Pontifícia Universidade Católica do Rio de Janeiro

Manuel Calçada de Sousa

Multicriteria Decision-making Methods for Sustainable Development: A Longitudinal Science Mapping Approach

Dissertação de Mestrado

Dissertation presented to the Programa de Pós-graduação em Metrologia of PUC-Rio in partial fulfillment of the requirements for the degree of Mestre em Metrologia.

Advisor: Prof. Maria Fatima Ludovico de Almeida

Co-advisor: Prof. Rodrigo Flora Calili

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Pontifícia Universidade Católica
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Prof. Maria Fatima Ludovico de Almeida
Advisor
Programa de Pós-Graduação em Metrologia – PUC-Rio

Prof. Rodrigo Flora Calili
Co-advisor
Programa de Pós-Graduação em Metrologia – PUC-Rio

Prof. Helder Gomes Costa
Universidade Federal Fluminense – UFF

Prof. Antonio Marcio Tavares Thomé
Departamento de Engenharia Industrial – PUC-Rio

Rio de Janeiro, May 3rd, 2021

Manuel Calçada de Sousa

Bachelor of Science in Mechanical Engineering, Pontifical Catholic University of Rio de Janeiro, 2016.

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Abstract

Sousa, Manuel Calçada de Sousa; Almeida, Maria Fatima Ludovico de (Advisor); Calili, Rodrigo Flora (Co-advisor). **Multicriteria Decision-making Methods for Sustainable Development: A Longitudinal Science Mapping Approach**. Rio de Janeiro, 2021. 133p. Dissertação de Mestrado – Programa de Pós-Graduação em Metrologia, Pontifícia Universidade Católica do Rio de Janeiro.

The rise of sustainable development as a field of applied research has been observed across various disciplines. Within the UN 2030 Agenda scope, the achievement of 17 Sustainable Development Goals (SDGs) requires decision-making considering multiple decision criteria usually complex and in conflict. Multiple criteria decision-making methods (MCDM) have been widely employed in a wide range of fields and disciplines, including multicriteria decision analysis concerning sustainable development issues. Mapping and systemically analyzing the evolution of the research field covering applications of multicriteria decision-making methods for sustainable development in the last two decades can help governments and organizations in sociotechnical transitions towards sustainability. Thus, MCDM methods for sustainable development is emerging as a recent research domain within management and public policy fields. This dissertation aims to identify and visualize evolutionary pathways and build a scientific roadmap focusing on this research field. A bibliometric analysis was conducted to assess all peer-reviewed documents retrieved from the Web of Science (WoS) database, covering this field over the 2000-2020 timeframe. Based on the analyzed data of the most cited articles from a total of 3,473 initially retrieved documents, it was possible to identify and visualize a focused research field's longitudinal science map. The implications for ongoing, consistent policy and future research are discussed.

Keywords

Metrology; sustainable development; multicriteria decision-making methods; bibliometrics; science mapping.

Resumo

Sousa, Manuel Calçada de Sousa; Almeida, Maria Fatima Ludovico de (Orientadora); Calili, Rodrigo Flora (Co-orientador). **Métodos multicritério de apoio à decisão para o desenvolvimento sustentável: uma abordagem de mapeamento longitudinal da ciência.** Rio de Janeiro, 2021. 133p. Dissertação de Mestrado – Programa de Pós-Graduação em Metrologia, Pontifícia Universidade Católica do Rio de Janeiro.

A ascensão do desenvolvimento sustentável como um campo de pesquisa aplicada tem sido observada em várias disciplinas. No âmbito da Agenda 2030 das Nações Unidas, o cumprimento dos 17 Objetivos de Desenvolvimento Sustentável (ODS) exige a tomada de decisões considerando vários critérios geralmente complexos e conflitantes. Os métodos multicritério de apoio à decisão (MCDM) têm sido amplamente empregados em uma vasta gama de campos e disciplinas, incluindo a análise de decisão multicritério sobre questões de desenvolvimento sustentável. Mapear e analisar sistematicamente a evolução do campo de pesquisa cobrindo aplicações de métodos multicritério de apoio à decisão para o desenvolvimento sustentável nas últimas duas décadas pode ajudar governos e organizações nas transições sociotécnicas em direção à sustentabilidade. Assim, métodos MCDM para o desenvolvimento sustentável está emergindo como um domínio de estudo recente nos campos de gestão e políticas públicas. Esta dissertação tem como objetivo identificar e visualizar caminhos evolutivos e construir um roteiro científico com foco neste campo de pesquisa. Uma análise bibliométrica foi conduzida para avaliar todos os documentos revisados por pares recuperados do banco de dados Web of Science (WoS), cobrindo este campo no período de 2000-2020. A partir dos dados analisados dos artigos mais citados de um total de 3.473 documentos inicialmente recuperados, foi possível identificar e visualizar o mapa longitudinal da ciência de um campo de pesquisa em foco. As implicações para políticas contínuas e consistentes e pesquisas futuras são discutidas.

Palavras-chave

Metrologia; desenvolvimento sustentável; métodos multicritério de apoio à decisão; bibliometria; mapeamento científico.

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Acronyms

AAC – Average Articles Citation
AI – Artificial Intelligence
AHP – Analytic Hierarchy Process
ANP – Analytic Network Process
ARAS – Additive Ratio Assessment
CAGR – Compound Annual Growth Rate
CI – Collaboration index
COPRAS – COmplex PRoportional Assessment
CRITIC – CRiteria Importance Through Intercriteria Correlation
DANP – DEMATEL and AHP
DSS – Decision Support Systems
DEMATEL – Decision Making Trial and Evaluation Laboratory
EDAS – Evaluation based on Distance from Average Solution
ELECTRE – Elimination et Choix Traduisant la Realité
ENV – Economic and environmental
EVAMIX - EVAluation of MIXed data
EXPROM – EXtension of the PROMethee
GAHP – GIS and AHP
GIS - Geographic Information System
IDOCRIW – Integrated Determination of Objective CRIteria Weights
IS – Information Systems
IT – Information Technology
KEMIRA – KEmeny Median Indicator Ranks Accordance
KPI – Key Performance Indicators
MABAC – Multi-Attributive Border Approximation area Comparison
MACBETH – Measuring Attractiveness by a Categorical Based Evaluation TecHnique
MAUT – Multi-Attribute Utility Theory
MADM – Multi-attribute decision-making
MAC – Multiple Correspondece Analysis
MCDA – Multicriteria decision-aid
MCDM – Multicriteria decision-making
MDS – Multidimensional Scaling
MODM – Multi-objective decision-making
MCP – Multiple Countries Publication
MDG – Millennium Development Goal
MOORA – Multi-Objective Optimization Ratio Analysis
NLP – Natural Language Processing
ORESTE – Organization, Rangement Et Synthese De Données Relationnelles
PAMSSEM – Physical Asset Management Strategy Execution Enforcement Mechanism

PCA – Principal Component Analysis
PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-analyses
PROMETHEE – Preference Ranking Organization Method for Enrichment of Evaluations
QUALIFLEX – QUALItative FLEXible
SAW – Simple Additive Weighting
Sci2 – Science of Science
SCP – Single Country Publication
SD – Sustainable Development
SDG – Sustainable Development Goal
SIR – Superiority and Inferiority Ranking
SLR – Systematic Literature Review
SOC – Economic and social
SUS – Economic, environmental, and social
SMART – Simple Multi Attribute Rating Technique
SWARA – Stepwise Weight Assessment Ratio Analysis
TBL – Triple Bottom Line
TOPSIS – The Technique for Order of Preference by Similarity to Ideal Solution
UN – United Nations
VIKOR – VIekriterijumsko KOmpromisno Rangiranje
WASPAS – Weighted Aggregates Sum Product Assessment
WoS – Web of Science
WPM – Weighted Product Model
WSM – Weighted Sum Model

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1
Introduction

Sustainable development (SD) is by essence a complex issue, involving many variable systems and having many definitions. Similarly, the related term "sustainability" has proved an elusive concept, as it can mean different things in various fields as stated by White (2013). According to Kandakoglu et al. (2018), the most quoted definition remains as stated in Brundtland (1987), the report of the World Commission on Environment and Development entitled "Our Common Future": "Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: (i) the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given; and (ii) the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs." This definition highlights the need to simultaneously consider the economic, environmental, and social dimensions (figure 1.1). Decision criteria based on these three pillars should be considered concurrently when evaluating the consequences of decisions. Second, SD is built around a long-term vision that considers the indivisible nature of the environmental, social, and economic dimensions of development activities. Therefore, decision methods should take into account the immediate and future consequences of alternatives to avoid compromising the well-being of future generations.

Some global initiatives have been proposed to achieve SD over time, like the Agenda 21, the Millennium Development Goals, and the 2030 Agenda, that is the most recent initiatives. The 2030 Agenda comprises 17 Sustainable Development Goals (SDGs) and 169 global targets, all oriented to a systemic vision for a better and sustainable world. In September 2015, the SDGs were established by Heads of State and Government and High Representatives of 193 countries on a participatory basis (United Nations, 2015).

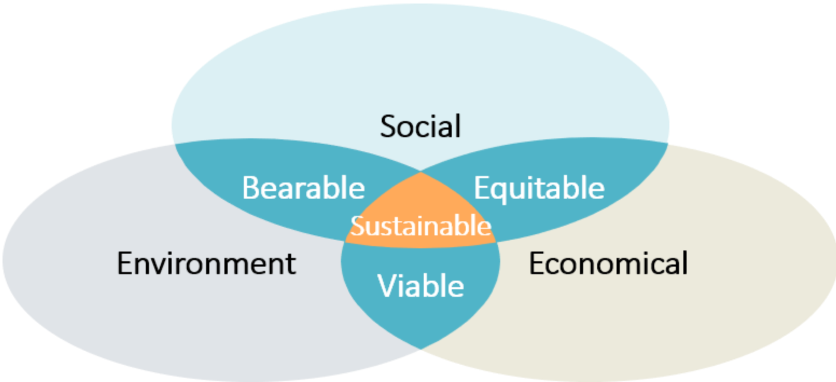

Figure 1.1 – Sustainable development pillars
Source: Kandakoglu et al. (2018).

The SDGs are a set of 17 interlinked goals designed to be a "blueprint to achieve a better and more sustainable future for all" (United Nations, 2017). They are: (1) ‘No Poverty’, (2) ‘Zero Hunger’, (3) ‘Good Health and Well-being’, (4) ‘Quality Education’, (5) ‘Gender Equality’, (6) ‘Clean Water and Sanitation’, (7) ‘Affordable and Clean Energy’, (8) ‘Decent Work and Economic Growth’, (9) ‘Industry, Innovation and Infrastructure’, (10) ‘Reduced Inequalities’, (11)’Sustainable Cities and Communities’, (12) ‘Responsible Consumption and Production’, (13) ‘Climate Action’, (14)’ Life Below Water’, (15) ‘Life On Land’, (16) ‘Peace, Justice, and Strong Institutions’, and (17) ‘Partnerships for the Goals’.

Figure 1.2 – Sustainable Development Goals
Source: United Nations (2015).

Following the stages of a generic policy-planning towards global targets achievement by 2030, the implementation of the 2030 Agenda framework started in 2016. From that time, an increasing number of guidelines, frameworks, methodological assessments, and academic studies on this subject have been published (Le Blanc, 2015; Jayaraman et al., 2015; United Nations, 2016; Nilsson et al., 2016; Nilsson et al., 2016; Allen et al., 2016; Constanza et al., 2016; Campagnolo et al., 2016; United Nations, 2017; Weitz et al., 2018; ICSU, 2017; IGES, 2017; Reyers et al., 2017; Collste et al., 2017; Stafford-Smith et al., 2018; Allen et al., 2018; Nilsson et al., 2018; Allen et al., 2019; Breuer et al., 2019). Nevertheless, all SDGs' achievements require decision-making processes, usually in complex contexts, considering multiple criteria, synergies, and trade-offs between objectives/targets. Accordingly, the request for methods to assess future risks and support decision-making for sustainability has increased time after time.

Roy (1990) distinguished multiple criteria decision making (MCDM) from multiple criteria decision aid (MCDA) approaches since the solutions obtained by solving well-formulated MCDM problems constitute a fundamental background for MCDA. He argued that MCDA aims to enable decision-makers to enhance the degree of conformity and coherence between the evolution of a decision-making process, besides the value system and the objectives of those involved in this process. For this research, we adopted the expression MCDM/A, understanding that it covers the conceptual considerations posed by Roy (1990).

In the last decade, MCDM/A approaches have been widely considered by researchers and scientists. They are considered a branch of Operational Research dealing with finding optimal results in complex scenarios, including various indicators, conflicting objectives, and criteria. Due to the flexibility for decision-makers to take decisions while considering all the criteria and objectives simultaneously, MCDM/A approaches have significant applications in several research fields, including management, engineering, science, and business.

As a result of growing interest by academicians and consultant firms in this subject, an increasing number of scientific and technical documents have been published from 2010 to 2020. By 2009, 4,606 scientific documents on MCDM/A had been published and indexed in the Scopus database, while in the last two decades the number of articles grew to 19,671 documents.

Although MCDM/A contributions to sustainable development issues have been highlighted in some systematic literature reviews and bibliometric analysis, to the best of our knowledge, no advanced bibliometric analysis and science mapping approaches (Noyons, 1999) has been performed that focused on the whole sustainable development research area, and decisions addressed resource mobilization, at MCDM/A approaches, country contributions, research area application or document level.

The findings presented in this dissertation can help policymakers, researchers, and practitioners by providing directions about MCDM/A applications in various contexts concerning sustainable development and SDGs achievements within the 2030 Agenda framework. Policymakers can better explore MCDM/A applications to prioritize projects and programs for SDGs achievement and define public policies addressed to the 2030 Agenda implementation in different contexts. Besides, public and private organizations from diverse sectors can replicate and improve existing MCDM/A models to enhance their strategic decision-making processes regarding resource allocation to corporate strategies associated with sustainable development.

This dissertation is part of the research line “Strategic Management of Innovation and Sustainability” of the Graduate Program in Metrology (PósMQI) of the Pontifical Catholic University of Rio de Janeiro (PUC-Rio).

1.1. Research problem definition

The research problem was formulated based on the following assumptions:

(i) SD is the overarching paradigm of the United Nations. The 1987 Bruntland Commission Report described the concept of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (United Nations, 1987);

(ii) All SDGs' achievements require decision-making processes, usually in complex contexts, considering multiple criteria, synergies, and trade-offs between objectives in a multi-stakeholder approach;

(iii) Due to the flexibility for decision-makers to take decisions while considering all the criteria and objectives simultaneously, MCDM/A have been applied in several research fields for several decades, and more recently in studies concerning SD issues;

(iv) During the literature review and documentary analysis covering the 2000-2020 period, research gaps could be identified addressed to bibliometric analysis of MCDM/A applications to SD issues, especially using a longitudinal science mapping approach.

Thus, the guiding research questions could be formulated as follows:

(i) "How to identify past research findings and present evidence-based insights?";

(ii) "How to represent evolutionary pathways and scientific roadmaps highlighting multicriteria decision-making methods for sustainable development?";

(iii) "How to show shifts in the boundaries of the focused MCDM/A methods applied to SD issues by revealing their interactions?".

1.2.
General and specific objectives

Aligned with the guiding research questions, the dissertation's general objective is to identify and visualize evolutionary pathways and build a scientific roadmap focusing on multicriteria decision-making methods applications for sustainable development issues by applying science mapping bibliometric analysis in various dimensions (e,g., document level, authors' level, countries' level, MCDM/A methodological approaches, and application areas).

In specific terms, the dissertation attempted to:

- Analyze past research findings and present evidence-based insights;
- Identify and visualize evolutionary pathways and scientific roadmaps highlighting multicriteria decision-making methods for sustainable development;
- Identify shifts in the boundaries of the focused MCDM/A methods applied to SD issues by revealing their interactions.

1.3.
Methodology

According to the taxonomy proposed by Vergara (2002), the research can be considered descriptive, methodological, and applied (as to the outcomes) and is classified as predominantly quantitative.

Figure 1.3 presents the research design, highlighting its components and methods, according to three main phases: (i) exploratory and descriptive; (ii) applied research; and (iii) conclusive. As for the mode of investigation, the methodology comprises:

- Bibliographic and documentary research on the central themes of the research, as indicated in the exploratory and descriptive research phase of figure 1.3;
- Comparative analysis of previous systematic literature reviews and bibliometric analysis studies on the MDCD approaches in sustainable development;
- Documentary and empirical research related to data gathering from academic articles in specialized databases, such as Web of Science, Scopus, and Dimensions databases;
- Bibliometric study strategy elaboration based on text mining and analysis state-of-the-art, as well as proceeding with the choice of techniques and software to be used;
- Collection of academic production data, application of adherence criteria filters, removal of missing values, text processing and indicators creation for further analysis;
- Descriptive statistical analysis to characterize the academic production of MCDM/A approaches in SD (according to the application areas, methodologies employed, and country collaboration);
- Application of science mapping techniques, such as network analysis, cross correlation matrix, longitudinal science map analysis, and co-occurrence matrix in order to verify the behavior of this research field in the analyzed years and to evaluate future trends.

The development and the expected results in each phase can be visualized in figure 1.3 (next page).

1.3.1. Exploratory and descriptive phase

This phase started with bibliographic and documentary research covering the period from 2010 to 2020, intending to raise conceptual works and reference documents to delimit the research's central theme - 'MCDM/A methods applications to sustainable development issues'. In sequence, the bibliographic review was extended to comparatively analyze the scopes and methods of MCDM/A adopted in the empirical studies of sustainability or sustainable development, especially of the systematic literature reviews and bibliometric studies of these areas, and to identify gaps be filled by this research. The theoretical framework was a conceptual orientation for the research, attending to compose the specialized vocabulary and organize the knowledge on this research's main subjects.

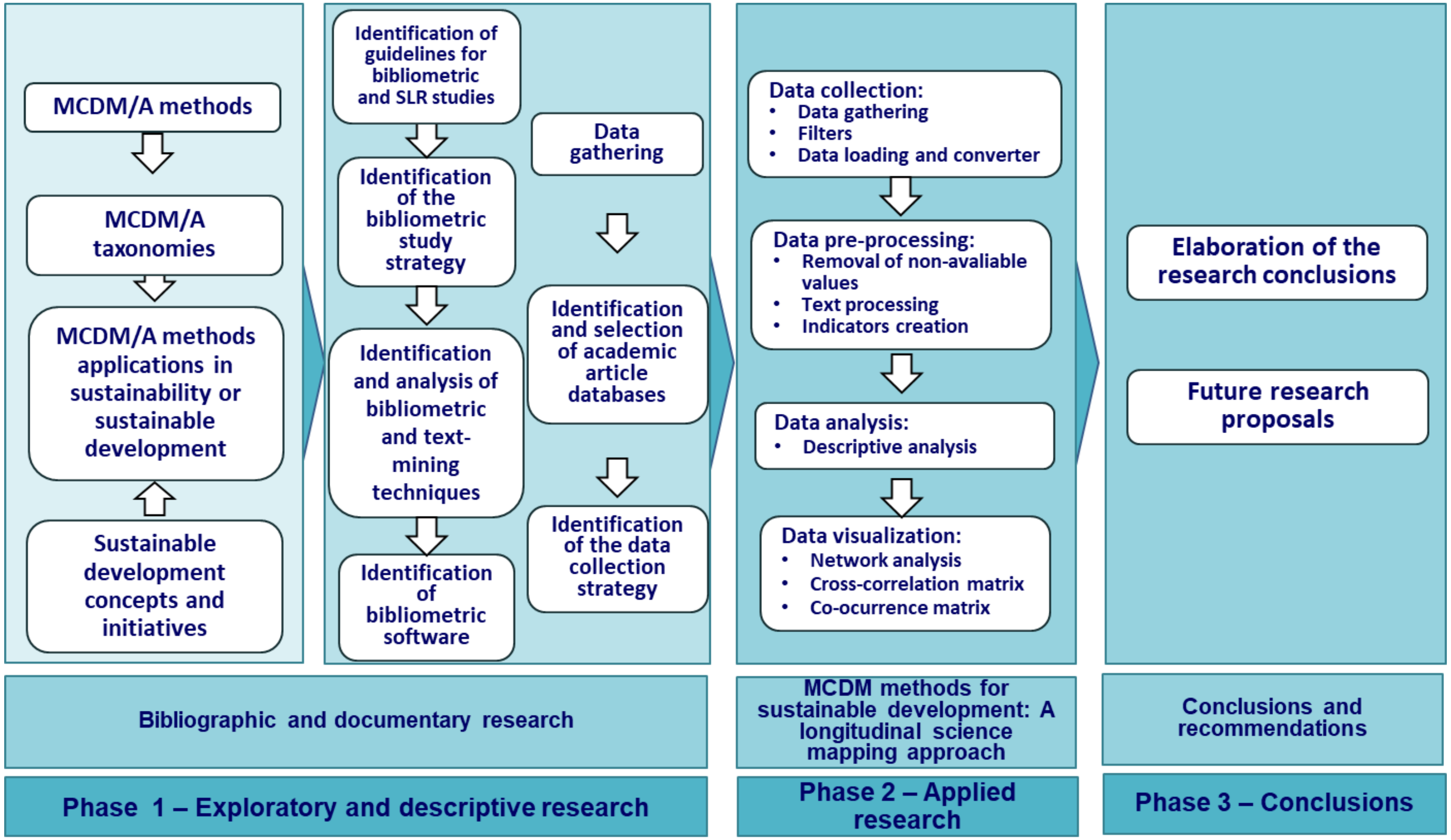

Figure 1.3 – Research design

The literature review and documental analysis evidenced that SD achievements require decision-making processes, usually in complex multi-stakeholder contexts, considering multiple criteria, synergies, and trade-offs between objectives.

