focuses of "evaluation or selection of projects, suppliers or resources", "product life cycle management or assessment" and "definition of decision criteria and standards for sustainable innovation performance". In addition, several MCDA tools have been successfully used for studies of sustainable innovations, demonstrating that there is no preferable method to use for a given focus.

Keywords Innovation sustainable · Multicriteria decision aid (MCDA) · Bibliometric research · Bibliometrix

1 Introduction

Innovation has been widely studied in business and economics due to the positive impacts it can have on organizations, regions and even entire countries, as well its critical role as an important tool for competitiveness in the global environment (Tidd 2001; Baregheh et al. 2009; Mexas et al. 2010; Gunday et al. 2011; Nalband et al. 2016; De Carvalho et al. 2017). In recent years, there is a growing necessity to incorporate the discussion of sustainability in organizational development and also in the context of innovation (Linnenluecke and Griffiths 2013; Lu et al. 2013; Jones and De Zubielqui 2017).

Sustainable innovation includes new or modified products, processes, practices, services, techniques and systems that improve social, environmental and economic factors (Boons et al. 2013; Ahmadi et al. 2020; Calik and Bardudeen 2016). This type of innovation can promote competitive advantage, cost savings, compliance with consumer needs and regulatory standards, and incorporate the environmental and social dimensions to profitability (Vasilenko and Arbačiauskas 2012; Sroufe 2017; Ahmadi et al. 2020). Considering these arguments, sustainable innovations can prove to be one of the main paths to competitiveness in the twenty-first century.

Decision-making in innovation does not encompass a single and well-structured problem, as it involves the need

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to aggregate the different points of view of specialists and the priorities and restrictions of organizations (Daher and Silva 2015). Innovating often requires numberless decisions and most of them are difficult to evaluate, and in the case of sustainable innovations, they encompass even more complex decisions (Ahmadi et al. 2020). Multicriteria decision aid (MCDA) is used in complex problem situations in which decision makers have the task of selecting the best one among many alternatives (Gupta and Barua 2018). Thus, MCDA can be an instrument to support sustainable innovations in the twenty-first century, making the decision-making process more effective.

Despite the fact that there is a wide discussion in the literature on the themes of innovation, multicriteria models of decision and sustainability—although considering these concepts separately—there is still an opportunity for further studies that can capture the theoretical structure on the use of MCDA in the context of sustainable innovations (Mousavi and Bossink 2017; Gupta and Barua 2018; Ahmadi et al. 2020). Bibliometric studies can capture more comprehensive, diversified and detailed information providing a holistic perspective, identifying the theoretical structure, the fields explored and possible gaps in the literature (Shi et al. 2020).

The objective of this article is to present the main discussions and theoretical approaches through bibliometrics on the application of methods to aid multicriteria decision in sustainable innovations. In addition, this research aims to answer the following questions using the bibliographic method: Which documents and journals are the most influential? Who are the central researchers in this field? What are the main topics and conceptual building blocks of the literature in question? And how have these topics evolved over time?

The next sections of the article are divided as follows: Sect. 2 presents a brief theoretical background about MCDA in sustainable innovations (hereinafter referred to as MIS), Sect. 3 presents the method employed, explaining the main activities performed in each step, Sect. 4 presents the main results and its discussions and finally, Sect. 5 presents the conclusions and implications of the research.

2 Theoretical support: multicriteria decision aid applied to sustainable innovations

Tidd and Bessant (2013) affirm that the economic scenario of the last years has favored organizations to mobilize knowledge and technological advances to structure the development of novelties in their offerings of goods and services. Innovation has become a way for companies to gain competitive advantages and remain sustainable (Ahmadi et al. 2020). For OECD and Eurostat (2018, p. 20) "an innovation is a new or improved product or process (or combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)". Thus, innovation can be conceived as the transformation of knowledge into commercial value (Gunday et al. 2011; Nalband et al. 2016).

Aspects such as the active involvement of suppliers, customers and communities, derived from a strategic focus on innovation and sustainability, have become effective drivers for organizations to gain market share and maintain their customer bases (Lopes et al. 2017). When it comes to sustainability, the concept includes social, environmental and economic aspects of the triple bottom line treated together and transformed into strategies to achieve better results and consequently bring benefits to stakeholders (Epstein et al. 2017; Shields and Shelleman 2015; Obal et al. 2020). Companies with a sustainability orientation tend to see customer-centric value creation for the development of new products, which consider sustainability perspectives, an aspect increasingly valued by consumers (Handelman and Arnold 1999; Luo and Bhattacharya 2006; Obal et al. 2020).

In fact, corporate sustainable innovation has for some time started a transformation in the competitive scenario, putting pressure on companies to rethink processes, products, technology, marketing and business models (Nidumolu et al. 2009; Lu et al. 2013). The results generated by the products must not only generate profits for the company but must also be equally important for people's concerns and the needs of the planet (Elkington 1994; Thomé et al. 2016).

The performance of sustainable innovation is one of the most significant factors for the sustainable development of companies, related to ecological products or processes e.g., innovation in technologies involved in the recycling of pollution residues, ecological product designs, energy savings and corporate environment management (Tzeng et al. 2002). However, there are relatively few efforts to integrate research and development of traditional new products with themes related to sustainable development (Thomé and Scavarda 2015; Thomé et al. 2016).

Sustainability addresses several issues and resources that involve the environment, ecology, social aspects, energy, transportation, management, marketing, distribution, finance, health, research and development (R&D) and many other topics. With this, it is possible to affirm that the sustainability problems involve multiple appendages, which can be called criteria. Thus, a model or method to support decisions must be created in order to contemplate these associated aspects (Hopwood et al. 2005; Shen and Tzeng 2018).

Montis et al. (2004) and Silva et al. (2019) noted that sustainable development has been extensively studied during the last fifteen years; but an important criticism has been the inaccuracy of recommendations and the lack of operational applications. There are discussions that mention that measuring sustainable innovation is a challenging task, since there is a need for complex analysis considering social, political and economic issues (Gan et al. 2017; Silva et al. 2019). With this, practical mathematical models combined with technological and analytical solutions can assist managers and decision-makers (Gonzalez et al. 2015; Silva et al. 2019).

MCDA can be applied, in relation to the different inclusions of the aspects of sustainability and innovation, to compare alternatives and classify them (Norese et al. 2020). Multicriteria analysis is an effective method of supporting decision making, analyzing the benefits and negative points of different alternatives (Geneletti 2019). Since the 1960s, a large number of articles, as well as theoretical and applied books on MCDA have been produced, which expanded the field of operational research and, more generally, clarified the decision-making contexts (Linkov et al. 2021; Geneletti and Ferretti 2015).

The classifications that can be performed by MCDA are tools that contribute significantly to decision making, highlighting success stories and benchmarks and, eventually, helping to outline the desired paths (Meijering et al. 2014; Araújo 2014; Neofytou et al. 2020). Even when decision makers have subjective evaluation, it is possible to classify, select and order alternatives according to the aspects of the criteria (Silva et al. 2019).

A decision-making process can derive from complex comparisons between alternative options that can often require hierarchical analysis and could be based on conflicting criteria. A large number of external variables play an important role in guiding decision making (Ozil and Ozpinar 2008). Some of them can be manipulated by numerical models, such as cost–benefit analysis, market penetration strategies and environmental and social impacts (Beccali et al. 2003).

MCDA has been increasingly applied to sustainability decision problems. This can integrate factual research or modeling information, with value-based information collected through stakeholder engagement (Strager and Rosenberger 2006; Nordström et al. 2011; Adem Esmail and Geneletti 2018; Geneletti 2019). In addition, MCDA assists in sustainable decision problems, since these are characterized by the existence of several conflicting criteria and subjective or poorly structured evaluation processes (Kandakoglu et al. 2019).

The following studies are examples of how the topic of selection and evaluation is used in sustainability indicators (Nesticò and Maselli 2020), sustainable projects portfolio (Tran et al. 2020), materials based on their sustainable performance (Domingos and Rato 2019; Mathern et al. 2019), critical success factors of sustainable shipping management (Tran et al. 2020), sustainable alternatives for solid waste management (Pongpimol et al. 2020), sustainable conceptual design (Chunhua et al. 2020), transport services based on sustainability criteria (Paul et al. 2019), sustainable energy management (Pohekar and Ramachandran 2004), sustainable energy scenarios in cities (Simoes et al. 2019) and international energy policy classifications (Siksnelyte et al. 2019).