In this exploratory and descriptive phase, the lack of scientific studies that have analyzed MCDM/A contributions to SD issues with advanced bibliometrics or that focused on the whole SD area was evidenced. Previous work was restricted to elemental analysis, mostly with descriptive statistics, and focused on SD subthemes, like energy, water, and urban nexus.

The bibliographic research also included the analysis of data gathering from the main databases of peer-reviewed scientific literature (E.g., Web of Science, Scopus, and Dimensions), and the definition of the data collection strategy, based on the major themes of this research. Singh et al. (2020) founds that these bibliographic database are at diferent extremes on the scale of exhaustivity and selectivity. They argue that Web of Science has the most selective journal coverage, especially in life sciences, physical sciences, and technology area, while Scopus cover the same areas but with more journals than WoS. On the other hand, Dimensions appears to have a significantly better coverage of social sciences and arts & humanities and provides a much wider and exhaustive coverage in journals. Another theme included in the exploratory phase was bibliometric study strategies based on text-mining and analysis' state-of-the-art techniques, software, among other bibliometric methodological aspects. Figure 1.4 (next page) presents a general and schematic overview of this first phase results in the form of a conceptual research map.

1.3.2. Applied research phase

In the applied research phase, bibliometric analysis was conducted following these steps: (i) bibliometric study design, including the choice of the bibliographic database; (ii) data collection; (iii) data analysis; and (iv) data visualization.

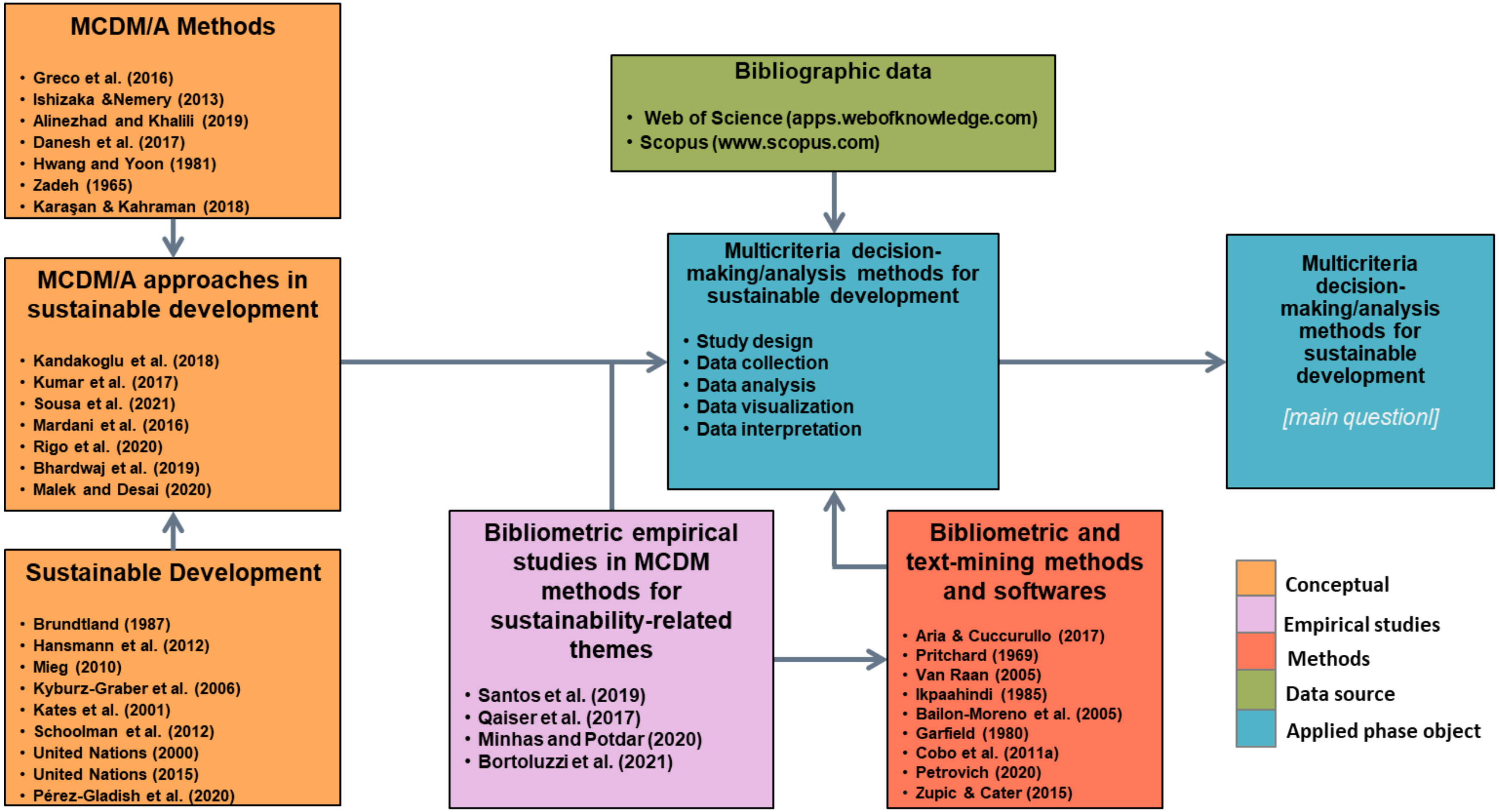

Figure 1.4 – Research conceptual map

The data collection phase comprised: (i) data gathering in Web of Science, which was the selected database for the purpose of this research amongst the databases of peer-reviewed scientific literature explored in the first phase; (ii) application of defined adherence criteria filters; and (iii) data loading and conversion to the chosen bibliometric software. Then, the obtained data was pre-processing with the removal of non-available or missing values, tokenization, stemming, and the creation of quantitative indicators for further analysis. Next, the data were analyzed using descriptive statistical analysis to characterize the academic production of MCDM/A approaches in SD and sustainability (according to the research areas in which they were applied, adopted methodological approaches, authors and sources, and country collaboration). The data visualization phase proceeds, using network analysis, cross-correlation matrix, and co-occurrence matrix to visualize the structure of knowledge representing relations among concepts or words in a set of publications.

1.3.3. Conclusive phase

In the third phase, the main conclusions were addressed to the guiding research questions. The implications for ongoing, consistent policy were discussed, and a set of suggestions for future academic studies was proposed in the last chapter of the dissertation.

1.4. Structure of the dissertation

The dissertation is structured in six chapters, including this introduction.

In chapter 2, the basic concepts related to sustainable development, and MCDM/A methods, are presented. Also, this chapter presents the conceptual works and reference documents to delimit the research's central theme - 'MCDM/A methods applications to sustainable development issues' attending to compose the specialized vocabulary and organize the knowledge on this research's main subjects. The previous bibliometric studies on this subject are presented and discussed in light of the guiding research questions. Research gaps could be evidenced after this analysis.

In chapter 3, the fundamentals for bibliometric analysis are presented, such as the bibliometrics' laws, bibliographic data, text mining, science mapping, bibliometric workflows, and bibliometric analysis software.

Chapter 4 presents the materials and methods to be used, according to the bibliometric workflow, divided into four phases: (i) bibliometric study design, including the choice of bibliographic database; (ii) data collection; (iii) data analysis, and (iv) data visualization.

In chapter 5, the results of the analyzes are presented and discussed, according to the previously mentioned phases, at the: (i) scientific production; (ii) author profile analysis; (iii) country contributions; (iv) document level analysis; (v) MCDM/A methodological approaches; (vi) source analysis; (vii) MCDM/A applications by research area.

Finally, in chapter 6, the research conclusions are formulated, and proposals for future studies are addressed, such as natural developments and the deepening of relevant aspects that emerged from this dissertation.

2
Multicriteria decision-making approaches for sustainable development and sustainability issues

Before starting the discussion about multicriteria decision-making approaches in sustainable development, it is necessary to present the basic concepts regarding MCDM/A methods, including their proposed taxonomies, as well as the notions behind the use of fuzzy set theory and sensitivity analysis in a multiple criteria analysis. Also, it is essential to introduce the sustainable development concepts and the global initiatives through the years.

This chapter reviews the literature concerning sustainable development initiatives, MCDM/A methods and taxonomies, and MCDM/A approaches in SD. In this last point, it is also presenting a comparative study of the systematic literature reviews and bibliometric analysis about the central theme of this research.

2.1.
Sustainable development initiatives

According to the document "Our Common Future" (Brundtland, 1987), adopted by the World Commission on Environment and Development in 1987, sustainability implies an integrative concept that includes environmental, economic, and social aspects, so these three aspects are often referred to as the three pillars of sustainability.

Elkington (1994) states that the social and economic dimensions of the agenda – which had already been flagged in 1987’s Brundtland Report (1987) – would have to be addressed in a more integrated way if real environmental progress was to be made, so he coined the phrase "triple bottom line" (TBL) as his way of measuring performance in corporate America. The idea was that a company can be managed in a way that not only makes money but which also improves people's lives and the planet. The triple bottom line aims to measure the financial, social, and environmental performance of a company over time. The TBL consists of three elements: profit, people, and the planet, and the TBL theory holds that if a firm looks at profits only, ignoring people and the planet, it cannot account for the full cost of doing business.

These three dimensions have been denoted as pillars of sustainability, which reflect that responsible development requires consideration of natural, human, and economic capital. However, approaches aiming to balance these three pillars have been criticized since they involve different types of values (e.g., biodiversity, beauty of landscape vs. costs, profits vs. equity, health and cultural values, etc.) that are not directly commensurable relative to each other (Mieg, 2010). Furthermore, controversial interests of different stakeholders frequently conflict within a single pillar of sustainability (i.e., social conflicts; economic conflicts; conflicts over environmental issues; or preferences), and therefore balancing their interests regarding one pillar is sometimes more in the foreground than to balance social, economic, and environmental aspects (Kyburz-Graber et al. 2006). The metaphor of balancing the three pillars does not appropriately account for the complex interrelationships between human activities and the environment as conceptualized in theories on human–environment systems (Kates et al., 2001; Schoolman et al., 2012)

The United Nations have adopted sustainable development as a guiding principle for economic, environmental, and social development that aspires to meet 'the needs of the present without compromising the ability of future generations to meet their own needs' and an 'equitable sharing of the environmental costs and benefits of economic development between and within countries'.

In September 2000, the UN General Assembly adopted the Millennium Declaration (United Nations, 2000), establishing a global partnership of countries and development partners committed to eight voluntary development goals to be achieved by 2015. Representing ambitious moral and practical commitments, the Millennium Development Goals (MDG) (figure 2.1) called for action to: (i) eradicate extreme poverty and hunger; (ii) achieve universal primary education; (iii) promote gender equality and empower women; (iv) reduce child mortality; (v) improve maternal health; (vi) combat HIV/AIDS, malaria and other diseases; (vii) ensure environmental sustainability; and (viii) develop a global partnership for development. There has been an unprecedented mobilization of resources around MDG-related activities across a broad spectrum of global and national initiatives, and the development community has convened regularly to assess progress.

Figure 2.1 – Millennium Development Goals
Source: United Nations (2000).

In September 2015, the UN General Assembly proposes the 2030 Agenda (United Nations, 2015), that comprises 17 Sustainable Development Goals (SDGs) as described in the introductory section, and 169 global targets, all oriented to a systemic vision for a better and sustainable world.

A fundamental issue in implementing the UN 2030 Agenda in different contexts refers to the systemic analysis of global targets' interactions, considering the context-specific understanding of these interactions within a long-term vision. Another critical issue is how to apply and combine multicriteria approaches to provide a consistent analysis for evidence-based decision-making on the SDGs and respective global targets.

Pérez-Gladish et al. (2020) suggest that exponential increase in economic activity and high consumption levels have hindered long-term planning and made sustainable management across different areas more difficult. Therefore, it has become increasingly necessary to combine the interests of the various stakeholders involved in – or affected by – long-term planning measures to achieve a balance between their needs, those of the environment and future generations, and the need for economic development.

As highlighted by Kumar et al. (2017), with the increase in the complexity and multiplicity of SD issues, single-objective optimization or analysis is no longer a general approach. MCDM/A is considered an evaluation structure to solve environmental, socio-economic, technical, and institutional barriers involved in energy planning. MCDM/A has become popular in energy planning as it enables the decision-maker to give attention to all the criteria available and make an appropriate decision as per the priority. Since multiple dimensions govern a perfect design, thus a good decision-maker, in certain situations, may look for the parameters like technical or economical that can be compromised. MCDM/A helps a decision-maker who quantifies particular criteria based on their importance in the presence of other objectives.

Nevertheless, all SDGs' achievements require decision-making processes, that will be introduced in the next section, usually in complex contexts, considering multiple criteria, synergies, and trade-offs between objectives. Accordingly, the request for methods to assess future risks and support decision-making for sustainability has increased time after time.

2.2.
MCDM/A methods and taxonomies

MCDM/A methods aim to provide a choice, ranking, description, classification, and sorting of alternatives based on a set of decision criteria. Accordingly, an MCDM/A method comprises four stages: (i) determining the relevant criteria and alternatives; (ii) weighting the importance of each criterion concerning the goal and determining thresholds and other preferences if needed; (iii) rating the preference of each alternative concerning criteria; (iv) and aggregating the overall scores of alternatives using either scoring or outranking methods.

As a subfield of Operations Research that deals with the evaluation of a set of options in terms of multiple, usually conflicting decision criteria, MCDM/A approach is especially useful for SD decision-making problems for at least three reasons (Greco, Ehrgott, and Figueira, 2016; Ishizaka and Nemery, 2013). First, it is possible to concurrently consider the economic, social, and environmental impact of alternatives in the decision-making process. Second, MCDM/A approach offers the ability to process quantitative and qualitative assessments of alternatives that are common in SD contexts. Each alternative assessment can be quantitative (evaluated on a ratio or interval scale) or qualitative (evaluated on an ordinal scale or using linguistic variables). Furthermore, SD decisions involve multiple stakeholders with different and ultimately conflicting points of view.

Although managing MCDM/A methods in such contexts might be time-consuming, such approaches make it possible to reach a consensus so that the final decision is less questionable and more sustainable in the long-term horizon.

Alinezhad and Khalili (2019) stated the following definitions of MCDM/A that are necessary to be considered:

- Alternative: In this methodology, there are several predetermined, limited, and independent alternatives, and each of them satisfies a level of the desired attributes of the decision-maker;
- Criterion: The criterion is the basis for evaluation, which means measuring the effectiveness rate and is divided into the objective and attribute;
- Objective: It is something pursued until its final achievement;
- Attribute: It is the property that should be in an alternative. Depending on the idea of the decision-maker, each alternative is associated with several relevant attributes;
- Decision matrix: A matrix with the number of the alternative versus the number of attributes represents the value of alternatives for each attribute;
- Positive attributes: They refer to the attributes with positive desirability from the decision-makers' perspective; namely, their more significant amount is more favorable. Positive attributes are usually as the profit, income, or productivity;
- Negative attributes: Attributes with negative desirability from decision-makers' perspective mean that their lower amount is more desirable to the decision-maker. Negative attributes are usually as loss or cost;
- Non-compensatory attributes: The attributes in which the advantage of a desired value cannot cover the disadvantage of an undesirable value in an attribute in another attribute;
- Compensatory attributes: These attributes can interact with each other; in other words, the disadvantage of an undesirable value in an attribute can be covered by the advantage of a desirable value in another attribute;
- Independent attributes: Attributes which are absolutely uncorrelated to the other attributes;
- Dependent attributes: Attributes which are correlated to at least one of the other attributes;
- Quantitative attributes: Attributes with a unit of measurement, which are expressed numerically and are measurable;

- Qualitative attributes: Attributes usually without a unit of measurement which cannot be expressed numerically and are immeasurable.

Many attempts have been made to classify MCDM/A methods into taxonomies. One of the most used taxonomy is proposed by Hwang and Yoon (1981), who have classified the MCDM/A methods into two categories: multi-objective decision-making (MODM) and multi-attribute decision-making (MADM). The MODM category has been widely studied using mathematical programming methods with well-formulated theoretical frameworks. MODM methods have decision variable values determined in a continuous or integer domain with either an infinitive or a large number of choice alternatives, the best of which should satisfy the DM constraints and preference priorities. On the other hand, MADM methods have been used to solve problems with discrete decision spaces and a predetermined or limited number of choice alternatives. The MADM solution process requires inter and intra-attribute comparisons and involves implicit or explicit tradeoffs (Hwang and Yoon, 1981).

Another taxonomy that is very widespread in the field of MCDM/A approaches and accommodates their advancements and evolution was proposed by Danesh et al. (2017). This taxonomy expands the previous proposed by Hwang and Yoon (1981) by adding a classification for the most used decision-making methods, not limited to MCDM/A methods. In another words, in addition to the MCDM/A methods, this taxonomy includes for example artificial intelligence (AI). Danesh et al. (2017) classify MCDM/A methods in: (i) utility-based; (ii) outranking; (iii) compromise; and (iv) other MCDM/A methods.

Utility-based methods, also known as multi-attribute techniques, compensatory methods, or performance aggregation-based methods, aims to allocate a utility amount to every alternative, considering uncertainty and providing options for the alternatives to communicate with each other. These methods do not consider choices to be mutually independent and tend to be more user-friendly than other MCDM/A methods.

The compromise methods are an interactive MCDM/A approach that drivers by aggregating features that provide bonding to the ideal solution and a foundation for discussions concerning decision-making based on the factors' weight.

The outranking methods, also known as partially compensatory or preference aggregation-based methods, asses a set of preferences to determine whether one option is at least as effective as another. These methods do not assume that only one best option is available, and they do not consider the relative levels of importance of under and over performances.

The multi-objective decision-making methods, also known as continuous methods, or mathematical programming methods, simultaneously deal with various targets without having a clear direction as to which refer to performances and which to issues by applying a mathematical optimization solver, expecting to optimize more than one objective function simultaneously.

Finally, the 'other MADM category' are discrete methods that cannot be categorized as utility-based, outranking, or compromise methods, due to their complexities.

It is important to highlight that MCDM/A methods cannot consider the ambiguity and vagueness of selecting, scoring, and weighting unless fuzzy set theory is combined with them to accommodate human judgments' subjectivity as stated by Zadeh (1965), and Karaşan and Kahraman (2018). Also, the use of sensitivity analysis in MCDM/A results can add further value to a given study because it allows decision-makers to judge whether the results are accurate and robust enough to decide on the report of Beldon and Hodgkin (1999), and Breu et al. (2020). Moreover, it provides a means for judging the stability of results when the parameter values are changed.

Table 2.1 shows a list of the most relevant methods applied to SD studies. A brief description is presented below. Previous work published by Alinezhad and Khalili (2019) was the basis for in-depth descriptions of existing methodologies.

The SMART (Simple Multi Attribute Rating Technique) method, introduced in 1986, is a suitable decision-making technique based on qualitative and quantitative attributes. Based on this method, the qualitative attribute is converted to the quantitative attribute, and the effective weight of the alternative is calculated in each attribute. Then, the alternatives are evaluated by calculating the final weight, and the best alternative is selected by providing the rating of other alternatives for the decision-maker.

Table 2.1 – MCDM/A methods

MCDM/A methods	**Ref.**
AHP	Saaty (1980)
TOPSIS	Hwang and Yoon (1981)
ANP	Saaty (2004)
DEMATEL	Chang, Chagn and Wu (2011)
VIKOR	Duckstein and Opricovid (1980)
PROMETHEE	Brans and Vincke (1985)
ELECTRE	Roy (1968)
COPRAS	Zavadskas et al. (1994)
SWARA	Keršuliene et al. (2010)
TODIM	Gomes and Lima (1992)
MAUT	Keeney and Rayffa (1976)
WASPAS	Zavadskas et al. (2012)
ARAS	Zavadskas and Turskis (2010)
MOORA	Brauers (2004)
CRITIC	Diakoulaki et al. (1995)
MACBETH	Bana et al. (1994)
EDAS	Ghorabaee et al. (2015)
SMART	Chou and Chang (2008)
MABAC	Pamucar and Cirovic (2015)
QUALIFLEX	Paelinck (1976)
REGIME	Hinloopen et al. (1983)
EVAMIX	Voogd (1982)
KEMIRA	Krylovas et al. (2014)
ORESTE	Roubens (1980)

The REGIME method was introduced in 1983. In this method, there is no need to convert qualitative attributes to quantitative attributes, and attributes are independent. First, it calculates the superiority identifier and impacts matrix using superiority attributes by representing an attribute in which an alternative is at least as good as the other alternative. Ultimately, this technique introduces the superior alternative using the REGIME matrix and compares other alternatives.

The ORESTE method was introduced in 1980. The decision-maker provides an analyst with an initial ranking of attributes and alternatives for decision making, and there is no need to convert the qualitative attribute into quantitative. First, the position matrix, where the ranking of alternatives is based on the attribute, is formed, and block distances are calculated. Then, the superior alternative is introduced, and the block distance matrix presents the ranking of other alternatives.

The VIKOR (*VIekriterijumsko KOmpromisno Rangiranje*) method, which was proposed in 1998, is one of the compromising methods by finding the closest alternative to the optimal solution using the LP-metric method. In this method, the attribute should be independent, and the qualitative attribute should be converted to the quantitative attribute.

The PROMETHEE I (Preference Ranking Organization Method for Enrichment of Evaluations) method was first introduced in 1986. The providers of this technique have sought to find an essential solution to improve decision-making evaluation. Therefore, it is known as an efficient method. Also, only the partial ranking of alternatives is done. However, in the PROMETHEE II method, a complete ranking of the alternatives is done according to the net flow. In the PROMETHEE III method, the final ranking is done based on the intervals. In these methods, the independence of the attributes is not obligatory.

The QUALIFLEX (QUALItative FLEXible) method was introduced in 1976 and its root dated back to the permutation method. In this technique, every possible ranking of the existing alternatives is examined; namely, ranking the alternatives is evaluated based on the number of permutations, and ultimately, the most appropriate alternatives are chosen for the final ranking. On the other hand, the attribute should be independent, and there is no need to convert the qualitative attribute to the quantitative attribute.

The TOPSIS (The Technique for Order of Preference by Similarity to Ideal Solution) method was introduced in 1981. This method evaluates the performance of alternatives based on the distance from the ideal solution. So, the preferred alternative must have the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution.

The EVAMIX (EVAluation of MIXed data) method, introduced in 1982, is one of the compensatory methods, with two completely different approaches to the quantitative and qualitative attributes, which calculates the total dominance and the rating score of each alternative by performing separate operations on quantitative and qualitative attributes. Then, it introduces the best alternative and ranks the alternatives.

The ARAS (Additive Ratio Assessment) method, which was suggested in 2010, aims to select the best alternative based on several attributes. In this technique, as one of the multiple attribute decision-making methods, the qualitative attributes should be converted to the quantitative attributes, and attributes should be independent to choose the best alternative.

The MOORA (Multi-Objective Optimization Ratio Analysis) method, introduced in 2004, is a compensatory method and is also considered an objective (non-subjective) technique, in which desirable and undesirable attributes are simultaneously used for ranking. Also, attributes are independent.

The COPRAS (COmplex PRoportional Assessment) method was proposed in 1994 and as a compensatory method was used to evaluate the value of both the maximizing and minimizing indexes. The effects of the maximizing and minimizing indexes of attributes on the outcome evaluation are considered separately.

The WASPAS (Weighted Aggregates Sum Product Assessment) method was proposed in 2012. This technique combines Weighted Sum Model (WSM) and Weighted Product Model (WPM). Also, the attributes are independent, and the qualitative attributes are converted to the quantitative attributes.

The SWARA (Stepwise Weight Assessment Ratio Analysis) method was suggested in 2010. This method was done by weighting method, and the relative significance and initial priority of the independent attributes are determined according to the opinion of the decision-maker, and then, the relative weight of each attribute is determined. Finally, the priority and ranking of the attributes are done.

The DEMATEL (Decision Making Trial and Evaluation Laboratory) method, which was introduced in 1971 as a compensatory method, was used to construct a network design to examine the attributes' internal relationships.

The MACBETH (Measuring Attractiveness by a Categorical Based Evaluation TecHnique) method was introduced in 1994. This interactive technique examines alternatives with multi-attribute and opposite objectives. Given that there is no need to convert the qualitative attributes to quantitative attributes, a wide range of qualitative and quantitative attributes are examined.

The AHP (Analytic Hierarchy Process) method was introduced in 1980. This method allows the hierarchizing of a decision problem and performs pairwise comparisons to measure the relative importance of elements at each level of the hierarchy and evaluates alternatives at the lowest level of the hierarchy to make the best decision among multiple alternatives.

The ANP (Analytic Network Process) method was introduced in 1996 as a compensatory method and a generalization of the AHP method in a network form, the independence of the attributes is not obligatory, and a decision-making problem is decomposed into several different levels. The sum of these decision-making levels forms a hierarchy and solves interdependence and the feedback among attributes and alternatives in the real world by considering all types of dependency.

The MAUT (Multi-Attribute Utility Theory) method was introduced in 1976. The simplicity of this technique and great freedom of action of decision-makers make the results of this technique more accurate and realistic. Also, this is a compensatory method, and attributes are independent of each other.

The EDAS (Evaluation based on Distance from Average Solution) method was introduced in 2015. This compensatory method is primarily applied in conditions with contradictory attributes, and the best alternative is chosen by calculating the distance of each alternative from the optimal amount. Additionally, qualitative attributes are converted to quantitative attributes, and attributes are independent of each other.

The ELECTRE (*Elimination et Choix Traduisant la Realité*) methods were first suggested in 1990, and all alternatives are evaluated using outranking comparisons, and ineffective and low-attractive alternatives are eliminated. Therefore, the final ranking of alternatives may be increasingly problematic, and ELECTRE II and ELECTRE III methods are presented to solve this problem. Further, the qualitative attributes should be converted to quantitative attributes.

The MABAC (Multi-Attributive Border Approximation area Comparison) method was introduced in 2015. The basic assumption in this compensatory method is the definition of the distance of the alternatives from the approximate border area. Each alternative can be evaluated and ranked by specifying the difference between the distances. Besides, experts convert the qualitative attributes to quantitative attributes.

The CRITIC (CRiteria Importance Through Intercriteria Correlation) method was introduced in 1995 and was mainly used to determine the weight of the attributes. In this compensatory method, the qualitative attributes should be converted into the quantitative ones in the decision matrix, and the independence of the attributes is not obligatory.

The TODIM method was introduced in 1992. The main idea of this compensatory method is to measure each alternative's dominance degree over other alternatives using the overall value, and alternatives are evaluated and ranked concerning the independence of the attributes.

The KEMIRA (KEmeny Median Indicator Ranks Accordance) method was introduced in 2014. After determining the attributes' priority and weight in two different groups, and in the form of a decision matrix determined by the experts, the final ranking of alternatives is performed. This technique is one of the compensatory methods and requires the conversion of qualitative attributes into quantitative ones.

This section introduced the MCDM/A methods and taxonomies as a basis of further the discussion on applications of MCDM/A approaches in SD issues.

2.3. MCDM/A applications in SD and sustainability issues

Decision-making problems in SD and sustainability contexts are complex because of conflicting decision-making criteria, diverse stakeholder views and values, long-term consequences that must be assessed in an uncertain future, and the inaccuracy of data upon which they are based. MCDM/A methods are suitable tools for dealing with complex sustainable decision problems characterized by multiple conflicting and incommensurable criteria, subjective and ill-structured evaluation processes, uncertainties, and the participation of multiple stakeholders.

Covering the time frame 2010 to 2020 and focusing more specifically on previous studies that employed the systematic literature review (SLR) or bibliometric analysis approaches, a scoping review was conducted by accessing and filtering review articles from the main databases of peer-reviewed scientific literature (e.g., Web of Science, Scopus, and Dimensions). This scoping review aimed to give a comprehensive overview of what has been done in the MCDM/A research field. According to Arksey and O'Malley (2005), a scoping review seeks to present an overview of a potentially large and diverse body of literature regarding a broad topic. It yielded 197 reviews, but only a few were concerned with MCDM/A applications for sustainable development issues (Kandakoglu et al., 2019; Sousa et al., 2021; Santos et al., 2019; Kumar et al., 2017; Qauser et al., 2017; Mardani et al., 2016; Minhas and Potdar, 2020; Bertoluzzi et al., 2021; Rigo et a., 2020; Bhardwaj et al., 2019; Malek and Desai, 2020).

Here, a descriptive overview of the reviewed material was conducted without critically appraising individual studies or synthesizing evidence from different studies, as suggested by Arksey and O'Malley (2005) and Brien et al.(2010).

Kandakoglu et al. (2019) presented a systematic review of the literature on MCDM/A methods, covering 343 articles dealing with decision-making in sustainable development contexts, published in the period from 2010 to 2017. The selected articles were reviewed and categorized by methods used for preference modeling, uncertainty approaches, sensitivity analysis, long-term assessment, and stakeholder involvement. The authors showed that AHP/ANP were the most used among the MCDM/A methods, followed by TOPSIS/VIKOR, ELECTRE, PROMETHEE, and MAUT (Multi-Attribute Utility Theory).

Besides, Kandakoglu et al. (2019) suggested critical factors for developing and implementing multi-criteria decision analysis methodologies to support sustainable decision making, which need to be considered by researchers. These factors encompass: (i) participatory approach; (ii) triple bottom line; (iii) temporal planning; (iv) uncertainty modeling; and (v) theoretical and practically applicable to promote sustainability. Figure 2.2 summarizes and illustrates these principal factors.

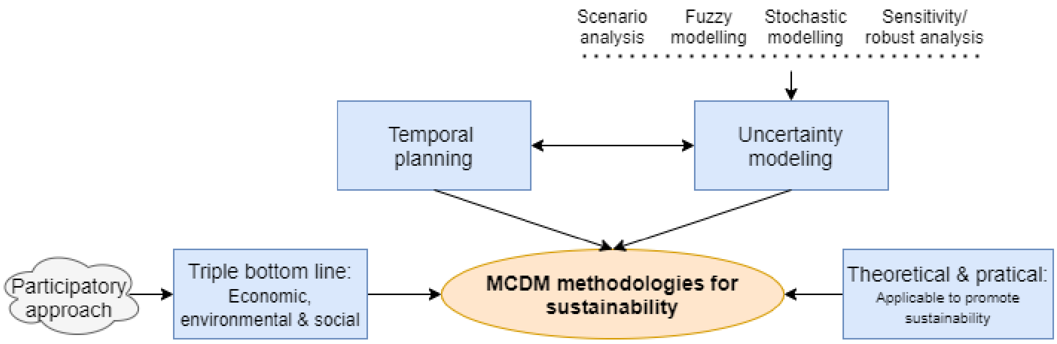

Figure 2.2 – Critical factors for implementing multicriteria decision analysis for sustainability challenges
Source: Kandakoglu et al. (2019).

Kandakoglu et al. (2019) concluded that 65% considered the three dimensions of SD (economic, environmental, and social). The social dimension was the most frequently ignored in these articles; 17% of the articles (60 articles) considered the economic and environmental dimensions without considering any social indicator. Although SD attempts to balance the short and the long terms, 95% of the articles analyzed in this survey did not consider long-term consequences. Also, the results show that 34% of articles dealt with uncertainty in its larger context, including the imprecision of evaluations, which cannot be ignored considering the long-term impact of alternatives. In summary, despite the importance of the temporal impact of decisions in SD contexts, few articles offer an appropriate aggregation framework that can simultaneously account for the long-term effect of the alternatives and model the uncertainty inherent to their evaluations and related preferences. Besides, the authors state three avenues for future research in MCDM/A approaches in SD.

The first research stream consists of integrating the social dimension more regularly when evaluating projects in SD contexts. In particular, decision-making processes will have to examine the social well-being and include stakeholders' participation. Multicriteria participatory approach is a valuable approach to deal with this research issue. The second research avenue consists of considering the long-term evaluation of alternatives in the decision-making process. These long-term impacts must be anticipated and included in the analysis and need to integrate proper uncertainty modeling tools (fuzzy/stochastic modeling and scenario analysis). When dealing with the future, there should be some provision for unforeseen events that might impact the distant ratings of alternatives. The third research avenue involves investigating theoretical work that fosters sustainability without being excessively difficult to implement in practice. Research on sustainability is not relatively easy to implement and may not lead to the desired outcome. Future work's objective should be to develop sequences of theoretical and practical works whose methodologies can converge to be practically applicable to promote sustainability (Kandakoglu et al., 2019).

Sousa et al. (2021) conducted a systematic literature review (SLR) on the MCDM/A applications concerning SDGs achievements in various contexts, covering 143 selected articles published from 2016 to 2020. The reviewed articles were classified into five categories: (i) the 2030 Agenda for Sustainable Development; (ii) multiple SDGs; (iii) economy (SDG 8, SDG 9, SDG 10, and SDG 12); (iv) society (SDG 2, SDG 3, SDG 4, SDG7, and SDG 11), and (v) biosphere (SDG 6, SDG 13, SDG 14, and SDG 15). The results shed light on the main MCDM/A applications to support decisions concerning the 2030 Agenda as a whole, multiple SDGs issues, and single SDGs classified into three categories: economy, society, and biosphere; also, they showed that AHP was the most used among the MCDM/A methods, followed by TOPSIS, DEMATEL, PROMETHEE, and VIKOR techniques. Furthermore, their findings reveal that major studies apply an integration of the MCDM/A methods (in a hybrid way), followed by the combination of MCDM/A and non-MCDM/A methods, mainly to address a national context level.

The results also confirm two methodological trends observed in the MCDM/A literature, i.e., the integration of MCDM/A methods and the combination of MCDM/A with non-MCDM/A methods. Concerning the integration of MCDM/A methods, the authors indicated that the most common is the hybrid AHP-TOPSIS method. The integration of ANP and DEMATEL methods can also be highlighted since DEMATEL is used in more than 70% of the studies in which ANP is employed. In turn, focusing on the articles that combine MCDM/A and non-MCDM/A methods, some studies include MCDM/A methods with SWOT analysis, Delphi technique, Geographical Information Systems (GIS), and Artificial Intelligence (AI) tools. The most popular MCDM/A and non-MCDM/A combinations are those related to the AHP method with GIS. This combination appears in 83% of articles when GIS is used.

In terms of the higher incidence of MCDM/A applications within the 2030 Agenda framework, the category with more MCDM/A applications is ‘Society’, encompassing 56 studies, being 24 studies focused on decision-problems concerning SDG 7 (‘Affordable Energy’). Following this category, ‘Biosphere’ comprises 36 studies, and ‘Economy’ 33 studies. Finally, 18 studies are associated with the 2030 as a whole and with multiple SDGs.

Santos et al. (2019) conducted a systematic literature review and bibliometric analysis on AHP method supporting decision making for sustainable development. In this regard, they analyzed and reviewed 173 manuscripts published between 2014 and 2018, which were indexed by the Web of Science, Scopus, and Science Direct databases. Their findings objectively mapped the advancements in the state-of-the-art of the AHP method’s contributions for sustainable development issues. Implications for research and practice, as well as promising challenges for further research, were presented.

Kumar et al. (2017) have reviewed MCDM/A techniques for renewable energy development. They developed an insight into various MCDM/A techniques, discussed progress made by considering renewable energy applications over MCDM/A methods and future prospects in this area.

Based on 40 journal papers from 2004 to 2015, Qaiser et al. (2017) conducted a review and bibliometric analysis about decision support systems (DSS) for sustainable logistics, which revealed the existing state-of-art in this area and researchers and organizations working to develop emerging subjects in this field. The reviewed papers were classified into three categories, based on their focus on certain dimensions of sustainability, namely ENV (economic and environmental), SOC (economic and social) and SUS (economic, environmental, and social). It is revealed that 27 papers addressed both economic and environmental aspects, however, interestingly only one paper focused on economic and social dimensions. The trend of incorporating all the three dimensions of sustainability started relatively late with a total of only 12 intermittent publications since 2007.

To provide a systematic literature review on the application and use of decision making approaches in regard to energy management problems, Mardani et al. (2016) selected and reviewed 196 published papers, from 1995 to 2015, chosen from the "Web of Science" database. They concluded that hybrid MCDM/A and fuzzy MCDM/A approaches (27.92%) had been used more than other approaches. Besides, AHP and fuzzy AHP approaches (24.87%) had the second rank. ELECTRE, fuzzy ELECTRE, and multicriteria analysis approaches with 25 papers had the third and fourth rank (12.69%). Moreover, TOPSIS, fuzzy TOPSIS, PROMETHEE and fuzzy PROMETHEE held fifth and sixth rank with 10 papers (5.08%).

Minhas and Potdar (2020) have developed a bibliometric analysis about DSS in construction by analyzing 2,185 and 3,233 peer reviewed articles from Web of Science and Scopus databases respectively, covering the period from 2000 to 2016. These articles mainly talk about to select sustainable construction materials in the building and commercial construction projects. This study provides bibliometric insights and future research directions for researchers and practitioners who use DSS by illustrate of the research and technology shifts in the field of construction informatics and help to understand the overall revolutionary impact that information systems (IS) and information technology (IT) have made in the field over the last two decades. The results also indicate ongoing growth in research output in this area since 2007. However, numerous independent studies were found to lack proper cohesion, which is mostly attributed to the fact that the researchers followed their own personal research trajectories in isolation from other researchers.

Bortoluzzi et al. (2021) performed a bibliometric analysis of renewable energy types using key performance indicators (KPI) and multicriteria decision models in 143 peer reviewed papers from Web of Science. The results of this study pointed out: (i) the use of synthesis models rather than overlap models; (ii) the relevance of adding policy and technical indicators beyond those related to the triple bottom line in decision-making; (iii) the important role of MCDM/A models in achieving the Sustainable Development Goals presented in the 2030 United Nations Agenda. Also, this paper describes a guide for future research in the field of the MCDM/A approach in renewable energy technology from a sustainable development perspective.

Based on a review of 163 documents on renewable energy issues associated with MCDM/A methods, Rigo et al. (2020) identified the most common MCDM/A methods in the renewable energy area and the energy problems they solve. The authors identified five categories of problems solved by MCDM/A techniques, namely: source selection, location, sustainability, project performance, and technological performance.

Bhardwaj et al. (2019) investigated how MCDM/A approaches have been employed in energy policy decisions for considering multiple social and environmental objectives. They review 167 articles and concluded that MCDM/A methods can be helpful to the implementation challenges of the SDGs and the Paris Agreement, which create incentives for energy decision-makers to consider development and climate issues simultaneously.

Malek and Desai (2020) conducted a comprehensive descriptive study through a systematic literature review of 541 selected articles (from January 2001 to March 2019) aiming to investigate how sustainable manufacturing research has grown in the last few years. Out of these articles, only 122 (22.55%) studies are reported with the application of MCDM/A methods which shows limited interest of researchers in ranking and prioritizing the significant factors of sustainable manufacturing. The content analysis identified that AHP/fuzzy AHP is the most utilized MCDM/A method with 30 manuscripts, followed by TOPSIS/fuzzy TOPSIS with 19 and DEMATEL with 16 publications.

This scoping review provided the basis for the study of MCDM/A applications in SD issues and allowed to identify gaps in the literature, namely: no advanced bibliometric analysis has been performed considering SD research area at MCDM/A approach, country contribution, research area application or document levels. In the next chapter, the bibliometric analysis fundamentals to investigate MCDM/A applications in SD issues will be presented.

3
Bibliometric analysis and science mapping

Bibliometrics refers to the “quantitative analysis of bibliographic data” and Noyons (1999) states that it is applied within at least four areas, as follows: (i) performance analysis, in which the performance of scientific research units is evaluated concerning activity, productivity and impact; (ii) information retrieval, in which bibliometric methods are used in the process of information seeking; (iii) Library management, in which bibliometrics is used in the context of libraries (e.g., to manage journal collections); and (iv) science mapping, which is concerned with the analysis and visualization of the structure and development of a scientific field. This research focuses on the last area, i.e., science mapping.

From this perspective, this chapter aims to present the fundamental concepts of the bibliometric analysis, focusing on the bibliometric laws and science mapping.

3.1.
Bibliometric analysis

Pritchard (1969) defined bibliometrics as "the application of mathematics and statistical methods to books and other media of communication". In this way, quantitative methods are used in bibliometrics to make pronouncements about qualitative features of scientific studies. Unlike traditional narrative reviews, which always rely on researchers' experience and knowledge, bibliometrics examines science as a knowledge-generating system (van Raan, 2005) and provides a perspective that can easily be scaled from micro to macro-level (Wallin, 2005). Bibliometrics is different from the ‘Preferred Reporting Items for Systematic Reviews and Meta-analyses’ (PRISMA) proposed by Moher et al. (2009), although both involve more objective analysis methods, which evaluate papers by analyzing data provided from the database more quantitatively and qualitatively.