There are also some approaches to using MCDA methods in sustainable innovation projects. Debnath et al. (2017), Cheng et al. (2017) and Silva et al. (2020) carried out an analysis to support the selection and classification decisions of innovation projects. Debnath et al. (2017) carried out a sensitivity analysis to support decisions incorporating social responsibility aspects. Cheng et al. (2017) assumes that superior innovation projects are a crucial factor for technology companies to sustain in the long run. In addition, De Gracia et al. (2019) carried out a selection of the most promising innovative projects using the AHP (Analytic Hierarchy Process) method, while Le Boennec et al. (2019) used the MCDA to assess innovative mobility offers for certain territories and scenarios.

Comăniță et al. (2018) applied the MCDA to assess the eco-efficiency of a reformulated and redesigned product based on eco-innovation and eco-design approaches. Silva et al. (2017) showed a structured work with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for a simple obtaining of the Global Innovation Index 2015 of the most innovative countries in Latin America and the Caribbean; Silva et al. (2019) discussed the sustainable dimensions of Sachs (2008) to the Global Innovation Index 2017 innovation indicators.

Thus, it can be noted that there are several studies involving theoretical and applied approaches on MCDA and sustainability, as there are on MCDA and innovation. This implies that there is still an opportunity for studies that can capture the theoretical and applied domain of using MCDA in the context of sustainable innovations (Mousavi and Bossink 2017; Gupta and Barua 2018; Ahmadi et al. 2020). A bibliometric research is a powerful method to conduct a detailed and comprehensive analysis to understand this line of research more broadly.

3 Method

In this article, a bibliometric analysis of publications on the application of MCDA in sustainable innovations (MIS) was used. Bibliometry makes a quantitative analysis of academic and technical publications through statistical and mathematical methods (Rostaing 1997; Silva 2004). This method helps to know the stage in which a research in a given area is and the analysis of research priorities in an entire discipline (Macedo et al. 2007; Neff and Corley 2009; Shi et al. 2020).

Co-citation and co-word analysis "use bibliographic data from publication databases to construct structural images from scientific fields" (Zupic and Čater 2015, p. 430). These types of methods objectively evaluate the scientific literature (Chubin and Garfield 1980) and allow to verify issues that are often hidden, such as informal research networks that are often not formally related (Crane 1988; Price 1965). This method is used mainly for scientific mapping that aims to reveal the structure and dynamics of scientific fields (Cobo et al. 2011).

The research was conducted using the approach of Zupic and Čater (2015) that synthesize a method for conducting bibliometrics in management and organization studies, which can be seen in Fig. 1. The method consists of five basic steps: research design, compilation of bibliometric data, analysis, visualization and interpretation.

Table 1 Bibliometric methods adopted and research questions. Source: Adapted from Zupic and Čater (2015)

Citations analysis
Document types
Main information of publications
Publications by year
Most influential journals
Countries with more publications
Most cited publications
Co-citation analysis
Who are the central researchers?
Co-word analysis and thematic evolution
What are the main topics and conceptual building blocks of the literature in question? And how have they evolved over time?

3.1 Research design

In the first stage, research planning was carried out, in which the research objective and questions presented in the first section of this article were elaborated. In addition, the bibliometric methods that can answer the questions were selected, which are highlighted in Table 1. The methods used were the citation analysis, co-citation and co-word analysis, the latter also incorporated thematic evolution and Table 1 also presents the issues addressed in each type of analysis.

Citation analysis measures impact, so the main skill of citation analysis is to find the most influential journals and general trend of interrelationship between articles in a specific research stream (Zupic and Čater 2015; Ohno 2019). This analysis is one of the fastest growing analyzes in bibliometric research and provides an overview of the documents published (Sun and Grimes 2016; Pinto et al. 2016).

Co-citation is the most widely used and validated bibliometric method, which is able to denote kinship of authors who treat the same subject (Zhao and Strotmann 2008; Zupic and Čater 2015). A co-citation occurs when paper A and paper B cite paper C, and, in view of that, calculates the frequency with which two authors are cited together (Small 1973). In addition, connecting authors with co-citation has proven to be reliable, since the citation number offers a method for filtering the most important works (Zupic and Čater 2015). This type of analysis represents the existing proximity between the authors, that is, the closer the authors are to each other it means that they were more often cited together in other works and the greater the likelihood of the content being related (Pasadeos et al. 1998; Zupic and Čater 2015; Pinto et al. 2016). To perform the co-citation map, a normalized similarity matrix was produced, and the association strength normalization was used.

Co-words analysis aims to map the main conceptual elements of a list of publications using terms extracted from keywords, titles or abstracts in bibliographic information (Ronda-Pupo and Guerras-Martin 2012; Zupic and Čater 2015; Aria and Cuccurullo 2017). One of the most interesting aspects is that this method can discover links between themes and structural aspects in a research area,

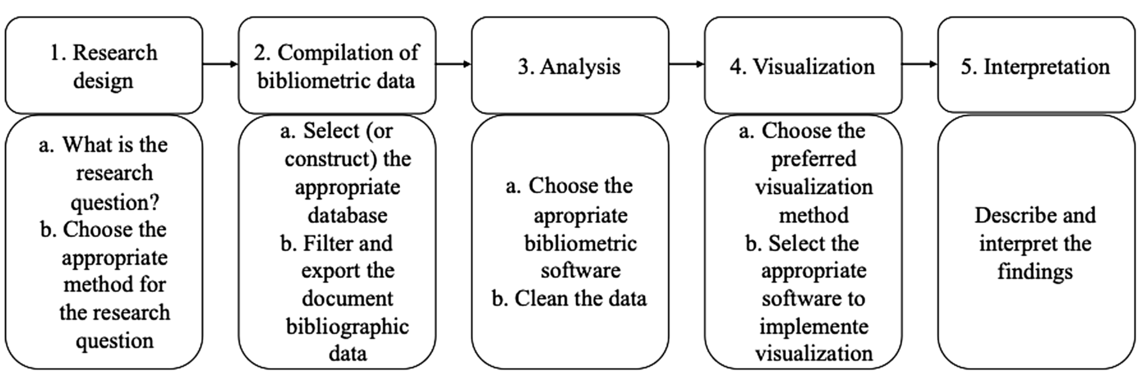

Fig. 1 Steps of the method used for bibliometrics. Source: Adapted from Zupic and Čater (2015)

in addition to monitoring its evolution (He 1998; Zupic and Čater 2015; Di Matteo et al. 2018).

3.2 Compilation of bibliometric data

The bases used to survey the set of main documents were selected. For this, an initial research was carried out to determine the search sequences, that is, the terms that could be used in the base search tool. Clarivate's Web of Science (WOS) databases and Elsevier's Scopus databases were selected for their vast collection of abstracts and citations. According to Zupic and Čater (2015, p. 441) "the WOS database is most frequently used database for bibliometric studies in management and organization" and has more than 171 million records and more than 34,000 journals (Clarivate 2020). And Scopus has a collection of abstracts and citations from more than 25,100 journals (Elsevier 2020).

To identify the main terms and expressions of interest for the search strings, an initial exploratory search was carried out on titles, abstracts and keywords on both bases using the generic string "innovation AND sustainability AND multicriteria". With that, adding the results from the two databases, 97 articles were identified. After removing the redundant documents, 85 unique documents were obtained.

A first set of data, separated by their source base, comprising the titles, keywords and abstracts of these 85 documents, was obtained and manipulated through the VOSviewer software. The software was used to identify the main terms used in the selected documents and that could be used in the search sequences to carry out a broader research of articles in the three themes that are part of this research. 1968 main terms were identified, of which 111 were selected as of interest. The terms were filtered and associated according to the three themes of MIS.

Complementarily, the select terms were presented to two experts who complemented and validated them. The search strings were built in research chains, as can be seen in Table 2. It is worth noting that an attempt was made to include the terms "green" and "eco" in the sustainability and "decision making" in the MCDA in Table 2. These terms inadequately expanded the search results, including documents that were not associated with the domain of interest. Thus, they were not included in the search strings.

The research sequences presented in Table 2 were applied to the Scopus and Web of Science databases, selecting documents published in both databases until the year of 2020. An analysis of a broader and more inclusive set of publications was carried out, in this way, only filters of area of interest and language were implemented. Therefore, only articles in the English language were considered. And in the Scopus database the following subject areas were selected: "Business, Management and Accounting", "Decision Sciences", "Energy", "Engineering", "Environmental Science" and "Multidisciplinary". And, in its turn, the following subject areas were considered to the Web of Science database: "Automation Control Systems", "Business", "Ecology", "Energy Fuels", "Engineering Environmental", "Engineering Industrial", "Engineering Manufacturing", "Engineering Multidisciplinary", "Environmental Sciences", "Environmental Studies", "Green Sustainable Science Technology", "Management" and "Multidisciplinary Sciences". As a result, 589 documents were identified in the Scopus database and 430 in the Web of Science database. The two databases were integrated into one, thus building a third database, using the open source Bibliometrix library in the R package.