Hjørland (2013) states that bibliometrics helps recognize candidate terms and organize knowledge by relating scientific papers to their authors, thus indicating their relatedness and semantic differences. In this way, Hicks and Melkers (2013) conclude that this method is an unparalleled opportunity to take advantage of the rich information embedded in scientific research's written products to determine the output and influence of funded scholars.

According to Mryglod et al. (2013), this approach provides a vast map of knowledge from the micro-level (researchers, organizations, and campuses) to the macro-level (countries and continents). These techniques can offer information about the relationship between different research directions among various knowledge structures.

Traditional bibliometric indicators include leading research areas, productive institutions, journals, authors, and corresponding publication volume and citation analysis. Bibliometric techniques can be used as a tool for analyzing research activities and figuring out future research directions in different fields. Citation and content analysis represents the most widely used measures that can show the citation trends in a specific field of knowledge and describe modern research's direction by presenting the most widely used author keywords.

Although bibliometrics is mainly known for quantifying the scientific production and measuring its quality and impact, it is also helpful for displaying and analyzing the intellectual, conceptual, and social structures of research and their evolution and dynamical aspects.

In this way, bibliometrics aims to describe how specific disciplines, scientific domains, or research fields are structured and evolve. In other words, bibliometric methods help map the science (so-called science mapping) and are very useful in research synthesis, especially for the systematic ones.

It is well known that bibliometrics is an academic science founded on statistical methods that can be used to analyze scientific data quantitatively and their evolution over time and discovers information. The network structure is often used to model the interaction among authors, papers/documents/articles, references, keywords, etc. The bibliometric fundamental laws are showed in the next section.

3.2. Bibliometric laws

The bibliometric laws have fundamental importance to the development of bibliometrics, scientometrics, and informetrics fields, and the earliest of these was Lotka's law which provided a relationship between authors and papers (Lotka, 1926). Bradford's law dealt with the dissemination of articles on a scientific subject/field through scientific journals (Bradford, 1934). Zipf's law was concerned with word frequency or occurrences (Zipf, 1949). Although Bradford', Zipf', and Lotka's laws are considered the foundations of the mentioned three fields, some authors consider two other laws, namely: (i) Price's law and (ii) Pareto's law. Based on previous works (Ikpaahindi, 1985; Sengupta, 1992; Wilson, 2001; Glanzel and Moed, 2002; and Weingart, 2004), the bibliometric laws are presented, and their interrelationships are discussed in this section.

3.2.1. Lotka's law

Statistician Lotka (1926) points out that some authors in a field are more productive than other authors and have more publications in the related field. Consequently, Lotka's Law estimates that a small number of authors writes a significant majority of publications in a field.

Empirically, if the authors are arranged according to their productivity in a research area, so the probable conclusion is that most of them publish few works, while only a select portion is highly productive. From Lotka (1926), the expression that related the number of authors to their productivity indicates that the number of authors who publish a certain quantity of works is inversely proportional to these works' square, as shown in equation (1). The $A(R)$ is the number of authors that publish R works, R is the number of works that an author publishes, and $A(1)$ is the number of authors that publish only one work, that is around 60% of the total according to Lotka (1926).

$$A(R) = \frac{A(1)}{R^2} \tag{1}$$

According to Bailon-Moreno et al. (2005), subsequent studies in different subject areas have confirmed the accuracy of the above inverse power expression, although with the exception that the exponent is not always two but rather a variable value. Consequently, Lotka's law is generalized by the equation (2), where *m* is the Lotka exponent.

$$A(R) = \frac{A(1)}{R^m} \tag{2}$$

Ruiz-Baños indicates that the value of the Lotka exponent is related to productivity by a scientific community. Furthermore, it depends on the subject area considered, on the community of scientists studied, and even, when maintaining the above variables constant, on the historical moment.

Lotka's law performs good fits of observed values in the area of low works production. On the other hand, when it approaches very productive authors' points, the fits by regression substantially worsen. Hence, the value of $A(1)$ in equations (1) and (2) is usually inclined to substantial error.

To address this problem, some suggestions have been proposed. The Pao (1985) equation stands out as an equation as a calculation method that improves the results. The algorithm consists of submitting the authors' logarithms and works to linear regression in the usual way. From the slope, the Lotka's parameter is determined and an improved $A(1)$, using decimals for the percent, by the equation (3) where P is an arbitrary value greater than or equal to 20.

$$A(1) = \frac{1}{\sum_{R=1}^{P-1} \frac{1}{R^m} + \frac{1}{(m-1)P^{m-1}} + \frac{1}{P^m} + \frac{m}{24(P-1)^{m+1}}} \tag{3}$$

3.2.2.
Bradford's law

Also known as Bradford's Law of Scattering, Garfield (1980) defined this law as a "distribution or scattering of literature in a particular field or topic across journals".

Mathematician Bradford (1934) proposed this law based on observation and research conducted on Bradford's geophysics publications. The law states that when articles of a specific topic or field in a journal are sorted by exponentially diminishing returns, journals can be divided into core journals publishing in a particular field or topic or multiple groups and regions that involve approximately equal numbers of articles with the core group.

Bradford divided articles into three groups in the bibliography he has formed at the end of his research. If articles in the journals are sorted by diminishing returns, they are divided into a core group that forms publications directly related to the topics and regions with diminishing returns involving an equal number of publications with core groups.

This statement introduces the concept of a nucleus, which coincides, according to Bradford, with the first area resulting from dividing articles of a subject matter given in equal parts. So, Bradford's Law classifies publishing sources into generally three zones, namely: (i) core zone or nucleus, that is the primary sources for a subject; (ii) middle zone or straight zone; and (iii) minor or gross droop zone.

Brookes (1969) argues that frequently researches find not only that the Bradford distribution presents an initial area or nucleus and later a straight fraction, but they may also find an area beyond the straight line in which the number of articles slowly increases, called as the gross droop. Figure 3.1 presents the distribution of the three fractions of an example bibliographic data.

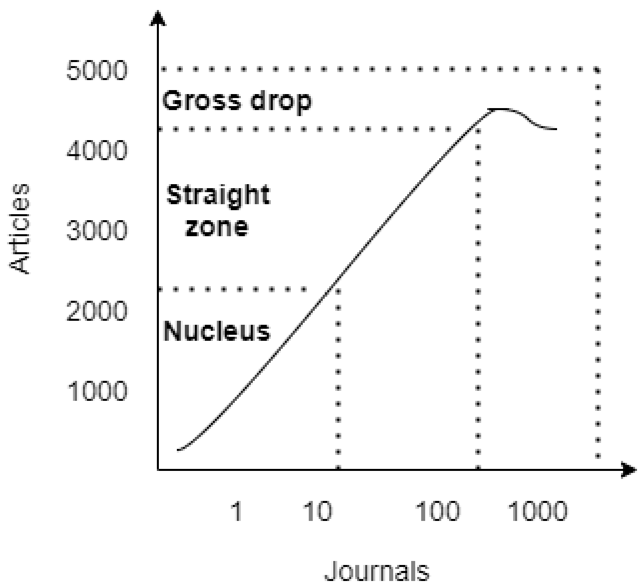

Figure 3.1 – Fractions or zones on the Bradford distribution
Source: Bailon-Moreno et al. (2005).

3.2.3. Zipf's law

The linguist Zipf (1949) proposed this law that consist in rank the frequency of the words from the most frequent words to the least ones by using statistical methods and estimates that the values produced by multiplying frequencies and rank numbers are approximately constant.

Bailon-Moreno et al. (2005) argue that, in natural language text, when the list of all the words is arranged in descending frequency order, the word's rank denotes this word's position in the list, as mentioned earlier. The most straightforward relationship that links the frequency of appearance and the rank lies in equation (4), where F is the frequency of appearance of a word in a text, R is rank, and k_z is the Zipf constant. That is, the frequency is inversely proportional to the rank of the word.

$$F = \frac{k_z}{R} \tag{4}$$

So, if the frequency is represented against rank in a double-logarithmic diagram, a straight line for which the ordinate at the origin is a logarithm of k_z with a slope equal to -1 will be obtained.

Zipft (1949) concluded that humans tend to prefer more familiar words over rarely used ones, guided by the principle of least effort, which favors the common and discourages the uncommon. In general, the most frequent words are also the shortest and most accessible to pronounce.

3.2.4
Other bibliometric laws

Sengupta (1992) argued that Price's square root law has its basis in Lotka's law. Price's law states that half of the publications on a subject are contributed by the square root of the total number of authors publishing in that area.

In addition to that, Pareto's law, also known as the 80/20 law, estimates that 80% of publication parts (like the number of articles and citation) produce 20% of the sources (like journal and author) (Weingart, 2004; Glanzel and Moed, 2002).

This section discussed the fundamental bibliometric laws. Next, the science mapping analysis will be presented and described, including its classifications, analysis unit, and possible interpretations.

3.3.
Science mapping

Science maps, also known as scientographs, bibliometric network visualizations, and knowledge domain maps, are visual representations of scholarly knowledge's structure and dynamics. According to Cobo et al. (2011a), they are usually generated based on the analysis of extensive collections of scientific documents. They aim to show how fields, disciplines, journals, scientists, publications, and terms correlate (Börner et al., 2005; Chen, 2013; Rafols et al., 2010; Small, 1999; Van Raan, 2019).

Science mapping is the collection of methods and techniques that have been developed for generating science maps. As Van Raan (2019) explains, science mapping has a long tradition in bibliometrics and scientometrics, i.e., the quantitative studies of science. Moreover, Börner et al. (2005) pointed out that it has increasingly become an interdisciplinary area in the last years, witnessing significant contributions from data science, where science mapping belongs to the more significant and increasingly important area of information visualization.

With several applications, this methodology serves to determine what factors define the emergence of new scientific fields and the development of interdisciplinary areas (Leydesdorff and Goldstone, 2014) and helps answer questions such as: (i) What are the main topics within a particular scientific domain?; (ii) How do these topics relate to each other?; (iii) How has a specific scientific domain developed over time?; and (iv) Who are the key actors (researchers, institutions, journals) of a scientific field?.

Petrovich (2019) indicates that science maps, especially the global maps, also known as atlases of science, can help classify the sciences by showing their mutual relationships (e.g., by showing the citation flows between fields). In this sense, science maps are valuable tools in knowledge management and have been used to build classification systems with a bottom-up approach as applied by Waltman and van Eck (2012), and at the same time, the application of science maps is not restricted to knowledge management but extends to the sociology of science and science policy. Nevertheless, Petrovich (2019) also indicates that standard methods of science mapping are not based on and do not result in semantic relationships between categories but association measures between units of analysis. In this way, the closest to semantic relations that standard science mapping approaches can produce is the relation of inclusion obtained by clustering techniques, in which higher-order clusters include lower-order clusters.

3.3.1. Science mapping classification

Petrovich (2020) indicates that science maps can be classified into different types depending on the kind of data and the kind of network they are based on. In principle, any feature of the scientific enterprise that can be represented in relational terms, i.e., as a network of nodes and links, can generate a science map.

According to Petrovich's classifications, the citation-based maps, the units of analysis (the nodes) are publications or aggregates of publications (like journals or authors), and the relationships between them (the links) are citations or association measures based on citations (bibliographic coupling and co-citation). On the other hand, in the term-based maps, the units of analysis are textual items (themes, keywords, or terms), and the relationships are co-occurrence frequencies (e.g., the number of times two keywords are used together in a set of publications). In the same way, co-authorship maps units are the authors, and the links are the number of co-authored publications. Last but not least, in interlocking editorship maps, the units are the journals, and the links are the number of persons shared between the editorial boards of two journals). In addition to these, there are also science maps based on patent data and geographic maps of science.

Garfield (1994) also introduced the concept of longitudinal mapping. In longitudinal mapping, a series of chronologically sequential maps can be used to detect advances in scientific knowledge. Analysts and domain experts can use longitudinal maps to forecast emerging trends in a subject domain. Since domain visualizations typically identify key works, they enable the novice to become familiar with a field through the easy location of landmark articles and books, as well as members of invisible colleges or specialties.

3.3.2. Science mapping temporal analysis

There are several options to include the dimension of time into science maps. Cobo et al. (2011a) proposed a longitudinal mapping analysis based on the publication year of the bibliographic records, subsets of publications belonging to different time spans, which are created, and each of them is mapped separately (in any technique). Each map represents a sort of photograph of the field under investigation in a certain time span and allows visualizing the field's temporal dynamics.

Besides, White and McCain (1998) represented on the same map the trajectories of the units that change their relative position in subsequent maps.

Leydesdorff and Schank (2008) animated the map instead of a static visualization by creating a short movie to interpolate the network's layouts in different moments.

Petrovich (2020) argued that the first maps that include the temporal dimension used a timeline to represent time. For historiographs by Garfield (2004), each node of the network (classically, a publication in a citation network), in this approach, is linked to a specific point in time (e.g., the publication year). The visualization uses two dimensions: (i) the vertical one is the timeline, whereas (ii) the horizontal one is used to represent the items' relatedness.

Rosvall and Bergstrom (2010) used an alluvial map to represent timeline-based visualizations in another form. Starting from different phases in the evolution of a network, the networks relative to each phase are divided into different clusters, and then the trajectories of corresponding clusters in subsequent networks are visualized as a stream. The fusions and fissions of clusters over time are visualized as multiple streams flow over time.

3.3.3.
Science mapping interpretation

As unsupervised clustering models, the interpretation of science maps typically involves close interaction with experts of the mapped domain, i.e., experienced researchers with a deep, albeit qualitative, knowledge of the structure of the target field (Tijssen, 1993). Interpreting a science map means linking the map's visual and geometrical properties to substantive features of the mapped area or field, providing further insights and helpful knowledge for policy proposals.

Petrovich (2020) suggested that clusters of co-cited publications can be mapped to scientific sub-specialties or research topics, bibliographic coupling networks can be interpreted as the research fronts of scientific specialties, co-authorship networks as invisible colleges of scientists, and clusters of journals sharing many editors as structures of academic power.

Petrovich (2020) also expressed that a critical aspect to consider in the interpretation is the analysis level of the science map, i.e., the units of analysis and the type of relationship displayed by the map, because units and relations affect the scale of the map and the dimension of the scientific enterprise that is captured. Lucio-Arias (2009) reinforced that term-based maps and citation-based maps using the document as the unit of analysis highlight the epistemic or cognitive dimension of science, what philosophers of science call the "context of justification". Co-authorship maps, author co-citation analysis, and interlocking editorship maps, on the other hand, shed light on the social network underlying science, i.e., the "context of discovery" in philosophical terms. When the source is selected as a unit of analysis, the communication system is highlighted (Cozzens 1989). Hence, the different science mapping methodologies offer a partial representation of the multi-dimensional nature of science and scholarship that should be considered during the interpretative phase.

Chen (2017), Boyack and Klavans (2019), and Scharnhorst et al. (2012) have employed general theories and models of the structure and dynamics of science to support their interpretation of science maps, providing comprehensive and interpretative insights.

In the network graphs, the elements are represented by vertices or nodes and their connections by edges. Statistical measures are helpful for the intended network analysis, like the centrality, that measures the intensity of the connections of a given cluster, and it can be calculated by the average value of the connections between the nodes. In other words, centrality aims to find the most critical nodes in a network.

The most common metrics for measuring centrality are: (i) weighted degree centrality – the number of a node's interactions weighted by each edge's strength. A high value indicates the central role of a node in connecting widely with others; (ii) weighted in-degree centrality – a node receiving influences from others targets with a positive value for reinforcing effects and negative value for conflicting effects, weighted by the strength of each edge; (iii) weighted out-degree centrality – a node exerting influences to other nodes with a positive value for reinforcing effects and negative value for conflicting effects, weighted by the strength of each edge; (iv) eigenvector centrality – high eigenvector value indicates the central role of a node in both connecting with other targets and strategically linking with determinant targets; (v) betweenness centrality – is the number of times a node is present in the shortest path between two other nodes, higher values indicates the central intermediate role of a target in linking unconnected nodes; and (vi) closeness centrality of a node – is the average length of the shortest path from the node to all other nodes. A low value indicates the central role of a node in connecting closely with others and therefore, directly influence others. Furthermore, the weighted metrics are based on the number of edges for a node pondered by the weight of each edge (in, out, or both).

3.4. Bibliometric workflow

Börner et al. (2003) proposed a general science mapping workflow, as shown in figure 3.2 along some techniques using in these steps, namely: (i) data extraction; (ii) definition of unit of analysis; (iii) selection of measures; (iv) calculation of a similarity between units; (v) ordination, or the assignment of coordinates to each unit; and (vi) use of the resulting visualization for analysis and interpretation. Steps four and five of this process are often distilled into one operation, described as data layout.

Zupic and Cater (2015) proposed a standard workflow, based on Börner et al. (2003), which consists of five stages: (i) study design; (ii) data collection; (iii) data analysis; (iv) data visualization; and (v) interpretation.

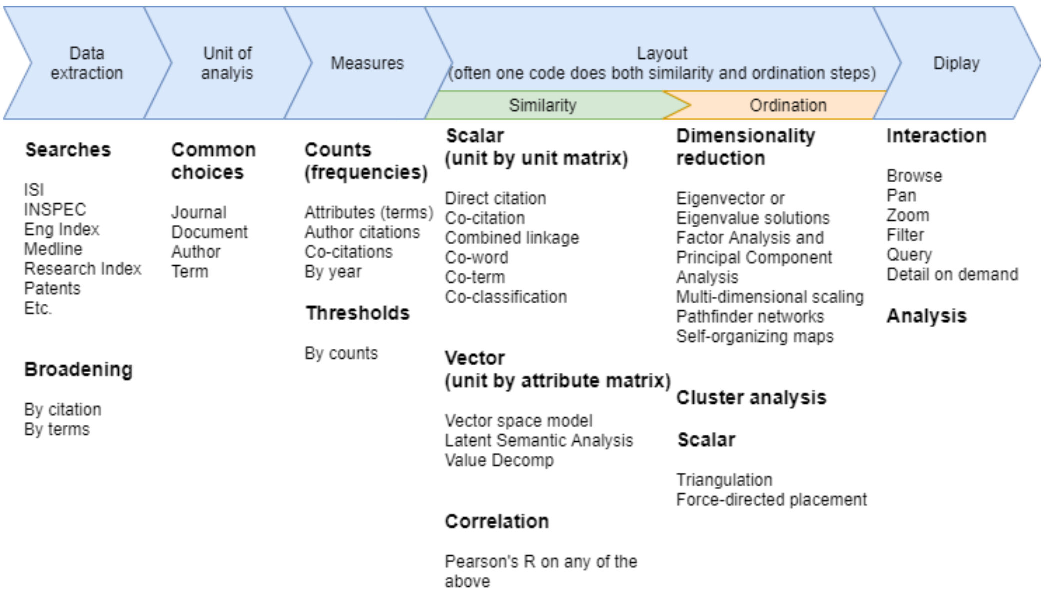

Figure 3.2 – Process flow for mapping knowledge domains
Source: Adapted from Börner et al. (2003).

Aria and Cuccurullo (2017) summarized these stages, as following. In the bibliometric study design section, the research questions are defined, and the appropriate bibliometric methods to answers these questions are described. Also, the analyze timespan are also defined based on previous objectives. The combination of an advanced bibliometric software, analytical capacity, and data processing provide a deep and vast methodological framework for dealing with different types of questions regarding the production of a particular research field.

Bibliographic collection metadata summarizes information about a scientific document and can be obtained by querying a bibliographic repository, such as Scopus; Web of Science; Science Direct; Dimensions; PubMed; Cochrane Library; Google Scholar; and go on.

In the data collection phase, the data source is defined or constructed, then the search strategy, and lastly, some filters, such as publication area; timespan; language; document type, etc., aiming to refine the obtained outputs are chosen. In the second step, the bibliographic data are exported and converted to a suitable format for the employed bibliometric software. Third, the data is pre-processed, to normalizing the database, handling noise, stemming, word tokenization and removing some incomplete entries, improving the data reliably, for example, cited references can contain multiple versions of the same publication; and the same keyword can be spelled in different ways that are not advantageous for the completeness of the analysis. Finally, at the fourth step, the processed database is loaded to any bibliometric or analysis tool.

As fundamental concepts of text-mining, stemming is the process of reducing inflected (or sometimes derived) words to their word stem, base, or root form, while word tokenization is splitting a large sample of text into words. This is a requirement in natural language processing tasks where each word needs to be captured and subjected to further analysis like classifying and counting.

The data analysis step employs one or more bibliometric or statistical software tools to perform the previously treated data analysis. Alternatively, scholars can write their computer code to meet their requirements. Data analysis involves descriptive analysis and network extraction using different approaches based on the required output.

Next, in the data visualization, the researcher decides what visualization method will be used on the third step's results and then employ the appropriate mapping software.

The last stage is interpretation, where the researcher interprets and describes their findings mainly with an expert aid. Although bibliometric methods will frequently reveal the structure of a field differently from the classification of traditional literature reviews, they are not a substitute for extensive reading in the field.

The second to fourth stages are typically software-assisted and include different sub-stages. The most commonly used software for these analyses will be presented in the next section.

3.5.
Bibliometric analysis software

Numerous software tools support bibliometric analysis. However, many do not assist researchers in a complete recommended workflow. The most relevant tools are CitNetExplorer® (van Eck and Waltman, 2014), VOSviewer® (van Eck and Waltman, 2010), SciMAT® (Cobo, López-Herrera, Herrera-Viedma, and Herrera, 2012), BibExcel® (Persson,Danell, and Schneider, 2009), Science of Science (Sci2) Tool (Sci2 Team, 2009), CiteSpace® (Chen, 2006), Metaknowledge® (metaknowledge.readthedocs.io), Pajek® (mrvar.fdv.uni-lj.si), and VantagePoint® (thevantagepoint.com). Aria and Cuccurullo (2017) proposes an R package that provides a set of tools for quantitative research in bibliometrics and scientometrics. It is developed in the R language, which is an open-source environment and ecosystem.

CitNetExplorer® and VOSviewer® are two free Java applications, designed by van Eck and Waltman, for analyzing and visualizing citation networks of scientific collections. CitNetExplorer® allows the user to: (i) analyze the development of a research field over time; (ii) identify the core literature on a research topic; and (iii) explore the publication oeuvre of a researcher and its influence on the publications of other researchers. VOSviewer® addresses the graphical representation of bibliometric maps and is especially useful for displaying large bibliometric maps in an easy-to-interpret manner.

SciMAT® is an open-source software tool developed to perform a science mapping analysis under a longitudinal framework. SciMAT® provides three different modules: (i) management of a knowledge base and its entities; (ii) science mapping analysis; and (iii) visualization of the generated results.

BibExcel® is designed to assist a scholar in analyzing bibliographic data or any data of a textual nature formatted in a similar manner. It generates data files that can be imported into Microsoft Excel or any program that accepts tabbed data records for further processing. However, BibExcel® does not include any module to visualize and map the results.

The Science of Science (Sci2) Tool is free software supporting the temporal, geospatial, topical, and network analysis and visualization of bibliographic collections.

CiteSpace® is a free Java application for visualizing and analyzing trends and patterns in scientific literature. It focuses on identifying critical points in developing a field or a domain, especially intellectual turning points and pivotal points.

Metaknowledge® is an open-source Python 3 package for doing computational research in bibliometrics, scientometrics, and network analysis. It can also be easily used to simplify the process of doing systematic reviews in any disciplinary context.

Pajek® is a program package for analysis and visualization of large networks (networks containing up to one billion of vertices, there is no limit—except the memory size—on the number of lines).

VantagePoint® is commercial software for science mapping analysis. Its major strength is reading virtually any structured text content and supporting more than 190 different import filters. Moreover, VantagePoint® includes a tool for visualizing the main bibliometric maps.

Bibliometrix® R-package is an open-source environment and ecosystem developed in R-language that supports a recommended science mapping workflow developed by Aria and Cuccurullo (2017). It combines performance analysis tools with a science mapping approach to analyze a research field and its conceptual thematic areas, themes, and topics, besides its thematic evolution in a given timeframe.

It is interesting to note that these software can be integrated to overcome possible flaws and weaknesses existing in each one. Besides, document databases generally offer online software that analyzes the search results in a less sophisticated and complex way. The bibliometric data will be present in next section.

3.6. Bibliometric data

Many online bibliographic databases, where metadata regarding scientific works are stored, can be sources of bibliographic information, such as Clarivate Analytics Web of Science (WoS) (webofknowledge.com), Scopus (scopus.com), Google Scholar (scholar.google.com), Dimensions (dimensions.ai), and Science Direct (sciencedirect.com). Waltman (2016) argues that they do not cover the scientific fields and journals in the same manner, and hence the choice is not neutral, also, they could display multidisciplinary or specialized paper. As mentioned in the introductory chapter, Singh et al. (2020) founds that Web of Science has the most selective journal coverage, specially in life sciences, physical sciences, and technology area, while Scopus cover the same areas but with more journals than WoS. On the other hand, Dimensions appears to have a signifcantly better coverage of social sciences and arts & humanities and provides a much wider and exhaustive coverage in journals.

These databases can organize a digital collection of references to published scientific literature, including journal articles, conference proceedings, patents, books and so on. They generally contain very rich subject descriptions in the form of keywords, subject classification terms, or abstract. The bibliometric metadata can be extracted through a query, which is a combination of terms (keywords, titles, abstracts, authors, journals, affiliations, language…) linked by Boolean operators.

The query results can be exported using various file extensions, and they are arranged in a semi-structured manner. The field tags from WoS exported metadata is shown in table 3.1 with each item's description.

Table 3.1 – Web of Science fields tag

Field Tag	Description
FN	File Name
VR	Version Number
PT	Publication Type (J=Journal; B=Book; S=Series; P=Patent)
AU	Authors
AF	Author Full Name
BA	Book Authors
BF	Book Authors Full Name
CA	Group Authors
GP	Book Group Authors
BE	Editors
TI	Document Title
SO	Publication Name
SE	Book Series Title
BS	Book Series Subtitle
LA	Language
DT	Document Type
CT	Conference Title
CY	Conference Date
CL	Conference Location
SP	Conference Sponsors
HO	Conference Host
DE	Author Keywords
ID	Keywords Plus®
AB	Abstract
C1	Author Address
RP	Reprint Address
EM	E-mail Address
RI	Researcher ID Number
OI	ORCID Identifier (Open Researcher and Contributor ID)
FU	Funding Agency and Grant Number
FX	Funding Text
CR	Cited References
NR	Cited Reference Count
TC	Web of Science Core Collection Times Cited Count
Z9	Total Times Cited Count
U1	Usage Count (Last 180 Days)
U2	Usage Count (Since 2013)
PU	Publisher
PI	Publisher City
PA	Publisher Address
SN	International Standard Serial Number (ISSN)
EI	Electronic International Standard Serial Number (eISSN)
BN	International Standard Book Number (ISBN)
J9	29-Character Source Abbreviation
JI	ISO Source Abbreviation
PD	Publication Date
PY	Year Published
VL	Volume
IS	Issue
SI	Special Issue
PN	Part Number
SU	Supplement
MA	Meeting Abstract
BP	Beginning Page
EP	Ending Page
AR	Article Number

DI	Digital Object Identifier (DOI)
D2	Book Digital Object Identifier (DOI)
EA	Early access date
EY	Early access year
PG	Page Count
P2	Chapter Count (Book Citation Index)
WC	Web of Science Categories
SC	Research Areas
GA	Document Delivery Number
PM	PubMed ID
UT	Accession Number
OA	Open Access Indicator
HP	ESI Hot Paper. Note that this field is valued only for ESI subscribers.
HC	ESI Highly Cited Paper. Note that this field is valued only for ESI subscribers.
DA	Date this report was generated.

This chapter presented the fundamental of bibliometric analysis, including its bases laws, science mapping approaches, main bibliometric software, bibliometric data sources, and the proposed bibliometric workflow. The next chapter will introduce the materials and methods to be used, according to the presented bibliometric workflow.

4
Materials and methods

This chapter presents the research methodology used to identify and visualize evolutionary pathways and build a scientific roadmap focusing on multicriteria decision-making methods applications for sustainable development issues by applying bibliometric analysis in various dimensions (e,g., document level, authors' level, countries' level, MCDM/A methodological approaches, and application areas).

Science mapping analysis can be carried out with different software tools, as argued by Cobo et al. (2011b) and Aria and Cuccurullo (2017). Here, the Bibliometrix® R-package (https://www.bibliometrix.org), the software VantagePoint® (https://www.thevantagepoint.com), and the software VOSviewer® (https://www.vosviewer.com) were chosen to develop a longitudinal conceptual science mapping analysis, as presented by Cobo et al. (2011b) and Börner et al. (2013).

Bibliometrix® (https://www.bibliometrix.org) was chosen because of its suitable descriptive statistics method and practical science mapping approach to analyze a research field and its conceptual thematic areas, themes, and topics, besides its thematic evolution in a given timeframe, also proven as the most completed software in the science mapping workflow.

As a complementary bibliometric tool, the VOSviewer® (https://www.vosviewer.com) was used to display a science map in different ways, emphasizing specific aspects of the map addressed to answer the research questions. The viewing capabilities of VOSviewer are especially useful for maps containing at least a moderately large number of items, which is the case in this bibliometric study (van Eck and Waltman, 2010).

Finally, the VantagePoint® (https://www.thevantagepoint.com) was used for its vast text processing tool, including data cleaning, steaming, natural language processing, creating quantitative indicators, and also some analysis for science mapping.

Before going any further, it is important to highlight that the analysis was carried out in the science mapping workflow proposed by Zupic and Cater (2015). Figure 4.1 represents the main stages of the recommended science mapping workflow, integrating both Bibliometrix® R-package, VOSviewer, and the VantagePoint.

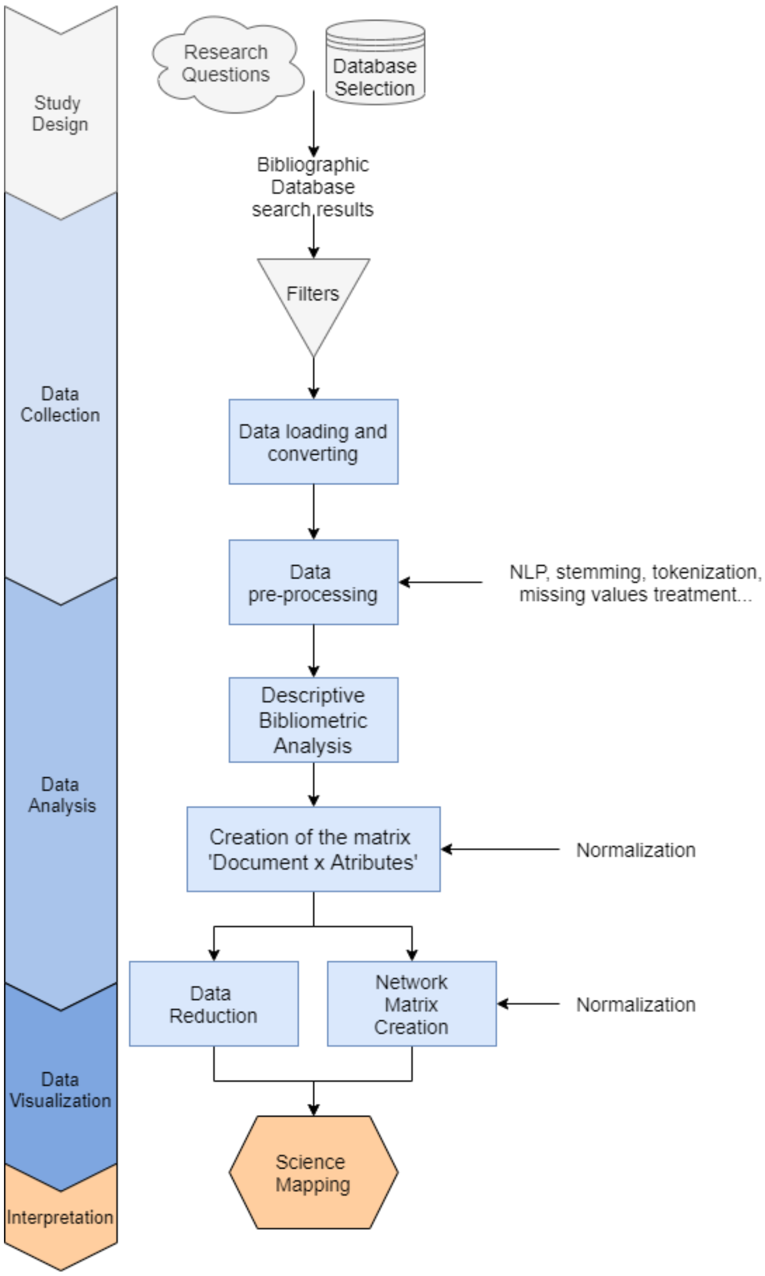

Figure 4.1 – Science mapping workflow
Source: Adapted from Aria and Cuccurullo (2017) and Zupic and Cater (2015)
Note: NLP – Natural Language Processing

4.1. Bibliometric study design

In the bibliometric study design section, the research questions are defined, and the appropriate bibliometric methods to answers these questions are described. Also, the analyze time span are also defined based on previous objectives. In this bibliometric study, the following research questions were posed: (i) how to represent evolutionary pathways and scientific roadmaps highlighting MCDM/A methods application trends for sustainability or sustainable development? (ii) how to identify past research findings and present evidence-based insights?; (iii) how to show shifts in the boundaries of the focused used MCDM/A methods by revealing their interactions? To achieve this objective, several research questions were identified and traced to specific bibliometric indicators, as shown in table 4.1. In addition, the MCDM/A methods reported in chapter 2 of this document were selected for the analysis.

The combination of an advanced bibliometric software, analytical capacity, and data processing provide a deep and vast methodological framework for dealing with different types of questions regarding the production of a particular research field.

4.2. Data collection

Data collection is divided in three sub-stages. The first is data retrieval from a bibliographic data source. The second sub-stage is data loading and converting, where scholars must convert data into a suitable format for the employed bibliometric tools.

The final sub-stage is data cleaning. The quality of the result depends on the quality of the data. Several preprocessing methods can be applied, for example, to detect duplicate and misspelled elements. Although most bibliometric data are reliable, cited references can contain multiple versions of the same publication and different spellings of an author’s name. Moreover, because their surname and initials typically abbreviate authors, a problem can arise with common names. Cited journals can also appear in slightly different forms.

Table 4.1 – Research questions and indicators

Objective	Question	Indicator	Phase
Scientific production	How is it configured the MCDM/A applied to sustainable development decision problems articles collection?	Bibliographic data collection	Data Collection
	How did scientific production evolve from 2010 to 2020? Global and by type of document?	Annual scientific production	
		Annual scientific production by document type	
Author profile analysis	Which authors have the highest volume of publication on the topic? Moreover, which are the most cited?	Most relevant authors in terms of volume and citation of scientific articles	Data Analysis
	What is the profile of the authors' publications with the highest volume of publication on the topic? How the line of research in which they are inserted evolve?	Top authors scientific production over time	
Country contributions	Which countries have the highest volume of publications on the research field? How do they cooperate?	Most relevant countries	
Document level analysis	What are the most relevant articles on MCDM/A applications for sustainable development? What are the most important backward references cited in these papers?	Most relevant papers by global and local citation	
		Most relevant references	
	What are the most important keywords associated with these papers?	Most relevant keywords plus	
		Trend topics per year	
MCDM/A approaches	What are the most used MCDM/A methods applied to decision problems on sustainability and sustainable development?	MCDM/A methods applied to decision problems on sustainability and sustainable development	
	How can MCDM/A methods be classified according to the taxonomy proposed by Danesh et al.?	Classification of the applied MCDM/A methods according to the taxonomy proposed by Danesh et al.	
MCDM/A applications by research area	What are the most relevant research areas in which MCDM/A methods are applied to solve sustainable development problems? How do MCDM/A applications by research area have evolved within the time-frame 2010-2020?	Most relevant research areas in which MCDM/A methods are applied to solve sustainability or sustainable development problems	
Source analysis	Which journals publish more articles on the topic? Furthermore, which are the most relevant (in terms of citations)?	Most relevant sources to the MCDM/A applications in sustainability or sustainable development field	

Table 4.1 – Research questions and indicators (cont.)

Objective	Question	Indicator	Phase
Country contributions	Which countries apply each MCDM/A method?	Correlation between countries and MCDM/A methods	**Data Visualization**
	How do countries collaborate to produce knowledge in this research field?	Countries collaboration network	
		Countries collaboration map	
	Which countries contribute the most to a particular research areas to solve sustainability or sustainable development problems?	Correlation between countries and research area	
	Which countries apply each MCDM/A method?	Correlation between countries and MCDM/A methods	
	How do countries collaborate to produce knowledge in this research field?	Countries collaboration network	
Document level analysis	How is the auto-correlation map configured among the most relevant keywords?	Auto-correlation map of keywords plus	
	How is the co-citation network configured among all papers on MCDM/A applications for sustainable development?	Documents co-citation network	
	What is the association between backward references, top authors, and applied MCDM/A methods?	Associations between references, top authors and MCDM/A methods	
MCDM/A approaches	Which are the MCDM/A methodological approaches identified in these papers? Integration of MCDM/A methods? Combination of MCDM/A and non-MCDM/A methods? Use of fuzzy set theory? Use of sensitivity analysis?	Auto-correlation map of MCDM/A methods	
		Co-ocurrence network of MCDM/A methods	
	What are the most used MCDM/A methods applied to decision problems on sustainability and sustainable development?	Annual evolution of MCDM/A methods applied to decision problems on sustainability and sustainable development	
	Which MCDM/A methods are most used in which research areas to solve sustainability or sustainable development problems?	Correlation between MCDM/A methods and research area	
	How are the MCDM/A applications by research area autocorrelation network configured?	Auto-correlation network of research areas	
	How the MCDM/A applications by research area have evolved within the time-frame 2010-2020?	Thematic evolution	
	What does the strategic diagram for the period 2010-2020 reveal about these research area's themes? (i) What themes are high developed or isolated? (ii) What themes are motor? (iii) What themes are emerging or declining? (iv) What themes are basic and transversal themes?	Strategic diagram concerning thematic evolution	
	What are the most relevant research areas in which MCDM/A methods are applied to solve sustainability or sustainable development problems? How do MCDM/A applications by research area have evolved within the time-frame 2010-2020?	Correlation between research areas and years	
Source analysis	Which sources are most relevant for each research areas to solve sustainability or sustainable development problems?	Correlation between sources and research area	

Books have different editions, which can appear as different citations. Besides, the data may be duplicated or with some missing required fields, which need specific treatments in these cases. Usually, the treatment for missing or noisy text data removes the entire register or replacement by the mode.

First, this data source is defined, then the search strategy, and lastly, some filters, such as publication area; time span; language; document type, etc., aiming to refine the obtained outputs are chosen. In the second step, the bibliographic data are exported and converted to a suitable format for the employed bibliometric software. Third, the data is pre-processed, to normalizing the database, handling noise, and removing some incomplete entries, improving the data reliably, for example, cited references can contain multiple versions of the same publication; and the same keyword can be spelled in different ways that are not advantageous for the completeness of the analysis. Finally, at the fourth step, the processed database is loaded to any bibliometric or analysis tool.

So, in the 'Data Analysis' step, the resulting data frame can be examined to produce information such as the characterization of the sample and the primary information about the collection such as total numbers of documents and their types; the total amount of sources (journals; books; among others which published one or more documents included in the bibliographic collection); authors; co-authors; citations; and some statistics concerning the contents of the papers.

To analyze these contents, it is necessary to define some concepts. First, the most used collaboration measure, Collaboration index (CI), also known as Average Collaboration rate, refers to the mean number of authors per joint paper as in (5). This measure represents the state of collaboration between authors in a given scientific field. For example, an index above 1 shows an excellent collaboration level, as it means that there are more shared works than authors in the sample.

$$CI = \frac{Total\ authors\ of\ joint\ papers}{Total\ joint\ papers} \tag{5}$$

Furthermore, another critical analyzed feature in bibliometrics is the most relevant keywords and their co-occurrence. This can be done using the author keyword, which is defined as a tag of the article by the authors, or the keyword plus, which is an index term automatically generated by a computer algorithm, and they do not necessarily appear in the title of the paper or as author keywords. Generally, keywords plus terms are able to capture an article's content with greater depth and variety (Garfield, 1993).

Despite the fewer articles than the Scopus and Dimensions database, Web of Science (WoS) was chosen as the primary source of data for bibliometric analysis due to the most selective journal coverage and majority of their coverage in Life Sciences, Physical Sciences and Technology Area. In this bibliometric study, the difference in WoS articles was less than 10% of those compared by the Scopus database results. It is worth mentioning that the combination of data from different databases is a challenging task, and it is not possible to perform it using current bibliometric tools because of the difference in papers indexing between these databases.

In this research, the data was initially processed using R language, and was converted again to a format like WoS metadata and inserted latter in the various bibliometric software used in this phase of the research. In VOSviewer®, the only treatment was the use of a thesaurus to justify the spelling of countries and keywords. In contrast, VantagePoint® was used to a more extensive preprocessing and text-mining, using Natural Language Processing (NLP), fuzzy logic for grouping similar words, stemming, tokenization, stop words' removal and to create some quantitative indicators to further analysis in the next phases.