Table 2 Terms used in the search

Theme	Research sequences
Innovation	"design and development" OR "design process" OR innovat* OR "new design*" OR "new innovati* project*" OR "new process*" OR "new product*" OR "new service*" OR "process* design" OR "process* development" OR "product* design" OR "product* development" OR "service* design" OR "service* development"
MCDA	mca OR mcda OR "multi criteria" OR multicriteria OR "multiple criteria" OR "multi perspective model approach" OR multiattribute
Sustainability	sustainab* OR "triple bottom line"

3.3 Analysis

In the third stage, bibliometric analysis tools were used. The authors chose to use the R package Bibliometrix library and the VOSviewer. Bibliometrix offers a set of high-quality open-source tools for quantitative research in bibliometrics and scientometrics (Aria and Cuccurullo 2017). Bibliometrix, in addition to removing duplicates, performs data standardization, such as spelling, authors' names, journals etc. VOSviewer is also a free program developed for the construction and visualization of bibliometric maps, allowing the maps to be examined in detail (Van Eck and Waltman 2010).

As a first stage of analysis, a pre-processing of the integrated database was performed so the redundant documents were removed, resulting in 722 unique documents. During the conduction of the main methods highlighted in the research design, some complementary analyzes were performed. A multiple correspondence analysis was implemented, which is a factor analysis used for a general understanding of how categorical variables are related (Greenacre and Blasius 2006). Cluster analyzes were also carried out that can group topics based on the distribution of keywords across dimensions and their relative positions (Shi et al. 2020). The keywords are distributed as points in the two-dimensional space and the closer they are presented on the map of the conceptual structure, the more similar they are in the distribution (Shi et al. 2020; Cuccurullo et al. 2016).

In addition, using the study by Shi et al. (2020), a thematic evolution was constructed. Sankey diagrams are generally used to show resource flows and to view arbitrary multidimensional data in a very different way (Schmidt 2008; Lupton and Allwood 2017). In this bibliometric study, its purpose is to analyze how the focuses identified by the multiple correspondence analysis interact with each other and to detect the main evolutionary paths of the themes (Shi et al. 2020).

Additionally, a study was carried out to categorize publications by applied MCDA method and by focus, which was identified through the multiple correspondence analysis. These were inspired by the work of Huang et al. (2011), Kurth et al. (2017) and Cegan et al. (2017). The main purpose of this categorization was to identify trends and new research opportunities. The identification of the focus and method were carried out by searching for terms in the author's keywords, keywords associated by ISI or Scopus database, abstracts and titles.

3.4 Visualization

In the fourth stage, the visualization method was chosen, which was a network analysis of a map based on authors, more specifically the co-citation map and the co-word analysis. The layout algorithm used was the visualization of similarities VOS-Fruchterman-Reingold through the VOSviewer distance-based map Kamada-Kawai (Van Eck et al. 2008). The software used to prepare the visualization was the R package Bibliometrix library (Aria and Cuccurullo 2017) and the maps were generated through VOSviewer (Van Eck et al. 2008).

3.5 Interpretation

And in the fifth and last stage, the results were described, interpreted and presented. The main focus of the interpretations resulting from bibliometric analysis is on the structure. That is, the focus is to analyze the relationships between groups of publications, authors, concepts and other bibliographic information to discover how they are related and influenced, as well as to identify subjective questions about the research field (Zupic and Čater 2015).

4 Analysis and discussion of results

4.1 Citation analysis

The types of documents are shown in Table 3. It can be seen that articles represent approximately 66% of publications and conference articles 20%.

Table 4 presents a summary of the main information from the 722 publications analyzed. In total 2131 authors were identified, with an average of approximately 0.3 documents per author and the collaboration index, which is the average of authors who collaborated in a publication, was 3.21. Keywords plus are those associated with Scopus and (or) Clarivate Analytics Web of Science databases.

Figure 2 shows an evolution of the number of publications per year. The first publication identified was in 1996 and from this year until 2004 there was a small number of publications, with an average of 1.7 publications per year. From 2005 onwards, a considerable and continuous increase in the number of publications was noticed, reaching a peak in 2020 with 144 publications. A number of 4 publications do not contain information on the date of publication.

Table 5, which was constructed using the study by Huang et al. (2011) as basis, aims show the quantity and percentage of sustainable innovation documents about MCDA on Web of Science. The WOS database was selected as a reference due to its extent and representativeness in relation to the total number of documents identified. The column "Number of MIS papers" represents the number of documents identified in this bibliometric study. The column "Total number of MCDA papers" represents the results, exclusively from Web of Science database, from the search string associated with MCDA presented in Table 2.

Although the number of publications on the MIS theme is still relatively minor within MCDA studies, it is noted that considerable growth has occurred since 2012. This indicates that the number of MCDA articles with sustainable innovation approaches has grown significantly in the last decade.

Table 3 Types of documents identified

Document type	Amount
Article	476
Article; early access	4
Book	2
Book chapter	11
Conference paper	123
Conference review	23
Editorial	2
Erratum	1
Proceedings paper	26
Review	27

Table 4 Main information of MIS publications

Dimension	Data	Dimension	Data
Timespan	1996:2020	Authors	2131
Sources	377	Authors of single-authored documents	47
Documents	722	Authors of multi-authored documents	2084
Average years from publication	5.05	Single-authored documents	73
Average citations per documents	11.97	Documents per author	0.339
Average citations per year per doc	2.05	Authors per document	2.95
Keywords plus	3807	Co-authors per documents	3.41
Author's keywords	2202	Collaboration index	3.21

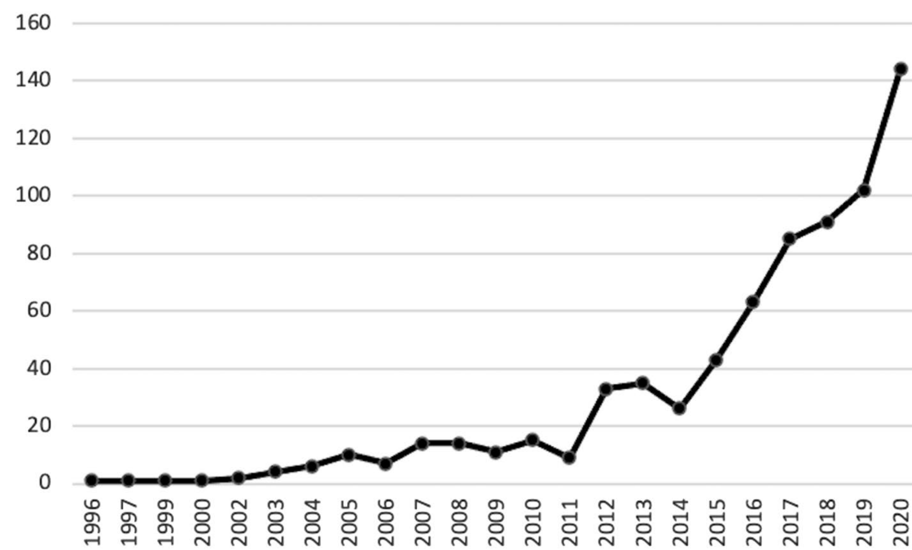

Fig. 2 Number of MIS publications per year

As a reference, considering only the year of 2020, the publications on MIS correspond to approximately 20% of the totals in column "Number of MIS papers", as can be seen in Fig. 2 and Table 5.

The sources with the most publications are shown in Table 6 in descending order and with their respective *h*-index. There is a clear concentration of publications in the first two journals "Sustainability" and "Journal of Cleaner Production", which concentrates 18% of the total. Among the journals presented in Table 6, there is a predominance of those aimed at sustainability. Among the journals with the highest *h*-index, that is, with the greatest influences and impact, the sources "Journal of Cleaner Production", "Sustainability" also stand out.

The authors with the most productions among the documents identified are shown in Table 7 together with their h-index, affiliation and fields of publication. The information on the last two columns was taken from the Google Scholar and ResearchGate websites. We realized that the authors are scholars of MCDA and sustainability, mainly. In this list there are no authors who are dedicated to the fields of innovation, specifically, but this does not imply that they have not published any related document.

Table 8 shows the classification of the first fourteen countries in number of publications. In addition to the number of publications, the following data are presented: the indexes of single country publications (SCP), multiple country publications (MCP) and the percentage of MCP (MCP Ratio). In these analyzes, a greater number of publications made in China, USA, United Kingdom and Italy are identified.

In addition to the total number of citations, Table 9 presents the average number of citations per document per country in the third and sixth columns. The data are presented in descending order of total citation and the first three columns are independent of the last three. Although Denmark is 15th place in total citations, this country has the best average citations per article. China despite having the largest number of publications and citations, in the average number of citations per article it is in sixth. In this list, we verified the predominance of European countries, which demonstrates that this continent has dominion on the publications in the fields of research related to MIS.

Table 10 shows the 10 most cited documents, each with at least 75 citations. The article by Bovea and Pérez-Belis (2012) received the highest number of citations, 259. Two articles out of the 10 most cited were published in

Table 5 Growth of sustainable innovation papers in MCDA

Year	MIS documents	MCDA documents (WOS only)	Percentage MIS/ MCDAWOS (%)
1996	1	659	0.2
1997	1	744	0.1
1998	0	785	0.0
1999	1	796	0.1
2000	1	830	0.1
2001	0	858	0.0
2002	2	876	0.2
2003	4	979	0.4
2004	6	1107	0.5
2005	10	1182	0.8
2006	7	1261	0.6
2007	14	1615	0.9
2008	14	1834	0.8
2009	11	1923	0.6
2010	15	2029	0.7
2011	9	2144	0.4
2012	33	2346	1.4
2013	35	2576	1.4
2014	26	2920	0.9
2015	43	3560	1.2
2016	63	4063	1.6
2017	85	4270	2.0
2018	91	4908	1.9
2019	102	5295	1.9
2020	144	5338	2.7

Table 6 Most relevant journals identified

Source	Documents	*h*-index
Sustainability	79	12
Journal of Cleaner Production	52	21
Science of the Total Environment	9	5
Energies	8	4
Resources Conservation and Recycling	8	2
Clean Technologies and Environmental Policy	7	4
International Journal of Sustainable Engineering	7	4
Journal of Environmental Management	7	7
Land Use Policy	7	4
Procedia Engineering	7	4

the Journal of Cleaner Production. The analysis of these works allowed us to identify that they cover different approaches within MIS, as presented in the "Purpose" column. As examples, Bovea and Pérez-Belis (2012), Patel et al. (2012) and Nielsen et al. (2016) carried out studies to evaluate the product development process; Zeng et al. (2007) and Chan and Chan (2004) developed studies to selection of projects, suppliers or resources; Doukas et al. (2007) and Madlener et al. (2007) presented research for sustainable innovation management decision with studies of new energy possibilities.

4.2 Co-citation analysis

The diagram obtained with the frequency of co-citations, also elaborated from the Bibliometrix and exported through the VOSviewer is shown in Fig. 3. In Table 11, the authors of each cluster of the co-citation map are presented.

Figure 3 was generated from the 19 authors with the more frequency citations and they have been cited at least 50 times among the analyzed references. Two main co-citation clusters were identified with a total of 149 links between the vertices. Among the authors presented in the two clusters, just one is listed in Table VII as the author with the highest number of publications: Zavadskas E K.

What can be inferred is that the central authors are those with the most links and the peripheral authors are those with the least links. Saaty T., Opricovic S., Kahraman C., Hwang C. L., Brans J. P., Ishizaka A., Govindan K. and Tzeng G. H. are the authors with the highest links, each has at least 17 connections with the other authors. And these same authors are the most central ones that make the connection between the two clusters. The most peripheral authors are Elkington J, Sarkis J, Mardani A, Munda G, Belton V and Wang J J.

In Table 12 are presented some information about central authors, such as, total number of publications, h-index, total number of citations, affiliation and main research fields. The data in this table were taken from the Web of Science in January 2020, except for the "Fields of publication" column that was searched in Google Scholar and ResearchGate authors' profile. Some of these authors are highly recognized in the field of MCDA. For example, Saaty who developed the AHP method, Kahraman is recognized authors in research on fuzzy logic and Tzeng for his work on MCDA, Brans was the creator of the PROMETHEE method, in addition to Ishizaka who has great contributions to MCDA applied to Supply Chain Management (SCM) and Sustainability. Govindan is recognized for his research in the environmental area and also in SCM.

Considering the parameters of the co-citation analysis, the results generated showed a concentration of authors that publish in the MCDA and sustainability fields. As in the analysis of the authors with the most citations presented in Table VII, in Table 12 there is also no author that is focused on issues related specifically to innovation. Thus, the central authors presented here are researchers focused mainly in the fields of MCDA and MCDA applied to sustainability.

Table 7 Authors with more publications

Author	Documents	*h*-index	Affiliation	Fields of publication
Zavadskas E	6	5	University Sauletekio, Lithuania	Civil Engineering, Multiple Criteria Decision Making, Decision Support Systems, Construction Engineering and Management
Bockstaller C	5	4	Université de Lorraine, France	Environmental Sustainability, Cropping Systems, Farming Systems, Sustainability Assessment
Bottero M	5	4	Politecnico di Torino, Turin, Italy	Sustainability, Environmental Impact Assessment, Sustainable Development, Urban Planning, Built Environment, Decision Support Systems
Streimikiene D	5	4	Lithuanian Energy Institute, Lithuania	Climate Change Mitigation
Tseng M	5	4	Asia University, Taiwan	Corporate sustainability, Sustainable supply chain management, Fuzzy set theory
Vinodh S	5	4	National Institute of Technology, India	Agile Manufacturing, Lean Manufacturing, Sustainable Manufacturing
Bui T	4	3	National Taiwan Ocean University, Taiwan	Organizational Studies, Environmental Economics, Green Economics
Kaklauskas A	4	2	Vilnius Gediminas Technical University, Lithuania	Civil Engineering, Multiple Criteria Decision Making, Construction Engineering and Management, Decision Support Systems
Kusi-Sarpong S	4	4	University of Southampton, United Kingdom	Sustainable Operations and Supply Chains, Circular Economy, Industry 4.0, Multi-Criteria Decision-Analysis, Corporate Sustainability
Tsai F	4	3	National Taiwan Ocean University, Taiwan	Decision Support Systems, Sustainability, Transport Systems

Table 8 Countries with the largest number of publications

Country	Documents	SCP	MCP	MCP ratio (%)
CHINA	54	45	9	16.7
ITALY	52	49	3	5.8
SPAIN	22	20	2	9.1
USA	22	19	3	13.6
CANADA	19	19	0	0.0
INDIA	18	17	1	5.6
POLAND	18	15	3	16.7
UNITED KINGDOM	17	16	1	5.9
FRANCE	17	16	1	5.9
SWITZERLAND	16	14	2	12.5
GREECE	15	15	0	0.0
BRAZIL	11	10	1	9.1
GERMANY	11	9	2	18.2
LITHUANIA	11	10	1	9.1
NETHERLANDS	54	45	9	16.7

4.3 Co-word analysis

In total, 6009 keywords were identified in the 722 articles and the main ones are listed in Table 13. Four columns are presented, the first two of which refer to the authors' keywords and the last two to the keywords associated with the Scopus and (or) Clarivate Analytics Web of Science databases. And the "Amount" column shows the frequency of these keywords in the integrated database. A dictionary was made of the main concepts extracted from the data of the publications and the terms were standardized.

In addition, Table 13 gives some evidence of the main themes associated with MIS research areas. The research topics and concepts will be more detailed and analyzed in sequence through Fig. 4. The keywords that appear most associated with MIS are sustainable development, sustainability assessment, circular economy, life cycle assessment, ecodesign, environmental impact, environmental protection, product design, energy efficiency, renewable energy, climate change and supply chain management.

Subsequently, a co-word analysis was carried out. The Bibliometrix *conceptualStructure* function was used and, with that, a map of the conceptual structure of the scientific field related to the MIS themes was generated, as shown in Fig. 4. This function "performs multiple correspondence analysis (…) to draw a conceptual structure of the field and K-means clustering to identify clusters of documents that express common concepts" (Aria and Cuccurullo 2017, p. 969).