For instance, the MCDM/A methods terms indicators were created in the following steps: (i) creation of a thesaurus to unify the spelling; (ii) stemming the words; (iii) tokenization of the words present in the abstracts, titles, and keywords; (iv) creation of a Boolean indicator indicating the MCDM/A method that the document applied. The same was also done for terms related to fuzzy logic and sensitivity analysis.

4.3. Data analysis

Following the bibliometric analysis workflow, this step employs one or more bibliometric or statistical software to perform the analysis of the previously treated data. Data analysis involves descriptive analysis and network extraction using different approaches based on the required output.

As shown in table 4.2, Aria and Cuccurullo (2017) present different developed approaches to extract networks using different analysis units. For instance, the co-word analysis proposed by Callon et al. (1983) used the most important words or keywords of documents to study a research field's conceptual structure. Hence, it is the only method that uses the documents' actual content to construct a similarity measure, while the others connect documents indirectly through citations. Furthermore, the co-word analysis can be applied to document keywords, abstracts, or full texts to produce semantic maps of a field that facilitates understanding its cognitive structure.

Table 4.2 – Most common bibliometric techniques per unit of analysis

Bibliometric technique taxonomy	**Unit of analysis used**	**Kind of relation**
Bibliographic Coupling	• Author • Document • Journal	• Common references in authors' oeuvres • Common references in documents • Common references in journals' oeuvres
Co-citation	• Author • Reference • Journal	• Co-cited authors • Co-cited documents • Co-cited journals
Co-author	• Author • Country from affiliation • Institution from affiliation	• Co-occurrence of authors in the author list of a document • Co-occurrence of countries in the address list of a document • Co-occurrence of institutions in the address list of a document
Co-word	• Keyword, or term extracted from title, abstract or document's body	• Co-occurrence of terms in document

Source: Aria and Cuccurullo (2017).

As proposed by Peters and VanRaan (1991), co-author analysis is another typical bibliometric analysis that focuses on examining the authors and their affiliations to study the social structure and collaboration networks.

Finally, according to Aria and Cuccurullo (2017), one of the most common analyses in bibliometrics is the citation analysis, which employs citation counts to measure similarity between documents, authors, and journals. Citation analysis can also be decomposed into the bibliographic coupling and co-citation analysis.

A bibliographic coupling (Kessler, 1963) connection is established by the authors of the articles in question, whereas a co-citation (Small, 1973) connection is established by the authors who are citing the documents analyzed.

As demonstrated by Yang et al. (2016), bibliographic coupling helps to detect the connections of research groups, while co-citation analysis, when examined over time, helps detect a shift in paradigms and schools of thought.

Once the network has been built, a normalization process can be commonly performed over the relations (edges) between its nodes (vertices) using similarity measures such as Salton’s cosine, Jaccard’s coefficient, and Pearson’s correlation. Finally, data reduction helps to identify subfields.

With the normalized data, different techniques can be used to build the map. Various dimensionality reduction techniques can be applied, such as Principal Component Analysis (PCA), Multidimensional Scaling (MDS), Multiple Correspondence Analysis (MCA), and some clustering algorithms.

At this stage, the introduction of some concepts is necessary. Documents refer to a scientific document (like article, review, or conference proceedings) included in a bibliographic collection, while reference refers to a scientific document included in at least one bibliography of the document set. Also, cited documents are scientific documents included in the reference and document at the same time.

In addition to that, global citations measure the number of citations that a document has received from documents contained in the entire database, i.e., this metric measures the impact of a document in the whole bibliographic database, including the impact in other disciplines. Besides, local citations measure the number of citations that a document has received from documents included in the analyzed collection, i.e., this metric measures the impact of a document in the analyzed collection.

Author keywords consist of a list of terms that authors believe best represent their paper's content, but they often need to be cleaned with stemming or a thesaurus, for example. In this way, keyword plus is generated by an automatic computer algorithm and are words or phrases that frequently appear in the titles of an article's reference and not necessarily in the title of the article or as author keywords. Zhang et al. (2016) argue that keyword plus is as effective as author keywords in bibliometric analysis to investigate the knowledge structure of scientific fields, but it is less comprehensive in representing an article's content.

It is also possible to extract words by titles or abstracts, but it needs more effort to be cleaned compared to keywords.

A fundamental concept for analysis at the author-level and source-level metrics is the citation metrics, which measure individual authors' bibliometric impact. In this way, H-index, G-index, and M-index were proposed to measure both the productivity and impact of a scientist or scholar's published work.

The H-index definition is: "a scientist has an index *h* if *h* of his/her papers has at least *h* citations each, and the other papers have no more than *h* citations each". For instance, to have an h-index of 5, an author must have five publications, each receiving at least five citations. G-index is a variant of the *h*-index that, in its calculation, gives credit for the most highly cited papers in a data set, while M-index is another variant of the *h*-index that displays *h*-index per year since first publication.

In this exploratory study, the bibliometric techniques used to extract useful information from the bibliographic metadata are: (i) Bibliographic Coupling with authors, documents, and journals as units of analysis; (ii) Co-citation with reference as a unit; (iii) Co-author with the country from authors affiliation as a unit; and (iv) Co-word analysis.

In the first technique, the connection is established by the manuscripts, to draw production trends along the selected period, i.e., the annual scientific production. This analysis is useful to verify the compound annual growth rate, the behavior of the production curve (if increases or decreases and how fast it does it), inflection spots, and also some jumps which can be associated with turning points in the analyzed field. Thus, the analysis goes to the sources' level, gathering the most crucial source information in terms of manuscript production and most cited sources, i.e., a source cited by one or more documents. To conclude this technique, the top authors in terms of production can be mined from da data and related to their documents and citations by year, thus enabling the analysis of an author's timeline.

In the next technique, using co-citation analysis, several possibilities of evaluation emerge. However, in this research, only the manuscripts inside the sample will be investigated, connecting than in a network perspective, in order to verify their relationships and monitor the construction of an evolution of a school of thought or paradigm' shift in the sample.

Last but not least, co-author techniques within the country from affiliation analysis are used in this research to reveal the most significant countries in the production of single-authored documents and multi-authored documents and to verify their relations using network theory in a country's collaboration network. These results allow verifying how countries are distributed concerning international cooperation, whether they belong to a cluster, how strong is the relationship with their partners, and how much documents they produce.

4.4.
Data visualization

Visualization analysis methods allow the extraction of valuable knowledge from data and to represent it through intuitive visualizations maps such as bi-dimensional maps, dendrograms, and social networks. As before, many methods may be employed to reach the defined objective, so it is essential to know what the study will require. As indicated by Aria and Cuccurullo (2017), the network analysis allows performing a statistical analysis over the maps generated to indicate different measures of the entire network or measures of the relationship or the overlapping of the different clusters detected.

Visualization techniques were used here to represent the knowledge structures by a longitudinal science map and 'strategic diagrams' as proposed by Cobo et al. (2011b) and Callon et al. (1991), respectively. It is crucial to say that this knowledge can also be represented by bi-dimensional maps, dendrograms, and social networks. Science mapping aims to display the structural and dynamic aspects of scientific research.

Alternatively, the temporal analysis aims to indicate the conceptual, intellectual, or social evolution of the research field by discovering patterns, trends, seasonality, and outliers. Burst detection, a temporal analysis, aims to identify features with high intensity over a finite duration of periods. Finally, the geospatial analysis aims to discover where an event occurs and its impact on the neighboring areas.

In addition to that, the 'strategic diagrams' area graphical plots that highlights the different themes of the sample and shows their importance in the entire research field as in figure 4.2. These plots are formed by four quadrants, as described by Cobo et al. (2011b): (i) upper-right quadrant: motor-themes, related to well-developed themes and important for the structure of the research field; (ii) lower-right quadrant: basic and transversal themes; (iii) lower-left quadrant: emerging or declining themes; (iv) upper-left quadrant: high developed and isolated themes. In synthesis, the themes are clustered and classified by their centrality using the keywords, which represents the importance of the theme to the research field and by their density, representing their stage of development.

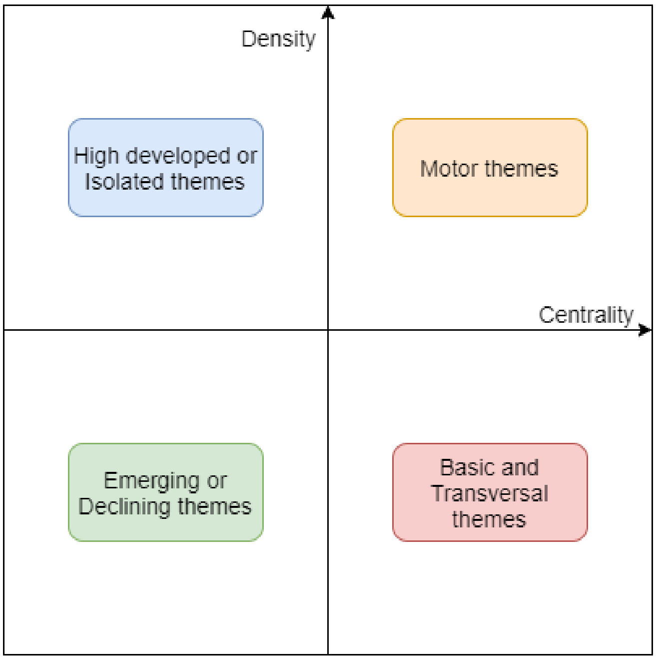

Figure 4.2 – Strategic diagram quadrants
Source: Cobo et al. (2011b).

Social networks are useful to analyze the co-occurrence between keywords. It displays the most prominent terms in the sample, as the linkage between these nodes. Once the network has been built, a normalization process can be commonly performed over the relations between its terms using similarity measures such as Salton's cosine, Jaccard's coefficient, and Pearson's correlation (van Eck and Waltman, 2010), several clustering algorithms as Louvain and Walktrap (Lancichinetti and Fortunato, 2009) to find similarities in the terms, and some network layouts.

Although Bibliometrix® provide the social co-occurrence network analysis, the VOSviewer® software was used for this purpose in this paper for the following reasons: (i) the possibility of using a thesaurus to correct the spelling of some terms (i.e., merging plural and singular forms and converting acronyms into their full forms), and (ii) the possibility of choosing the words that would be analyzed, in order to generate a more pertinent result to the research object, thus removing terms that would not help to meet the objective of this work.

VOSviewer® constructs a map based on a co-occurrence Matrix, in three steps: (i) calculating a similarity matrix is based on the co-occurrence matrix which can be obtained from the normalization process discussed above; (ii) constructing the science map using VOS mapping technique; and (iii) translating, rotating, and reflecting the social network resulting.

The last stage is interpretation, where the researcher interprets and describes their findings mainly with an expert aid. Even though bibliometric procedures will commonly reveal the structure of a field differently from the classification of traditional literature reviews, they are not a substitute for a systematic literature review and expert's knowledge.

For this research, temporal analysis is also fundamental because it aims to show the conceptual (the main themes, and trends), intellectual (how a work influences a given scientific community), or social (how authors, institutions and countries interact each other) development of the research field by discovering patterns, trends, seasonality, and outliers.

In addition to that, the VantagePoint® was used in complement of VantagePoint® to reach some auto-correlation maps and co-occurrence networks, specially using the MCDM/A methods quantitative indicators. Besides, VantagePoint® allows to do some bivariate analysis with different analysis units (e.g., year, MCDM/A methods, research area, countries and sources).

This chapter provided the materials and methods to be used for the study of MCDM/A in SD to describe how these disciplines, scientific domains, or research fields are structured and evolve, according to the bibliometric workflow, divided into four phases: (i) bibliometric study design, including the choice of a bibliographic database; (ii) data collection; (iii) data analysis; and (iv) data visualization. In the next chapter, the bibliometric analysis will be conducted to investigate MCDM/A approaches in SD.

5
Results and discussion

In this section, the general methodology described before is applied to analyze the research field of multicriteria decision-making approaches in sustainable development studies. First, will be presented the data collection, the applied adherence criteria filters, and the pre-processing. Following, the results of the three phases of the methodology of bibliometric studies adopted will be displayed and commented on, namely: (i) data collection; (ii) data analysis; and (iii) data visualization.

As stated in the introductory chapter, the following research questions are: (i) how to identify past research findings and present evidence-based insights?; (ii) how to represent evolutionary pathways and scientific roadmaps highlighting MCDM/A methods application trends for sustainability or sustainable development?; and (iii) how to show shifts in the boundaries of the focused used MCDM/A methods by revealing their interactions?.

Concerning the appropriate bibliometric methods for answering the above questions, this research used the indicators presented in Table 4.1.

5.1.
Data collection results

Initially, a search in the chosen database (Web of Science) was conducted covering all peer-reviewed documents and the relationship between the selected MCDM/A methods and SD or sustainability issues over the 2010-2020 timeframe period. This period was chosen due to the emergence of terms related to sustainability in the last decade, mainly leveraged by the definition of the sustainable development goals of the 2030 Agenda in 2015 (United Nations, 2015), which allows the comparison of the pre and post SDGs periods.

The data retrieved were refined using the following adherence criteria filters: (i) ‘publication years’: 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or

2014 or 2013 or 2012 or 2011 or 2010; and (ii) 'documents type': article or review or proceedings paper. This keyword search strategy yielded 3,473 articles, as shown in table 5.1.

Table 5.1 – Search strategy in Web of Science database

Ref.	Query	Documents
#1	TS="Simple Multi Attribute Rating Technique" AND TS= ("sustainability" OR "sustainable development")	8
#2	TS="REGIME METHOD" AND TS= ("sustainability" OR "sustainable development")	5
#3	TS="ORESTE" AND TS= ("sustainability" OR "sustainable development")	1
#4	TS="VIKOR" AND TS= ("sustainability" OR "sustainable development")	263
#5	TS=("PROMETHEE" OR "Preference Ranking Organization METHod for Enrichment of Evaluations") AND TS= ("sustainability" OR "sustainable development")	199
#6	TS="QUALIFLEX" AND TS= ("sustainability" OR "sustainable development")	4
#7	TS="Superiority and Inferiority Ranking" AND TS= ("sustainability" OR "sustainable development")	1
#8	TS=("EVAMIX" OR "EVAluation of MIXed data") AND TS= ("sustainability" OR "sustainable development")	3
#9	TS=("ARAS" OR "Additive Ratio ASsessment") AND TS= ("sustainability" OR "sustainable development")	38
#10	TS=("MOORA" OR "Multi-Objective Optimization Ratio Analysis") AND TS= ("sustainability" OR "sustainable development")	30
#11	TS=("COPRAS" OR "COmplex PRoportional ASsessment") AND TS= ("sustainability" OR "sustainable development")	73
#12	TS=("WASPAS" OR "Weighted Aggregates Sum Product Assessment") AND TS= ("sustainability" OR "sustainable development")	34
#13	TS=("SWARA" OR "Stepwise Weight Assessment Ratio Analysis") AND TS= ("sustainability" OR "sustainable development")	43
#14	TS=("DEMATEL" OR "DEcision-MAking Trial and Evaluation Laboratory") AND TS= ("sustainability" OR "sustainable development")	407
#15	TS=("MACBETH" OR "Measuring Attractiveness by a Categorical Based Evaluation TecHnique") AND TS= ("sustainability" OR "sustainable development")	18
#16	TS=("ANP" OR "Analytic Network Process") AND TS= ("sustainability" OR "sustainable development")	472
#17	TS=("MAUT" OR "Multi-Attribute Utility Theory") AND TS= ("sustainability" OR "sustainable development")	58
#18	TS=("IDOCRIW" OR "Integrated Determination of Objective CRIteria Weights") AND TS= ("sustainability" OR "sustainable development")	1
#19	TS="TODIM" AND TS= ("sustainability" OR "sustainable development")	38
#20	TS = ("EDAS" OR "Evaluation based on Distance from Average Solution") AND TS = ("sustainability" OR "sustainable development")	23
#21	TS = "PAMSSEM" AND TS= ("sustainability" OR "sustainable development")	0
#22	TS = ("ELECTRE" OR "ELimination Et Choix Traduisant la REalite") AND TS= ("sustainability" OR "sustainable development")	141

#23	TS=("EXPROM" OR "EXtension of the PROMethee") AND TS= ("sustainability" OR "sustainable development")	2
#24	TS=("MABAC" OR "Multi-Attributive Border Approximation area Comparison") AND TS= ("sustainability" OR "sustainable development")	16
#25	TS=("CRITIC" OR "CRiteria Importance Through Intercriteria Correlation") AND TS= ("sustainability" OR "sustainable development")	53
#26	TS=("KEMIRA" OR "KEmeny Median Indicator Ranks Accordance") AND TS= ("sustainability" OR "sustainable development")	3
#27	TS=("TOPSIS" OR "Technique for Order of Preference by Similarity to Ideal Solution") AND TS= ("sustainability" OR "sustainable development")	879
#28	TS=("AHP" OR "analytical hierarchy process") AND TS= ("sustainability" OR "sustainable development")	2,186
#29	#1 OR #2 OR #3 OR #4 OR #5 OR #6 OR#7 OR #8 OR #9 OR #10 OR #11 OR #12 OR #13 OR #14 OR #15 OR #16 OR #17 OR #18 OR #19 OR #20 OR #21 OR #22 OR #23 OR #24 OR #25 OR #26 OR #27 OR #28	3,869
#30	#29 DOCUMENT TYPES (ARTICLE OR PROCEEDINGS PAPER OR REVIEW)	3,864
#31	#30 LIMIT-TO (PUBYEAR, 2010:2020)	3,546
#32	#31 LANGUAGES (ENGLISH)	3,473

Despite having a high-quality data, it is important to highlight that the data obtained from Web of Science still present some duplicate or missing values, which could impact the analyzes described in the last section. For this reason, fundamental columns, such as (i) title; (ii) publication year; (iii) authors; (iv) document types; (v) research area; (vi) author's keywords or keywords plus; (vii) author's country; (viii) source; and (ix) total citations, were defined that could not present non-avaliable (NA) values and, to deal with this, these missing records were removed. Although there are some techniques for replacing these values, for the least impact on the sample, only the removal of these null values was considered.

Table 5.2 shows the bibliographic data collection of a total of 3,175 documents, resulted from the pre-processing of the 3,473 documents initially retrieved. This phase included: (i) removal of duplicates; (ii) removal of data outside the analysis scope; (iii) removal of NA values in the selected columns column using R programming language data frame manipulation, and the functions 'convert2df' and 'biblioAnalysis' from Bibliometrix®.

Table 5.2 – Bibliographic data collection

Description	**Results**
Documents	3,175
Articles	2,490 (78.42%)
Proceedings paper	594 (18.70%)
Review	91 (2.88%)
Sources (journals, books, among others)	1,156
Keyword plus	3,810
Author's keywords	8,051
Period	2010-2020
Average citations per document	13.10
Authors	7,645
Author appearances	10,910
Authors of single-authored documents	189
Authors of multi-authored documents	7,456
Single-authored documents	213
Documents per author	0.41
Authors per document	2.41
Co-authors per document	3.44
Collaboration index	2.52

Table 5.2 reveals that the majority of documents are articles, followed by proceedings papers, and reviews in the most inferior position. Furthermore, the publication profile of this area is more multi-authored, with only 7% of documents single-authored, while the remaining 93% have almost three co-authors on average. This behavior is also expressed by the collaboration index, defined as the mean number of authors per joint paper. This measure represents the state of collaboration between authors in a given scientific field. For these documents, the index is 2.52, which shows a good collaboration level. Also, the high number of sources concerning the total number of documents demonstrates a greater decentralization of this knowledge dissemination.

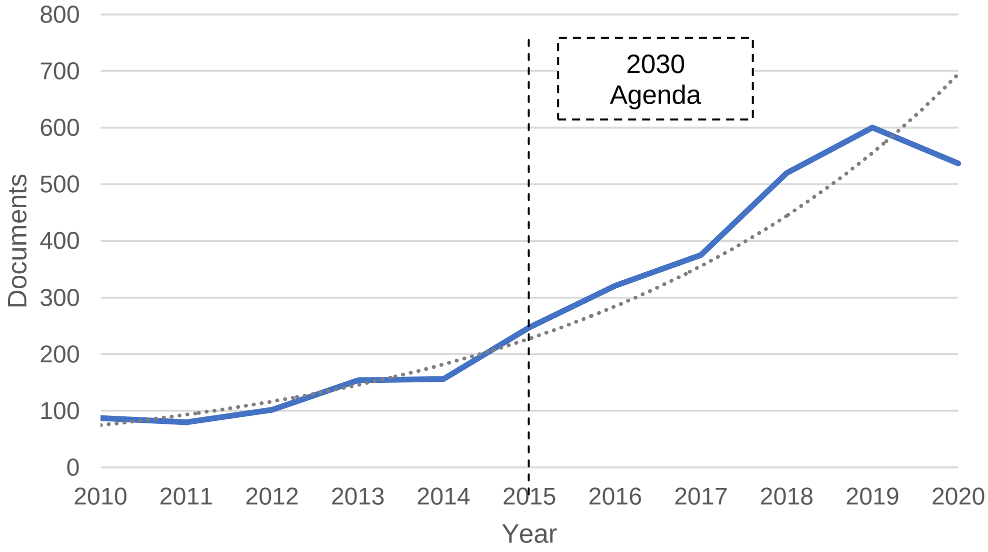

Figure 5.1 – Annual scientific production

Figure 5.1 shows the annual scientific production of the investigated research field (in blue) as the exponential trend line (in grey) with an almost 20% compound annual growth rate (CAGR).