In Fig. 4, only the keywords associated with the database were plotted considering those that had at least 30 occurrences. This figure illustrates the conceptual and semantic structure of the main themes and conceptual building blocks of the literature. The main topics are associated with the three clusters identified in the concept map, represented by the colors red, green and blue. Conceptual building blocks

Table 9 Total citations by country

Country	Total citations	Average document citations	Country	Total citations	Average document citations
CHINA	1076	19.9	GREECE	254	16.9
ITALY	673	12.9	INDIA	235	13.1
SPAIN	489	22.2	HONG KONG	220	36.7
USA	333	15.1	CANADA	198	10.4
UNITED KINGDOM	323	17.9	SWEDEN	170	17.0
FRANCE	295	17.3	POLAND	168	9.9
GERMANY	288	26.2	DENMARK	162	40.5
NETHERLANDS	261	23.7	LITHUANIA	158	14.4

Table 10 Most cited publications

Document	Total citation	Average citation per year	Purpose
Bovea and Pérez-Belis (2012)	259	25.90	Application of MCDA for e evaluate environmental requirements of design products
Zeng et al. (2007)	149	9.93	Application of an innovative systematic approach of MCDA for optimal selection of wastewater treatment alternatives
Ren et al. (2015)	119	17.00	Sustainability assessment using life cycle analysis and multicriteria decision-making (MCDM)
Chan and Chan (2004)	117	6.50	Application of AHP for supplier selection model
Doukas et al. (2007)	112	7.47	Application of MCDA to formulating sustainable technological energy priorities
Madlener et al. (2007)	108	7.20	Application of an innovative MCDA methodology that examines possible energy futures paths
Patel et al. (2012)	99	9.90	Development a method using MCDA for quick preliminary assessment of chemical processes at the laboratory stage
Karmperis et al. (2013)	85	9.44	Application of MCDA in the solid waste management area
Nielsen et al. (2016)	77	12.83	Application of MCDA for sustainable building renovation
Lin and Tseng (2016)	76	12.67	Application of MCDA in sustainable supply chain management

can be understood as central expressions, terms and concepts that conceptually and semantically support each topic.

The blue cluster has the highest number of keywords, 8 in total. The percentages of each dimension demonstrate the explained variance, that is, a value calculated objectively from the observed data to indicate the adequacy of a model or how close to the real values the proposed model comes to be (Nakagawa and Schielzeth 2013). This cluster can be characterized by the topic "multicriteria decision making applied to product development, production and distribution" and is based on some central conceptual building blocks such as "decision support systems", "AHP", "optimization" and "decision making". Other terms and concepts relevant to this topic such as "manufacture", "design" and "sustainable development" indicate an emphasis on decision making oriented to the phases of development per se (design and development) and post-development (production and distribution) of products. Thus, the topic associated with the blue cluster represents a set of decision-making methods and techniques related to the product development and post-development stages, with an emphasis on the selection of suppliers and issues related to production and distribution. Among the three clusters, blue is the one with the most widely spaced terms, that is, they are the least similar in their distribution. In addition to this observation, through the distribution of data it is possible to verify that the blue cluster together with the red cluster are the ones that most contribute to dimension 1. Some publications elucidate this cluster, such as, Vinodh et al. (2014) proposed a model that integrates the implementation of environmentally conscious quality function deployment (ECQFD), the theory of inventive problem solving (TRIZ) and the AHP for the innovative and sustainable development of automotive components. And Favi et al. (2018) used MCDA to determine optimal and viable design options during the conceptual product design phase.

The green cluster has three keywords that have the closest approximation between terms, demonstrating that they are

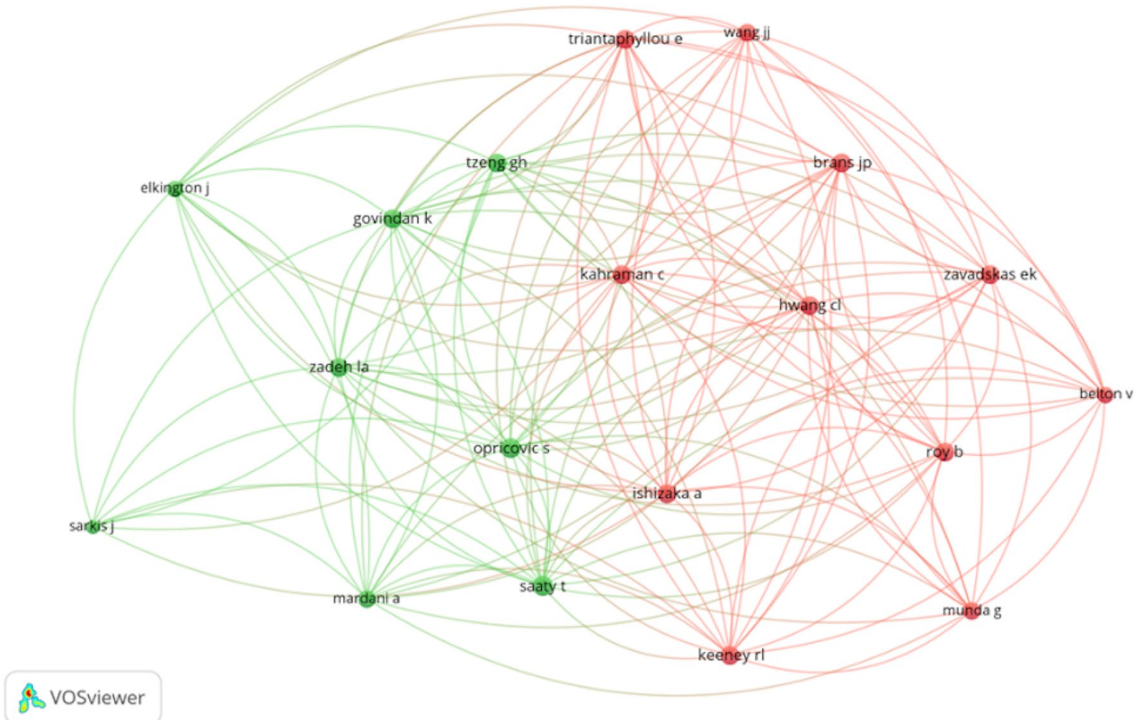

Fig. 3 Co-citation network of authors in the MIS field

Table 11 Identified authors in co-citation network of cited references in the MIS field

Cluster	Number of authors	Authors
Red	11	Belton V
		Brans J P
		Hwang C L
		Ishizaka A
		Kahraman C
		Keeney R L
		Munda G
		Roy B
		Triantaphyllou E
		Wang J J
		Zavadskas E K
Green	8	Elkington J
		Govindan K
		Mardani A
		Opricovic S
		Saaty T
		Sarkis J
		Tzeng G H
		Zadeh L A

similar and that they positively contribute to dimension 2, but have a negative contribution to dimension 1. It illustrates the second topic for the literature under analysis. This cluster is the most distinct among the others and can be represented by the topic "application of MCDA in sustainable innovation". The topic is supported by central conceptual building blocks such as "innovation", "sustainability", and "multicriteria analysis". Some documents indicate an emphasis on aspects related to management decisions and the definition of decision criteria and standards related to performance gain and evaluation impacts associated with sustainable innovations. As examples of articles from these cluster are Musaad et al. (2020) that present a study that used a fuzzy analytical hierarchy process for prioritizing barriers and solutions to adopt green innovations in the context of small and medium enterprises. And Chalvatzis et al. (2019) used MCDA to assess innovative electricity generation options against technical and sustainability criteria, encompassing environmental and social issues.

Finally, the red cluster consists of four keywords, and it has a positive contribution to the two dimensions. The cluster has terms that are similar to each other, however less similar when compared to the green cluster and more

Table 12 Information from central authors

Author	Total numbers of publications	*h*-index	Total citations	Affiliation	Fields of publication
Saaty, Thomas Lorie	173	43	16,924	University of Pittsburgh, USA	Decision Making, AHP, ANP
Opricovic, Serafim	16	10	3,978	University of Belgrade, Serbia	Agricultural Science, Environmental Science, Applied Mathematics, Statistics
Kahraman, Cengiz	421	55	9,935	Istanbul Technical University, Turkey	MCDA, Fuzzy Logic, Economic Analysis, Production Engineering Quality Management, Soft Computing, AHP, Green Supply Chain, Six Sigma
Hwang, Chia-Ling	23	15	1,891	National Chung Cheng University, Taiwan	Analytic Hierarchy Process Industry, Delphi Method, Management Science
Brans, Jean-Pierre	40	15	3,855	Vrije Universiteit Brussel, Belgium	Mathematical Programming, Management Science, Decision Analysis, Dynamic Programming, Optimization Theory, Multicriteria Analysis, Decision Support Systems, Decision Theory, Multiple-Criteria Decision Analysis, Operational Research, MCDM, Decision Aids, Multicriteria Decision
Ishizaka, Alessio	81	23	1,773	NEOMA Business School, France	Sustainability, Optimization, Operations Management, Supply Chain Management, Linear Programming, Heuristics, Corporate Social Responsibility, Business Administration, Management Science, Performance Measurement, Operations Research, Purchasing, Decision Analysis, Fuzzy Logic, Information Systems, Decision Processes, Manufacturing Systems, AHP, Outsourcing, Decision Support Systems, Decision Theory, Computer-Assisted Decision Making, MCDA, FMEA, MCDM, Computer-Aided Decision Making, Soft Systems Methodology
Govindan, Kannan	288	71	14,777	University of Southern Denmark, Denmark	Digitized Sustainable Circular Economy, Digital Supply chain management, Industry 4.0, Digitized Green and Sustainable supply
Tzeng, Gwo-Hshiung	284	64	14,119	Institute of Urban Planning, Taiwan	Research methods for problems-solving; MCDA; Fuzzy theory; Rough set theory, Statistics

cohesive and compact than the blue cluster. It illustrates the third topic for the domain under analysis and it can be characterized by the topic "sustainability assessment in product design" and is supported by some central conceptual building blocks such as "life cycle", "environmental impact", "product design" and "sustainability assessment". This topic represents a set of methods and techniques related to sustainability assessment in product design, with particular emphasis on assessing environmental impacts and managing the life cycle of products. The following documents demonstrate examples of this cluster: Mesa et al. (2020) propose a single generic indicator based on durability and environmental

Table 13 Most relevant keywords associated with MIS

Author Keywords	Amount	Keywords associated by WOS or Scopus database	Amount
Sustainability	119	Sustainable development	306
Multicriteria decision-making	65	Decision-making	275
Multicriteria analysis	62	Multicriteria analysis	185
AHP	46	Sustainability	121
Sustainable development	36	Innovation	113
Decision-making	28	Multicriteria decision-making	85
Life cycle assessment	28	Environmental impact	78
Innovation	19	Life cycle	67
Multicriteria	19	Product design	65
Sustainability assessment	18	AHP	58
DEMATEL	15	Decision support systems	53
Circular economy	13	Design	44
MCDM	13	Manufacture	31
Evaluation	11	Optimization	31
Optimization	11	Sustainability assessment	30
TOPSIS	11	Energy efficiency	29
Decision support	10	Climate change	28
Ecodesign	10	Environmental protection	28
Fuzzy AHP	10	Supply chain management	28
Renewable energy	10	Decision theory	27

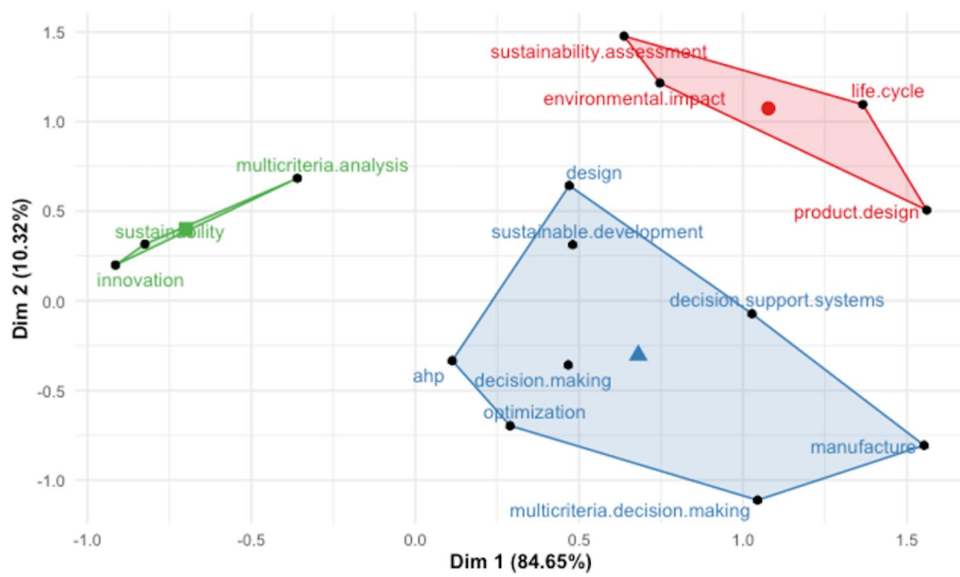

Fig. 4 Conceptual structure map of MIS thematic field

footprint for the selection of materials as an initial step in the design process to extend the product's life exposure and make a comparison of selection alternatives, including conventional and multicriteria approaches. And Mathern et al. (2019) suggest a structure to use machine learning and artificial intelligence for the optimization of structural design based on sustainability and construction criteria.

The two dimensions of the map in Fig. 4 together explain more than 94% of the variance, that is, the set of data is a good representation of the entire *corpus*. Most publications can be represented by the terms of the red cluster and mainly of the blue cluster, which has a bigger distribution. Therefore, the majority of publications are from MCDA applied to sustainability and sustainable product design, however other innovation approaches are little explored in the universe of analyzed publications.

These topics and conceptual building blocks were used to identify six research focuses related to sustainable innovation decision-making problems. The blue cluster with the topic "multicriteria decision making applied to product development, production and distribution" and concepts "decision support systems", "AHP", "optimization", "decision making", "manufacture", "design" and "sustainable development" resulted in the focuses:

"F1—product development, production and distribution"; and

"F2—evaluation or selection of projects, suppliers or resources".

The green cluster with the topic "application of MCDA in sustainable innovation" and concepts "innovation", "sustainability", and "multicriteria analysis" inspired the identification of the focuses:

"F3—sustainable innovation management decision"; and

"F4—definition of decision criteria and standards for sustainable innovation performance".

And the red cluster with the topic "sustainability assessment in product design" and concepts "life cycle", "environmental impact", "product design" and "sustainability assessment" resulted in the focuses:

"F5—environmental or social impact assessment"; and

"F6—product life cycle management or assessment".

Through the studies carried out, we can affirm that these focuses are the main areas within research about MIS is carried out. In Sects. 4.4 and 4.5, we will discuss how these research focuses have been explored over the years, the main trends of the MCDA focuses and methods used.

4.4 Thematic evolution analysis

A Sankey diagram presented in Fig. 5 was constructed to analyze the six focuses identified in Sect. 4.3. The diagram was constructed using the *thematicEvolution* function in Bibliometrix. It was considered that each word should have a minimum frequency equal to three. The periods for analysis were determined from the analysis of Fig. 2 and Table V, which showed similar growth trends in the periods 1996 to 2010, 2011 to 2015 and 2016 to 2020.

In the diagram, according to Shi et al. (2020, p. 2170) "each node represents a theme cluster which is labelled by the keyword with the highest frequency and the corresponding sub-period. The size of the node is proportional to the number of keywords for the corresponding theme (…). The edge width is proportional to the inclusion index between two linked themes". From a general perspective, it appears that the number of connections between the themes increases over time, mainly between 2011 and 2020. Most of the themes evolved and developed steadily, and some other themes gain importance and appear in the penultimate or last subperiod. We related the six focuses F1 to F6 for the trajectories and keywords presented in Fig. 5.

The trajectories of F1 and F2 can be described as (a) sustainable development → energy utilization → sustainable development, (b) industry → Sustainable development; assessment method; sustainability; climate change and (c) Optimization → environmental protection → climate change. The evolution path (a) shows that sustainable development has become the most important sub-area of the MIS field in the last 24 years, as highlighted by Montis et al. (2004) and Silva et al. (2019). In addition, between 2016 and 2020 this sub-area had aggregation of AHP, decision making process, artificial intelligence, buildings, energy utilization, industry, multicriteria analysis and innovation. This demonstrates that the linkage between sustainable development and innovations is currently present in several sectors, with emphasis on buildings, industries and energy. And tools for its implementation or analysis have been incorporated, such as MCDA, AHP method and artificial intelligence.

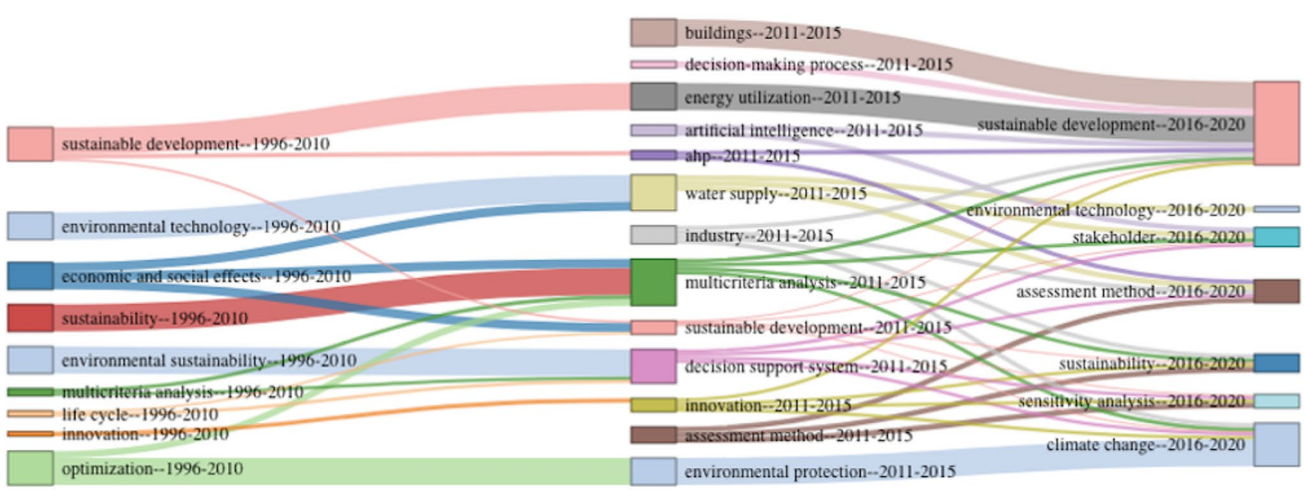

Fig. 5 Thematic evolution of MIS research (1996–2020)

The evolution of trajectory (b) was identified only from 2011 and shows that this cluster was divided into smaller ones, but that were strongly related to sustainability and climate change, incorporating assessment methods. This shows a strong relationship, mainly, between F1, F4 and F5. We observed that this sub-area in recent years has been concerned not only with developing sustainability, but also with evaluating it. The evolution path (c) starts with optimization and has its flow progressing in a concentrated way towards environmental protections culminating in issues related to climate change. We can see that in the last 10 years, interests in optimization or efficiency have been transformed into approaches that prioritize aspects of climate change. Currently, this sub-area has been identified as the second with the most prominence.