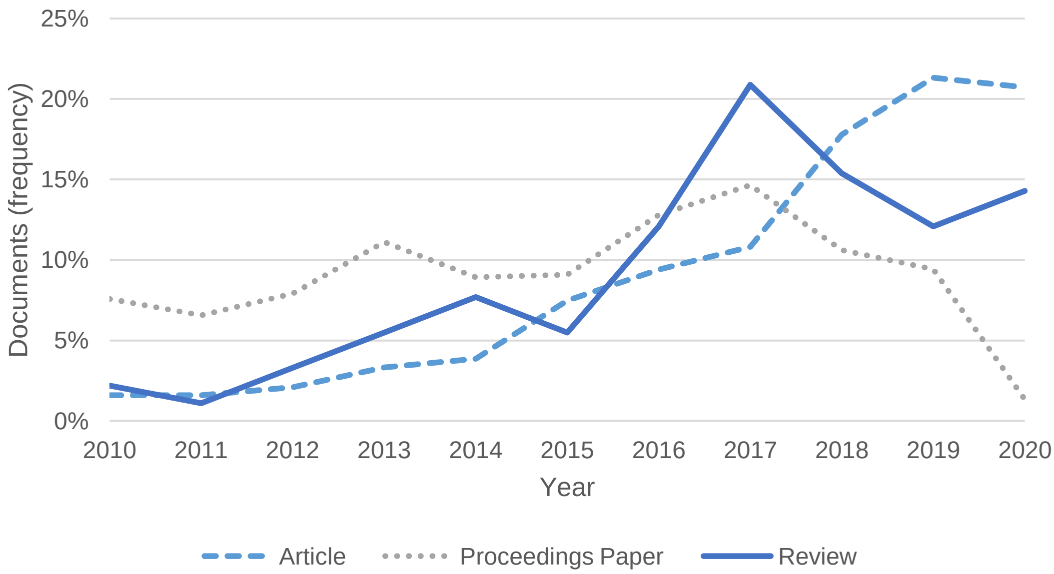

Figure 5.2 – Annual scientific production by document type

Although scientific production has increased during the 11 years of the observed period (2010 to 2020), there are not significant jumps throughout this period. However, it is interesting to note that since the 2030 Agenda for

Sustainable Development was launched in 2015 by the United Nations General Assembly, the annual growth rate of scientific production has intensified, accounting for almost 3/4 of the total publications from 2016 to 2020.

Another insightful analysis for this data is through the types of documents by the year of its publication. Figure 5.2 presents this analysis with the relative values of documents corresponding to each of the three types, namely: (i) articles; (ii) proceedings paper; and (iii) review article. It is possible to verify that the number of articles is overgrowing year after year and the number of review articles, demonstrating the maturity of the area of knowledge by consolidating the findings.

Some analysis of the next sections was carried out using the VantagePoint® text-mining software and the VOSviewer® in addition to the Bibliometrix® R package. So, the data treated using R was converted again to a format similar to Web of Science metadata and inserted in these software. In VOSviewer®, the only string's preprocessing was the use of a thesaurus to justify the spelling of countries and keywords. In contrast, VantagePoint® was used to a more extensive preprocessing and text-mining, using Natural Language Processing (NLP), fuzzy logic for grouping similar words, removing plurals and inflections to obtain the roots of the terms, removing stop words and words that did not add information to the analysis and to create some quantitative indicators to further descriptive analysis.

With the information imported and cleaned, the data analysis was shown in the next section, in a quantitative and qualitative approach regarding the bibliographic publication on the use of MCDM/A methods in sustainability and sustainable development.

5.2.
Data analysis results

Following the bibliometric process, this step involves descriptive analysis and extraction of co-occurrence and correlation networks using the Bibliometrix® R package and the VantagePoint® software to obtain the research's structure, dynamics, and specificities field from 2010 to 2020 as previously introduced.

These analyses take place at six levels, namely: (i) source analysis; (ii) MCDM/A methodological approaches; (iii) country contributions; (iv) MCDM/A applications by research area; (v) author profile analysis; and (iv) document level analysis.

5.2.1. Source analysis

A source is a journal, book, conference proceeding series which published one or more documents included in the bibliographic collection. At the level of sources metrics, quantitative indicators linked to the publishing source of the documents are analyzed, examining their distribution according to (i) Bradford's Law; (ii) number of published documents; (iii) citations; (iv) and the dynamics of the sources over the defined timeframe.

As previously, Bradford's Law classifies publishing sources into generally three zones, namely: (i) core zone or nucleus, that is the primary sources for a subject; (ii) middle zone or straight zone; and (iii) minor or gross droop zone. Figure 5.3 shows the number of sources and the number of published documents in each of these areas, corresponding to 20 journals, 212 journals, and 924 journals, respectively. That is, 20 journals were responsible for producing 1,055 documents, which represents 33.2% of the number of articles in the sample.

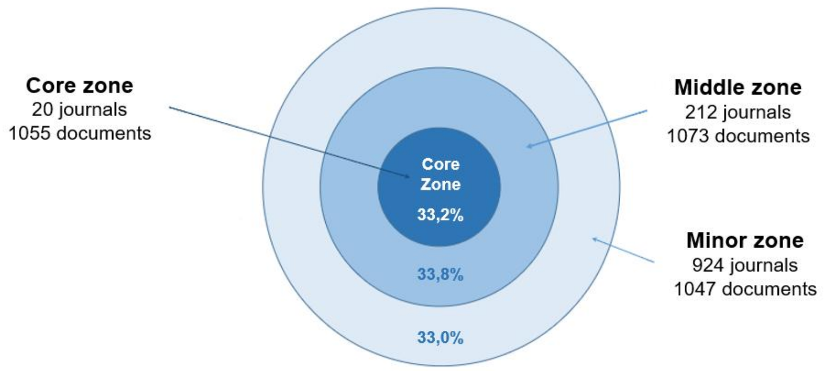

Figure 5.3 – Bradford’s law sources’ zones

Table 5.3 shows all sources belonging to the ‘core zone’ founds with the Bibliometrix® functions ‘bradford’ and ‘biblioAnalysis’, with their respective publishers, number of published documents, total citations, H index, G index, and

M index considering the documents in the articles' sample. Finding from this table indicates that the Sustainability (publisher: MDPI) and the Journal of Cleaner Production (publisher: Elsevier) are the top journals in the list as the most significant journals related to the sustainable development and MCDM/A approaches. 10.3% and 8% of the reviewed articles were published in those journals, respectively. They are followed by the Ecological Indicators (publisher: Springer), which published 1.2% of the selected articles. Most of these sources have an interdisciplinary character, which is in line with sustainability, that permeates several areas, and with MCDM/A applications, which have a broad portfolio application.

Table 5.3 – Most relevant sources

Sources	**Publisher**	**Documents**		**Citations**	**h index**	**g index**	**m index**
Sustainability	MDPI	328	10.3%	2,227	24	33	2.4
Journal of Cleaner Production	Elsevier	253	8.0%	6,063	42	64	3.5
Ecological Indicators	Elsevier	38	1.2%	1,160	19	33	1.7
Energies	MDPI	36	1.1%	315	11	17	1.1
Energy	Elsevier	36	1.1%	1,022	18	31	1.5
Renewable and Sustainable Energy Reviews	Elsevier	35	1.1%	1,525	20	35	2
Resources Conservation and Recycling	Elsevier	35	1.1%	954	16	30	1.4
Sustainable Cities and Society	Elsevier	34	1.1%	467	13	20	1.4
International Journal of Environmental Research and Public Health	MDPI	26	0.8%	116	7	9	1.4
Science of the Total Environment	Elsevier	26	0.8%	489	10	22	0.9
Expert Systems with Applications	Elsevier	25	0.8%	1,829	23	25	1.9
Symmetry-basel	MDPI	25	0.8%	158	7	11	1.4
International Journal of Production Economics	Elsevier	24	0.8%	1,229	18	24	1.8
International Journal of Production Research	Taylor and Francis	23	0.7%	956	15	23	1.2
Journal of Environmental Management	Elsevier	23	0.7%	415	10	20	0.8
Clean Technologies and Environmental Policy	Springer	18	0.6%	192	10	13	1

Computers and Industrial Engineering	Elsevier	18	0.6%	274	8	16	1.1
Sustainable Production and Consumption	Elsevier	18	0.6%	215	7	14	1
Mathematical Problems in Engineering	Hidawi	17	0.5%	148	5	12	0.5
Renewable Energy	Elsevier	17	0.5%	484	10	17	1.2

Although the top 3 journals are responsible for nearly 19.5% of the total publications in the sample, they are accountable for almost 30% of the total citations, indicating their relevance in these associated themes.

Even though Sustainability was the newspaper with the highest number of publications, the Journal of cleaner production appears to be the most influential source in the sample, with the highest H index, G index, M index, and almost three times total citations than Sustainability.

It is also relevant that table 5.3 does not include any conference proceeding series, even though they represent almost 20% of the total documents.

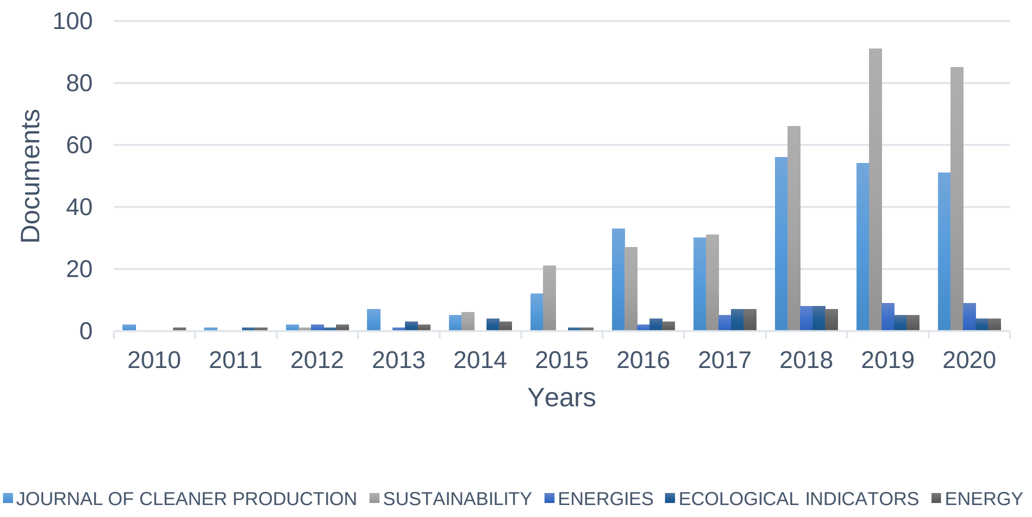

Figure 5.4 – Most relevant sources by year

It is possible to verify these sources' publications dynamics over the focused period of evaluation to confirm some turning points and their behaviors. Thus, figure 5.4 presents the annual production dynamics of the top 5 sources in terms of total publications and demonstrates the leadership established by Sustainability nearly every year.

5.2.2.
MCDM/A methodological approaches

Table 5.4 presents the 24 MCDM/A methods that were adopted in the reviewed articles. Accordingly, the most popular MCDM/A methods are the AHP method (1,445 articles), TOPSIS (542 articles), ANP (337 articles), DEMATEL (304 articles), and VIKOR (193 articles).

Table 5.4 – MCDM/A methods applied to sustainable development problems

MCDM/A methods	Classification (Danesh et al., 2017)	Documents		Use of fuzzy logic	Use of sensitivity analysis
AHP	Utility-based method	1,445	45.4%	469	27
TOPSIS	Compromise method	542	17.0%	277	8
ANP	Utility-based method	337	10.6%	124	2
DEMATEL	Other MCDM/A method	304	9.5%	157	3
VIKOR	Compromise method	193	6.0%	98	7
PROMETHEE	Outranking method	123	3.8%	39	6
ELECTRE	Outranking method	65	2.0%	15	3
COPRAS	Compromise method	42	1.3%	13	3
SWARA	Utility-based method	28	0.8%	13	0
TODIM	Utility-based method	26	0.8%	18	0
MAUT	Utility-based method	20	0.6%	1	0
WASPAS	Other MCDM/A method	20	0.6%	8	0
ARAS	Utility-based method	19	0.6%	6	0
MOORA	Utility-based method	18	0.5%	8	0
CRITIC	Utility-based method	11	0.3%	4	0
MACBETH	Outranking method	11	0.3%	3	0
EDAS	Compromise method	10	0.3%	5	1
SMART	Other MCDM/A method	8	0.25%	0	0
MABAC	Compromise method	4	0.1%	2	1
QUALIFLEX	Outranking method	4	0.1%	3	0
REGIME	Utility-based method	2	0.0%	0	0
EVAMIX	Compromise method	1	0.0%	1	0
KEMIRA	Other MCDM/A method	1	0.0%	0	0
ORESTE	Outranking method	1	0.0%	1	0

Following the taxonomy proposed by Danesh et al. (2017), these methods could be classified into: (i) utility-based (9 methods), (ii) compromise (6 methods), (iii) outranking (5 methods), and (iv) other MCMD methods (4 methods). Besides, the use of fuzzy logic and sensitivity analysis could be identified in a significant number of articles.

It is possible to verify that the AHP method, a utility-based method, is the most used, corresponding to almost half of the documents, which was already expected given its wide dissemination, ease of use, simplicity, and ability to hybridize with MCDM/A and non-MCDM/A, such as AHP-TOPSIS or GIS-AHP. The TOPSIS, a compromise method, appears with 17% of the documents, while the ANP, a generalization of the AHP, also a utility-based method, appears with 10.6%. It is relevant to note that a paper can apply a combination of MCDM/A and non-MCDM/A methods and an integration of MCDM/A methods at the same time to improve the robustness of the system or framework, so the total number of documents in this table 5.4 is greater than the number of documents.

From table 5.4, it is possible to reach the figure 5.5, which shows the number of studies in each MCDM/A method category, which shows that the use of utility-based methods leads the MCDM/A applications in sustainable development to address the sustainability questions with 60% of the total production, followed by compromise methods (with 25% documents) and other MADM techniques (with 11% documents), on the other hand, the outranking methods appear in the last position with only 6% of the studies.

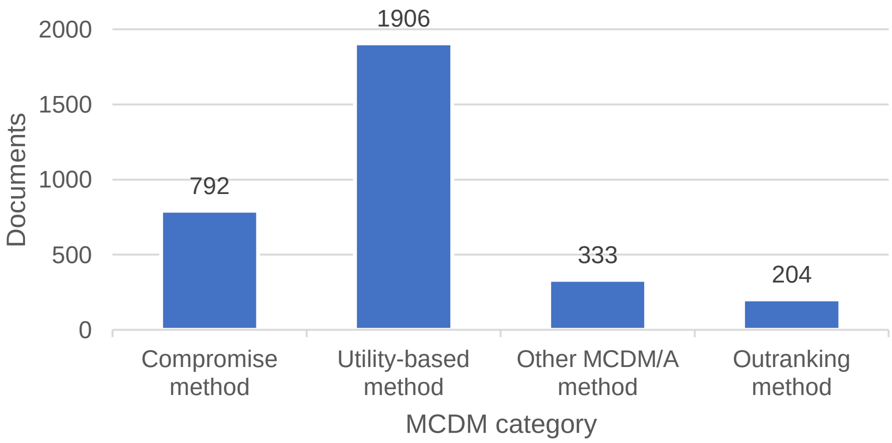

Figure 5.5 – Classification of used MCDM/A methods

Combining sensitivity analysis with the MCDM/A results can add further value to a given study because it allows decision-makers to judge whether the results are accurate and robust enough to decide. Moreover, it provides a means for judging the stability of results when the parameter values are changed. In this context, only 1.5% of studies from the reviewed articles incorporated sensitivity analysis to improve the results' robustness, mainly with AHP, TOPSIS, VIKOR and PROMETHEE methods. MCDM/A methods cannot consider the ambiguity and vagueness of selecting, scoring, and weighting unless fuzzy logic is combined with them to accommodate human judgments' subjectivity. In the sample, 28% of the studies have incorporated fuzzy logic, mainly used with AHP, TOPSIS, DEMATEL, and ANP methods.

5.2.3. Country contributions

Table 5.5 shows the top 20 countries according to the number of articles produced, the number of single country publications (SCP), multiple countries publications (MCP), and the average articles citations (AAC) of each country. This steps also uses the 'biblioAnalysis' function in Bibliometrix® package.

Table 5.5 – Most relevant countries

Country	Number of articles		SCP	MCP	Ratio of MCP	AAC
China	952	30.3%	738	214	22.5%	10.3
India	265	8.4%	232	33	12.5%	12.9
Iran	213	6.8%	164	49	23.0%	10.9
Spain	151	4.8%	119	32	21.2%	14.5
Turkey	145	4.6%	131	14	9.7%	12.8
Italy	116	3.7%	79	37	31.9%	14.9
Lithuania	87	2.8%	54	33	37.9%	25.6
United Kingdom	80	2.5%	36	44	55.0%	25.5
USA	78	2.5%	46	32	41.0%	21.1
Malaysia	77	2.4%	47	30	39.0%	24.5
Brazil	73	2.3%	59	14	19.2%	5.8
Australia	58	1.8%	34	24	41.4%	17.7
Canada	57	1.8%	38	19	33.3%	19.4
Poland	55	1.7%	48	7	12.7%	6.0
Indonesia	46	1.5%	42	4	8.7%	3.5
Korea	46	1.5%	31	15	32.6%	8.5
Serbia	42	1.3%	36	6	14.3%	12.9
Germany	41	1.3%	27	14	34.2%	37.5
Denmark	34	1.1%	10	24	70.6%	44.7
Portugal	33	1.0%	23	10	30.3%	12.1

Abbreviations: SCP – Single Country Publications; MCP – Multiple Countries Publications; AAC – Average Articles Citations.

Metrics at the country level are directly related to the author's affiliation of the documents. In this field, it is possible to analyze the number of documents produced in each country and their international collaboration. Since the list of countries was extracted through the affiliation of the articles' authors (and the co-authors), the number of documents is higher than the total of articles. So, the ‘’Top 20’ countries contribute with practically 84% of the sample.

Table 5.5 shows that China is the largest producer of papers, with 30% of all studies produced, three times than the second place, both in SCP and MCP. However, the internationalization ratio, that is, the share of articles produced in international cooperation, is only 22%. The second and third places are India and Iran, with 8% and almost 7% of the sample, respectively. Despite being responsible for only 1% of the sample documents, Denmark has the highest internationalization ratio, with more than twice as many articles being produced in international cooperation, so this country's AAC is the highest of the analyzed, having almost 45 citations per article.

5.2.4.
MCDM/A applications by research area

Another critical dimension for the analysis of science mapping is the research area, which constitutes a subject categorization scheme in Web of Science databases and is mainly related to the publication source, keywords, title, and abstract. These research areas are classified into five categories, namely: (i) ‘Arts &Humanities’; (ii) ‘Life Sciences & Biomedicine’; (iii) ‘Physical Sciences’; (iv) ‘Social Sciences’; and (v) ‘Technology’.

Out of 66 research areas, 24 were selected as relevant due to the number of publications and also their alignment with the research theme, by consulting four selected senior specialists in MCDM/A methods and sustainability. Besides, the participation of four senior specialists and the proper definition of inclusion/exclusion criteria mitigated the risk of bias during the selection process. Since an article can have more than one research area simultaneously, the total number is greater than the number of articles in the sample.

These MCDM/A applications by research area are shown in table 5.6, with the number of documents published by them and the Web of Science category which it belongs. The 'Environmental Sciences & Ecology' area, belonging to 'Life Sciences & Biomedicine' category, has the most articles in the research sample, with 38% of all publications, followed by 'Engineering' and 'Science &

Technology' - Other Topics' with 35% and 29% of the number of articles, respectively. This information was extracted with the VantagePoint® software.