The trajectories of F3 and F4 can be described as: (d) innovation → innovation → sustainable development; sustainability; sensitive analysis; climate change, (e) sustainability → multicriteria analysis → multicriteria analysis → sustainable development; stakeholder; sustainability; climate change and (f) multicriteria analysis → multicriteria analysis → sustainable development; stakeholder; sustainability; climate change. The three trajectories culminate in similar sub-areas, demonstrating that the focus on "sustainable innovation management decision" and "definition of decision criteria and standards for sustainable innovation performance" are closely related with stakeholders. In addition, we found that innovation has smaller clusters, that is, a lower relevance compared to sustainability and MCDA.

The trajectories of F5 and F6 can be described as: (g) economic and social effects → water supply → environmental technology; stakeholder; assessment method, (h) environmental sustainability → decision support system → stakeholder; assessment method; sensitive analysis; climate change, (i) environmental technology → water supply → environmental technology; stakeholder; assessment method, and (j) life cycle → decision support system → stakeholder; assessment method; sensitive analysis; climate change. These trajectories show how the field of MIS research is based mainly on environmental issues and that this subject during the last 24 years has kept its prominence. F5, mainly represented by (g), (h) and (i), was the focus that had most trajectories represented in Fig. 5. The evolution of the three sub-areas shows that between 2011 and 2015 there was a concentration of research in water supply. In addition, MCDA and other decision support methods were incorporated into their trajectories. There is also currently a sub-area of environmental technology, but it has less relevance compared to the period from 1996 to 2000. What we realize is that environmental issues have now been subdivided into other sub-areas, such as climate change and assessment methods. F6, on the other hand, had only the trajectory (j) and small representation, which can be justified by the fact that it is a relatively recent topic and with few publications.

Table 14 Distribution of decision-making methods

Method	Publications		Number of implementations
	Frequency	Percentage (%)	
AHP/ANP	109	15.1	186
DEMATEL	8	1.1	28
ELECTRE	7	1.0	13
FUZZY	80	11.1	157
MAUT/MAVT	12	1.7	15
MCDA/MCDM	367	50.8	367
MULTIPLE	105	14.5	–
PROMETHEE	13	1.8	23
TOPSIS	21	2.9	56

Table 15 Multiple identified methods

Multiple method	Number of publications
AHP/ANP; FUZZY	38
FUZZY; TOPSIS	14
AHP/ANP; TOPSIS	10
AHP/ANP; DEMATEL	9
DEMATEL; FUZZY	6
AHP/ANP; FUZZY; TOPSIS	5
AHP/ANP; DEMATEL; FUZZY	3
FUZZY; PROMETHEE	3
AHP/ANP; DEMATEL; FUZZY; TOPSIS	2
AHP/ANP; FUZZY; PROMETHEE	2
AHP/ANP; PROMETHEE	2
AHP; OTHERS	2
ELECTRE; MAUT/MAVT	2
AHP/ANP; ELECTRE; FUZZY; PROMETHEE; TOPSIS	1
AHP/ANP; ELECTRE; FUZZY; TOPSIS	1
AHP/ANP; ELECTRE	1
AHP/ANP; MAUT/MAVT	1
ELECTRE; FUZZY	1
FUZZY; PROMETHEE; TOPSIS	1
PROMETHEE; TOPSIS	1

4.5 Trends in sustainable innovation decision methods and focuses

The distributions of the decision methods and focuses identified in Sect. 4.3 are shown in Tables 14, 15, 16, 17,

Table 16 Distribution of sustainable innovation decision-making focuses

Focus	Number of publications	Percentage (%)	Focus	Number of publications	Percentage (%)
F1	178	24.7	F1 and F5	58	8.0
F2	29	4.0	F1 and F6	22	3.0
F3	86	11.9	F2 and F4	5	0.7
F4	26	3.6	F2 and F5	6	0.8
F5	186	25.8	F3 and F5	21	2.9
F6	19	2.6	F4 and F5	13	1.8
F1 and F2	9	1.2	F4 and F6	1	0.1
F1 and F3	1	0.1	F5 and F6	9	1.2
F1 and F4	19	2.6	Others	34	4.7

Table 17 Distribution of sustainable innovation decision methods and focuses

	F1	F2	F3	F4	F5	F6
AHP/ANP	69	12	39	24	67	14
DEMATEL	13	2	4	3	10	1
ELECTRE	7	0	1	0	5	0
FUZZY	72	14	21	18	50	9
MAUT/MAVT	9	1	2	1	3	1
MCDA/MCDM	138	23	49	22	170	26
PROMETHEE	10	2	1	3	5	1
TOPSIS	20	4	12	6	16	3

Table 18 Distribution of MCDA methods between 1996 and 2020

Year	AHP/ANP	DEMATEL	ELECTRE	FUZZY	MAUT/ MAVT	MCDA/ MCDM	PRO-METHEE	TOPSIS
1996 to 2004	5	0	0	0	0	10	0	1
2005	1	0	0	0	2	7	0	0
2006	1	0	0	0	0	6	0	0
2007	2	0	0	3	1	7	1	0
2008	2	0	0	2	0	11	0	1
2009	4	0	0	3	0	6	0	0
2010	3	0	0	0	0	11	0	1
2011	3	1	0	0	1	5	0	0
2012	6	1	0	3	1	22	1	0
2013	9	0	1	7	1	17	2	2
2014	7	0	3	6	0	11	1	2
2015	8	1	1	12	0	20	2	4
2016	18	3	0	20	2	29	0	4
2017	26	1	1	19	0	44	2	4
2018	27	6	1	15	5	44	1	8
2019	23	6	2	18	1	58	2	9
2020	38	9	4	46	1	58	4	19

18 and 19. Methods with "MCDA/MCDM" representing all other multicriteria methods and "Multiple" present those studies that contain more than one multicriteria method. In Table 14 the column "Frequency" shows the number of publications that presented only the respective method, "Percentage" presents the percentage distribution, considering the data present in "Number of publications" and, finally, "Number of implementations" counts all implementations of the respective method, regardless of whether a single or more method was implemented. For

Table 19 Distribution of sustainable innovation decision-making focuses between 1996 and 2020

Year	F1	F2	F3	F4	F5	F6
1996 to 2004	3	0	3	0	8	2
2005	0	1	4	1	4	0
2006	3	2	1	0	2	0
2007	5	1	5	0	5	0
2008	10	2	0	1	4	0
2009	2	0	3	3	5	1
2010	6	1	1	2	7	1
2011	3	0	2	0	4	1
2012	11	5	0	5	12	1
2013	14	1	4	4	15	0
2014	10	1	2	4	13	1
2015	23	5	5	4	11	4
2016	34	4	7	5	27	5
2017	25	7	16	8	35	7
2018	37	7	16	5	38	9
2019	38	4	20	5	47	8
2020	62	8	18	17	54	11

example, if a publication with multiple uses the AHP and TOPSIS method, it will be counted for both the first and the second method in "Number of implementations". In Tables 17 and 18, we consider the number of implementations for presenting the data.

We can see through Table 14, in "Number of implementations", that there is a concentration of publications that use AHP/ANP, fuzzy, multiple and MCDA/MCDM. Among the combinations of methods presented in Table 15, there are three highlighted: AHP/ANP and fuzzy; fuzzy and TOPSIS; AHP/ANP and TOPSIS. This fact is expected, since these methods and combinations are more usual.

Table 16 present the distribution of the focuses identified in Sect. 4.3, with "Others" means that it is not related to the six specific focuses. And we identified that there are some documents with two focuses. The combinations that do not appear in Table 16 are because they have zero publications. In Tables 17 e 19 we double count the publications with two simultaneous focuses. Therefore, these values are different from the data presented in Table 16.

In Table 16 we can see that most publications are concentrated in the "F1—product development, production and distribution", "F5—environmental or social impact assessment" focuses. And we can see, in Table 17, in general, distributions of methods are close among the focuses. The areas "F2—evaluation or selection of projects, suppliers or resources", "F6—product life cycle management or assessment" and "F4—definition of decision criteria and standards for sustainable innovation performance" are those with the lowest representation in number of publications, which shows that there is more space to explore these areas.

Besides that, Table 17 shows that the methods with the most applications by theme are MCDA/MCDM, except in F4. We realized that several MCDA tools have been used successfully for studies of sustainable innovations. This demonstrates that in general, there is no preference for the method to be used per study focus, as also commented on by Huang et al. (2011) and Cegan et al. (2017) in their studies on the application of MCDA methods in environmental studies. However, Cinelli et al. (2014) and Cegan et al. (2017) highlighted that this situation may be due to the fact that the researchers are not aware of the merits of each MCDA method and its distinctions, such as the treatment of uncertainty or the robustness of the results.

Tables 18 and 19 show the chronological distribution of MCDA methods and distribution of focuses, respectively, between 1996 and 2020. In Table 18 until 2004, there were only publications of the AHP/ANP, MCDA/MCDM and TOPSIS methods. Unlike what was found by Huang et al. (2011) who identified that MCDA applications in environmental areas grew steadily between the years 2000 to 2010, we can see that the growth was quite different between the methods and between the years. We can see that all methods have seen considerable growth, especially since 2015, but with different rates. Some questions that drew attention were that the TOPSIS and fuzzy methods had a number of applications much higher in 2020 compared to other years.

In Table 19 we noticed that all six sustainable innovation decision-making focuses experienced significant growth during this period. We noticed that the publications of F1 and F5 have balanced growth rates and the other focuses had higher growth starting in 2015. For the focus F6 we observed that before 2015, there were a small number of publications, which can be justified by the fact that it is a relatively recent topic as mentioned.

5 Conclusions

Bibliometric studies offer an opportunity to identify and explore the research landscape. This article addresses the main discussions and theoretical approaches through bibliometrics on the application of methods to aid multicriteria decision making in sustainable innovations.

With the research carried out about the themes involving MIS, a very large variation of applications and different publications were found, but prevailing articles. Despite this variation, most of the documents are oriented to the discussion of decision making, MCDA and sustainability. Other findings were that most of the authors, more specifically 97%, have published more than one article among the 722 identified. This demonstrates that the authors have a certain recurrence in publications on MIS.

Another conclusion is that the number of MIS articles has grown significantly in the last two decades. We identified the MCDA and MIS publications between 1996 and 2020 and the growth rate was relatively slow until 2010, from the 2011 onwards there was a considerable and continuous increase in the number of publications. However, the growth rate is even higher in the period between 2015 and 2020, with an annual average growth of 1% for general MCDA publications and 28% for MIS. As mentioned by Huang et al. (2011), this growth can be attributed both to the increase in the complexity of decisions and to regulatory and stakeholder pressure for transparency in the decision-making process. In addition, we believe that MIS publications have also followed this trend, since there is a need to incorporate sustainability into activities and organizational decisions. And through innovation, institutions are able to meet some sustainable needs of their market, the regulatory requirements and stakeholders. The growth trend found is similar to that identified for environmental applications by Huang et al. (2011) and Cegan et al. (2017) and the curve shown in Fig. 2 is similar to the exponential curve presented by Huang et al. (2011).

In the co-citation analysis, Fig. 3, two clusters were identified, which delimit the central researchers, that are presents in Table 12: Saaty T., Opricovic S., Kahraman C., Hwang C. L., Brans J. P., Ishizaka A., Govindan K. and Tzeng G. H. We found that the most influential MIS researchers are focused on MCDA and applied MCDA on sustainability. Through the analysis of the most cited authors, co-citation and co-words it was verified that the innovation axis is the link with less relevance in this field of research. With that, we identified an opportunity to expand sustainable innovation research linked to the application of MCDA.

Another discovery was that the main topics and conceptual building blocks about MIS. They are presented in Sect. 4.3 and resulted in the following sustainable innovation decision-making focuses: "product development, production and distribution"; "evaluation or selection of projects, suppliers or resources"; "sustainable innovation management decision"; "definition of decision criteria and standards for sustainable innovation performance"; "environmental or social impact assessment"; and "product life cycle management or assessment". According to the authors' perception, these focuses are the most central in the discussion related to MIS and they show the themes that have been well discussed in the literature and others on the rise.

In thematic evolution analysis we find that the sub-area sustainable development has become the most important theme in the MIS field in the last 24 years. Another finding is that the publications migrated from a focus on optimization, that existed until 2010, to a predominance in discussions about climate change, which currently is the second most relevant sub-area. Environmental issues since the beginning of the analyzed period remain highlighted in MIS publications. However, currently they have been segregated for climate change, mainly, and have added assessment methods. In addition, it was found that in recent years, stakeholders have gained notoriety in MIS research.

The main trends in decision-making problems in sustainable innovation are present in Sects. 4.5 and the focuses identified with the largest number of contributions are "F1—product development, production and distribution" and "F2—environmental or social impact assessment". These trends are in consonance with the thematic evolution analysis. F1 is more related to sustainable development and the F2 maintained a significant number of publications possibly due to the wide discussion of the global needs for environmental and social adaptations derived from the climate change and new environmental laws.

And the themes "F2—evaluation or selection of projects, suppliers or resources", "F6—product life cycle management or assessment" and "F4—definition of decision criteria and standards for sustainable innovation performance" have been less explored in the literature. These three focuses had an increase in the number of publications from 2015 onwards, and MCDA, fuzzy and AHP/ANP methods are the main applications. We found few cases of application of PROMETHEE, TOPSIS and DEMATEL and no application of ELECTRE on theses focus. Therefore, these three focuses proved to be opportunities for future research. But the method to be adopted will depend on the study in question, the variables to be analyzed and the researchers' knowledge about the methods.

Regarding methods, the use of all major MCDA methods has also been expanded in recent years. We realized that there are more MIS studies that used MCDA, AHP/ANP, fuzzy logic and multiple methods. The highlights of the use of AHP were possibly due to the ease of use of the method and due to the "weight in AHP tends to be easier than in other MCDA methods, especially when a complex set of relationships among criteria" (Kurth et al. 2017, p. 141). Cegan et al. (2017) also comment that the age of a method can also influences its acceptance in a given field.

And when we analyze by focus, several MCDA tools have been also used successfully for studies of sustainable innovations. Only the ELECTRE, PROMETHEE, DEMATEL and MAUT/MAVT methods had little representation, about 5% in total of publications. However, it is worth mentioning that the selection of the MCDA method must be carried out considering the specific need of the decision problem, whether the criteria are conflicting or not, software availability, knowledge about the method, among other aspects (Guitouni and Martel 1998). As was done by Cegan et al. (2017), this article shows the occurrence of specific keywords associated with focuses and methods. But it is important to highlight that a deep individual analysis of each keyword in its specific context, for each document, is not part of scope of this article.

As general conclusions, the most explored approaches and the main gaps in the literature were identified. In view of this, there is an opportunity, both in theoretical and practical terms, for the amplification of the use of MCDA methods as a support mechanism for decision making in the dynamic and complex context of sustainable innovations.

Issues such as decisions about product portfolio management, defining and choosing attributes of goods and services, selecting a strategy for managing sustainable innovations, evaluating suppliers, partners and the structure of the green supply chain, choosing indicators for monitoring performance sustainable innovations, selection of research and development projects, selection of investments and life cycle assessment could be explored. Considering an increasingly intense demand for fast and assertive decision-making in the current global competitive environment, MCDA methods can be an important tool to reduce uncertainties and subjectivities in decision making about approaches, strategies, methods and tools related to sustainable innovations.

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Data availability We declare that the data supporting the results of this article, which constitute processing carried out in Bibliometrix and VOSviewer may be made available via email by the author Jamile Eleutério Delesposte, upon request. The database constructed with data from publications of 722 documents is being sent.

Declarations

Conflict of interest All authors declare that there are no conflicts of interest, whether financial or personal, with other people or organizations that can be interpreted as influencing research or its interpretation among the authors of the article, entitled: "Use of multicriteria decision aid methods in the context of sustainable innovations: bibliometrics, applications and trends" submitted for consideration in the journal Environment Systems and Decisions.

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