Table 5.6 – MCDM/A applications by research area

MCDM/A applications by research area	**Documents**		**Web of Science category**
Environmental Sciences & Ecology	1,214	38.1%	Life Sciences & Biomedicine
Engineering	1,112	34.9%	Technology
Science & Technology - Other Topics	911	28.6%	Technology
Business & Economics	350	11.0%	Social Sciences
Energy & Fuels	299	9.4%	Technology
Operations Research & Management Science	237	7.4%	Technology
Construction & Building Technology	128	4.0%	Technology
Water Resources	125	3.9%	Physical Sciences
Materials Science	107	3.3%	Technology
Geology	80	2.5%	Physical Sciences
Public Administration	72	2.2%	Social Sciences
Social Sciences - Other Topics	72	2.2%	Social Sciences
Transportation	69	2.1%	Technology
Agriculture	62	1.9%	Life Sciences and Biomedicine
Urban Studies	50	1.5%	Social Sciences
Automation & Control Systems	47	1.4%	Technology
Biodiversity & Conservation	41	1.2%	Life Sciences and Biomedicine
Education & Educational Research	29	0.9%	Social Sciences
Telecommunications	27	0.8%	Technology
Forestry	21	0,6%	Life Sciences and Biomedicine
Meteorology & Atmospheric Sciences	16	0.5%	Physical Sciences
Mining & Mineral Processing	14	0.4%	Physical Sciences
Oceanography	12	0.3%	Physical Sciences
Biotechnology & Applied Microbiology	10	0.3%	Life Sciences and Biomedicine

5.2.5.
Author profile analysis

Decreasing the granularity level in the data analysis, it is possible to check the most prominent authors' bibliographic production for a given field and extract the relationships between them at the co-authorship level and cooperation between countries.

As mentioned before, Lotka´s observation shows an asymmetric distribution with a concentration of articles among a few authors (most productive authors). In contrast, the remaining articles would be distributed among a significant number of authors. The association between authors and their productivity, in the case studied by Lotka, showed a negative outstanding, about '-2'. So, figure 5.6 shows the frequency distribution of scientific productivity at the sample (in blue) with the theoretical Lotka's distribution (dashed line) using 'lotka' function in Bibliometrix. It is possible to infer that 6,110 authors (nearly 80%) have written just one document, so they can be classified as 'occasional authors', while only 186 authors (just over 2%) have written more than five articles, composing the 'core authors' of the sample. The actual distribution is very close to the theoretical pattern, which means that the theoretical Lotka distribution can be a helpful model for predictions in this research field, despite the proportion of single paper authors slightly higher than that observed by Lotka (1926), which corresponded to 60%.

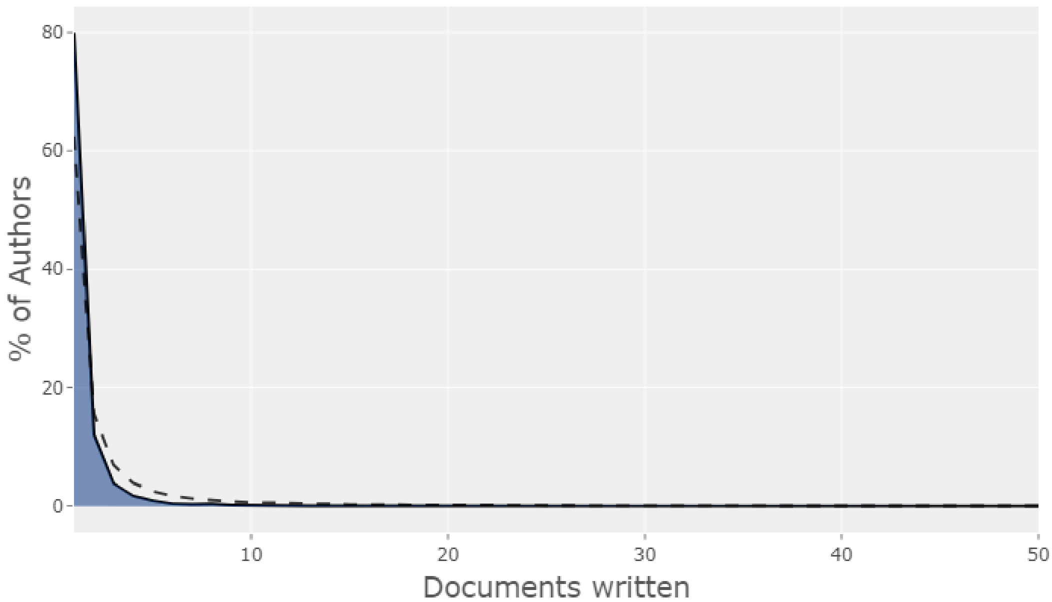

Figure 5.6 – Frequency distribution of scientific productivity

Table 5.7 refers to the top 20 authors in terms of published documents using the 'biblioAnalysis' function in Bibliometrix, as well as the first year in which they appeared in the sample and their citation metrics. The author with the largest number of publications is E.K Zavadskas, from Lithuania, with 50 documents in the research sample. This author also presents the highest citation metrics if the H, G, and M indexes are used. Following is J.Z. Ren, from China, and K. Govindan from Denmark. Interestingly, despite being the third author in terms of ‘h index’, ‘g index’, and ‘m index’ concerning the total bibliographic production, this author, who first appeared in the sample in 2013, presenting the highest absolute number of citations.

Table 5.7 – Most relevant authors

Author	h index	g index	m index	Citations	Documents	Publication start
Zavadskas EK	27	47	2.25	2,218	50	2010
Ren JZ	21	32	1.9	1,078	41	2011
Govindan K	19	29	2.1	2,355	29	2013
Mangla Sk	15	27	2.1	1,108	27	2015
Luthra S	15	25	2.1	993	25	2015
Tseng ML	11	24	1.5	584	24	2015
Sarkis J	17	23	1.4	1,376	23	2010
Wang Y	9	13	0.9	191	19	2012
Zhang L	7	11	0.5	134	18	2010
Liu Y	5	8	0.4	88	18	2010
Wu YN	10	16	1.6	268	18	2016
Turskis Z	10	17	0.8	980	17	2010
Wu KJ	8	17	1.1	401	17	2015
Kumar A	8	16	1.3	410	16	2016
Streimikiene D	9	16	0.9	378	16	2012
Tzeng GH	8	16	0.7	259	16	2011
Singh RK	8	12	1.3	151	15	2016
Mardani A	8	14	1.1	644	14	2015
Balezentis T	8	13	0.6	334	13	2010
Pamucar D	5	13	0.8	180	13	2016

Figure 5.7 shows the top 10 authors' production over time using the ‘authorProdOverTime’ function in Bibliometrix® and the plot by GGPlot2® R package (ggplot2.tidyverse.org). The line represents an author's timeline, the bubble size is proportional to the number of documents, and the color intensity is proportional to the total citations per year. With this information, it is possible to verify the construction of each author's line of research and verify where he contributed most to the area in the number of publications or being referenced by other authors.

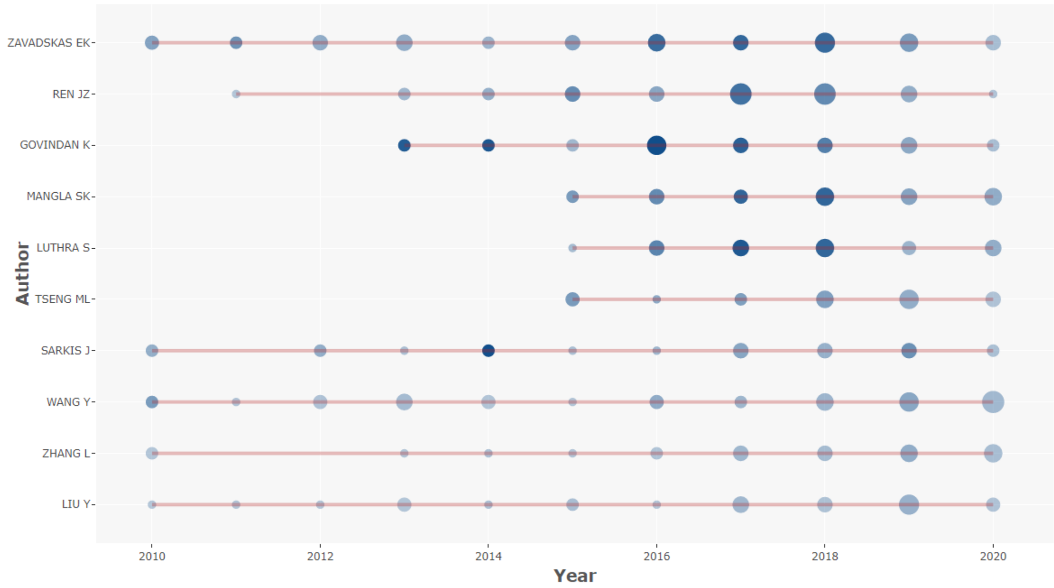

Figure 5.7 – Top authors' production over time

5.2.6. Document-level analysis

The data analysis was done at the document level, also analyzing its content and bibliography. Although the previous analysis at the level of MCDM/A methods is a by-product of the document level, it is assumed here that this part would be better understood and analyzed if separated from others given its importance to answer this research's questions.

As mentioned before, document refers to a scientific document (as article, review or conference proceedings in our investigation) included in a bibliographic collection, and reference are the document included in at least one of the reference lists of the document set.

Another definition necessary to understand the results is that of global and local citations. The first refers to the number of citations that a document received for documents contained in the entire database, in the Web of Science core collection in this case, so this measures the document's impact for the entire database and allows to count the citations received by other non-analyzed disciplines. Local citations are only counted with the sample, thus measuring a document's impact on the analyzed collection.

Table 5.8 presents the data from the most global cited papers. i.e., the documents with the most significant impact, by analyzing the entire Web of Science dataset using the ‘biblioAnalysis’ function in Bibliometrix.

Table 5.8 – Most relevant papers per global citations

Paper	**Global citations**	**Citations per year**	**Document type**
Brandenburg et al. (2014)	510	63.7	Review
Seuring (2013)	473	52.5	Review
Govindan et al. (2013)	427	47.4	Article
Zavadskas et al. (2011)	357	32.4	Review
Kuo et al. (2010)	311	25.9	Article
Shaw K et al. (2012)	306	30.6	Article
Cinelli et al. (2014)	294	36.7	Article
Mardani et al. (2015)	293	41.8	Review
Kumar et al. (2017)	291	58.2	Review
Buyukozkan and Çifçi (2011)	242	22.0	Article
Qin et al. (2017)	234	46.8	Article
Taylan et al. (2014)	226	28.2	Article
Luthra et al. (2017)	222	44.4	Article
Hashemi et al. (2015)	205	29.2	Article
Shen et al. (2013)	205	22.7	Article
Ahmad and Tahar (2014)	190	23.7	Article
Choudhary and Shankar (2012)	190	19.0	Article
Bathrellos et al. (2012)	158	15.8	Article
Kahraman and Kaia (2010)	156	13.0	Article
Jato-Espino et al. (2014)	155	19.3	Review

The document published by Brandenburg et al. (2014) presents the largest number of total citations, with 510 global citations, distributed at a rate of 64 citations per year and deals with a systematic literature review of the quantitative models for the sustainable supply chain management. Following is Seuring (2013) and Govindan et al. (2013) with 473 citations and 427 citations, respectively. These two articles also deal with sustainable supply chain management, demonstrating the importance of the theme. However, the first also deals with a systematic review of the literature on quantitative models, and the second is an application of a fuzzy-TOPSIS approach for selecting suppliers. Another document worth mentioning paper by the number of citations per year is Kumar et al. (2017). With 58 annual citations, this article deals a systematic review of the literature on MCDM/A methods applications for sustainable renewable energy development.

Most of the papers in table 5.8 are articles, but the review documents are the ones that hold the most considerable number of citations. After reading title and abstracts, it is possible to verify that the majority deals with: (i) green supply management (Brandenburg et al., 2014; Seuring, 2013; Govindan et al., 2013; Kuo et al., 2010; Shaw K et al., 2012; Buyukozkan and Çifçi, 2011; Qin et al., 2017; Shen et al., 2013); (ii) energy-related subjects (Kumar et al., 2017; Luthra et al., 2017; Hashemi et al., 2015; Ahmad and Tahar, 2014; Choudhary and Shankar, 2012; Kahraman and Kaia, 2010; and (iii) construction and urban related subjects (Taylan et al., 2014; Bathrellos et al., 2012; Jato-Espino et al., 2014). It is also worth noting that two articles deal with applications of MCDM/A methods for sustainable development and sustainability in general, (Cinelli et al., 2014; Mardani et al., 2015), while one evaluated the uses of MCDM/A approaches in economic studies (Zavadskas et al., 2011). Besides, table 5.9 shows the most relevant papers ranked by local citations.

Table 5.9 – Most relevant papers per local citations

Document	Local citations	Global citations	Document type
Govindan et al. (2013)	119	427	Article
Cinelli et al. (2014)	67	294	Article
Kuo et al. (2010)	64	311	Article
Buyukozkan and Çifçi (2011)	63	242	Article
Luthra et al. (2017)	62	222	Article
Kumar et al. (2017)	59	291	Review
Shaw et al. (2012)	50	306	Article
Shen et al. (2013)	50	205	Article
Ahmad and Tahar (2014)	42	190	Article
Hashemi et al. (2015)	42	205	Article
Seuring (2013)	41	473	Review
Brandenburg et al. (2014)	40	510	Review
Mardani et al (2015)	40	293	Review
Choudhary and Shankar (2012)	39	190	Article
Reza et al. (2011)	38	94	Article
Mangla et al. (2015)	37	150	Article
Su et al. (2016)	37	109	Article
Streimikiene et al. (2012)	36	135	Article
Zavadskas et al. (2011)	35	357	Review
Dai and Blackhurst (2012)	35	101	Article

Analyzing the local citations in table 5.9 using the 'biblioAnalysis' function in Bibliometrix, it is interesting to note that ten papers were also considered in table 5.8, possibly indicating the sample's representativeness for other sustainability areas in general. The highest number of local citations belongs to Govindan et al. (2013), previously analyzed as the third most cited globally. In sequence, Cinelli et al. (2014), with 67 local citations, analyzed the potentials of multi-criteria decision analysis methods to conduct sustainability assessment, while Kuo et al. (2010) integrated artificial neural network methods with traditional MCDM/A methods for green suppliers' selection. Unlike the results by global citations, analyzing the articles by local citations, articles had greater prominence, while the review articles were not the most cited. Additionally, it is possible to verify that only five articles in table 5.9 are not present in table 5.8. Mangla et al. (2015), Dai and Blackhurst (2012), and Su et al. (2016) investigate green supply management, while Streimikiene et al. (2012) deals with energy-related issues. Reza et al. (2011) hash out construction and urban related themes.

Finally, it is possible to analyze the articles' bibliographic citations in the sample using the 'biblioAnalysis' function in Bibliometrix, and the result is shown in table 5.10, that includes the most important articles for the analyzed documents, including the origin of some methods and the beginning of the study of specific areas. Most of the referenced articles were published after the 2000s, indicating the modern scientific field profile.

Saaty (1980) introduces the AHP method, while the works of Saaty (1990), Saaty (2008) and Vaidya and Kumar (2006) updated and discussed its improvements. In addition to that, Saaty (1996) presents the ANP method as an evolution of the AHP method. According to the results presented in table 5.4, these methods represent the first and the third place in the most used in SD issues respectively. Zadeh (1965) defines the fuzzy set, widely used in MCDM/A problems to deals with haziness, while Buckley (1985), Chang (1996), and Chen (2000) extended the AHP and TOPSIS methods to deals with fuzzy sets.

Hwang and Yoon review some MCDM/A methods in general, while Opricovic and Tzeng present a comparative analysis between TOPSIS and VIKRO methods. As discussed before, energy-related applications (Wang et al.

(2009), Pohekar and Ramachandran, 2004; Kaya and Kahraman, 2010) and green supply management (Seuring and Muller, 2008, Lee et al., 2009, Govidan et al., 2013, Buyukozan and Çifçi, 2012, Bai and Sarkis, 2010) are highlighted in table 5.10.

Table 5.10 – Most relevant cited references

Cited references	**Citations**
Saaty (1980)	663
Zadeh (1965)	318
Saaty (1990)	259
Hwang and Yoon (1981)	239
Saaty (2008)	217
Opricovic and Tzeng (2004)	160
Chang (1996)	158
Saaty (1977)	157
Wang (2009)	145
Saaty (1996)	136
Govindan et al. (2013)	119
Pohekar and Ramachandran (2004)	100
Seuring and Muller (2008)	98
Bai and Sarkis (2010)	90
Chen (2000)	88
Buyukozkan and Çifçi (2012)	86
Buckley (1985)	82
Kaya and Kahraman (2010)	82
Vaidya and Kumar (2006)	82
Lee et al. (2009)	80

Table 5.11 presents the 20 most prominent keywords plus in the sample using the ‘biblioAnalysis’ function in Bibliometrix. To select relevant words, additional filters and cleaning were performed in the database with The VantagePoint® toolbox. First, the terms related to the MCDM/A methods were excluded, like the terms 'sustainable development' and 'sustainability', and country names. Based on this information, it is verified that the keywords are related to applications, non-MCDM/A methods, and other emerging terms in sustainability, such as 'circular economy'.

Table 5.11 – Most relevant keywords

Keywords	Documents
Design	151
Supply chain management	135
Energy	134
GIS	133
Sustainability assessment	129
Life-cycle assessment	124
Industry	118
Renewable energy	111
Supplier selection	95
Construction	87
Performance evaluation	87
Technologies	87
Policy	73
City	54
Technology	53
Corporate social-responsibility	49
Innovation	49
Climate-change	42
Circular economy	38
Social sustainability	36

Table 5.12 presents search trends based on the emerging keywords (plus + authors') for each year. In 2010, studies related to topics involving the use of MCDM/A methods in agriculture were the most significant trend of the year, moving on to studies on MCDM/A in green energy in 2011 and 2017, that shows the relevance of this theme. In 2013, studies on forests and protected areas were on the rise, as opposed to 2014, where studies focused on multi-criteria applications for marine life, water pollution, and fishing. In 2015, sustainable development in cities came up strongly, especially in MCDM/A for transportation, smart cities, and green build purposes. In 2018, studies focused on life-cycle assessment, a technique for assessing and quantifying environmental impacts associated with a good or service. In 2019, a prominent topic in previous analyzes was increased: green supply chain management, ending with studies of air pollution and the use of hybrid MCDM/A methods in 2020. Hybrid MCDM/A methods are generated by combining different MCDM/A methods or a MCDM/A method with a non-MCDM/A method.

Table 5.12 – Trend topics per year

Topic	Year
Agriculture	2010
Green Energy	2011
Green construction	2012
Forest / Protected areas	2013
Sea	2014
Urban sustainable development	2015
Cleaner production	2016
Green Energy	2017
Life-cycle assessment	2018
Green supply chain management	2019
Air pollution / Hybrid MCDM/A	2020

From the information obtained in the data analysis phase, information crossings were then carried out to obtain science mapping and to analyze scientific production in more than one dimension simultaneously.

5.3. Data visualization results

Visualization techniques were used here to knowledge synthesis structures, drawing a big picture of scientific knowledge attempts to find representations of intellectual connections within the dynamically changing system of scientific knowledge (Small, 1997). Nevertheless, science mapping aims to display the structural and dynamic aspects of scientific research (Borner et al., 2003). This can be done using bivariate analysis or even multivariate analysis using the "structures of knowledge" to discover hidden patterns.

Science mapping allows investigating scientific knowledge from a statistical point of view, answering three questions: (i) "What science talks about?"; (ii) "How the work of an author influences a given scientific community?"; and (iii) "How authors, institutes, and countries interact with each other?" (Chen, 2013).

To answer these questions, the conceptual structure, the intellectual structure, and the social structure of using MCDM/A methods in SD and sustainability issues should be analyzed.

5.3.1.
Conceptual structure of knowledge

The conceptual structure of knowledge represents relations among concepts or words in a set of publications. The words and terms to relate their co-occurrence are used aiming to analyze their relationships, as well as to check bivariate intersections between different dimensions in order to verify the science mapping.

In figures 5.8 to 5.11, the nodes' size is related to the number of publications, while the edges' continuity is related to the strength between the nodes. That is, the more dashed the line, the less the areas are analyzed jointly.

Using the VantagePoint®, it was possible to create a co-occurrence map between those keywords, as shown in figure 5.8. The terms related to the application of the MCDM/A methods, the MCDM/A methods themselves, non-MCDM/A methods, and sustainability concepts are arranged in a map form, with the size of the node related to the frequency with which the term appears in the analyzed documents, and the edges related to the co-occurrence between them, that is, they are frequently used together.

From figure 5.8, it is possible to infer the relationships between these terms. For example, the close relationship between information and innovation, the relationship between the ANP and DEMATEL methods, often used together called DANP, the relationship between management, innovation, supply chain management, and industries, as of the use of fuzzy and TOPSIS for supplier selection. Another interesting relationship is between AHP and GIS, often used together called G-AHP, mainly for site selection, such as for agriculture and industries. Finally, the link between supply chain management and circular economy could be highlighted.

It is also possible to verify three major groups, the least of which is related to MCDM/A applications for construction and design. At the same time, the second is related to the analysis and construction of sustainability indicators and issues related to energy. Finally, on can see a larger one that comprises most of the analyzed MCDM/A techniques and is linked to sustainability in the industry.

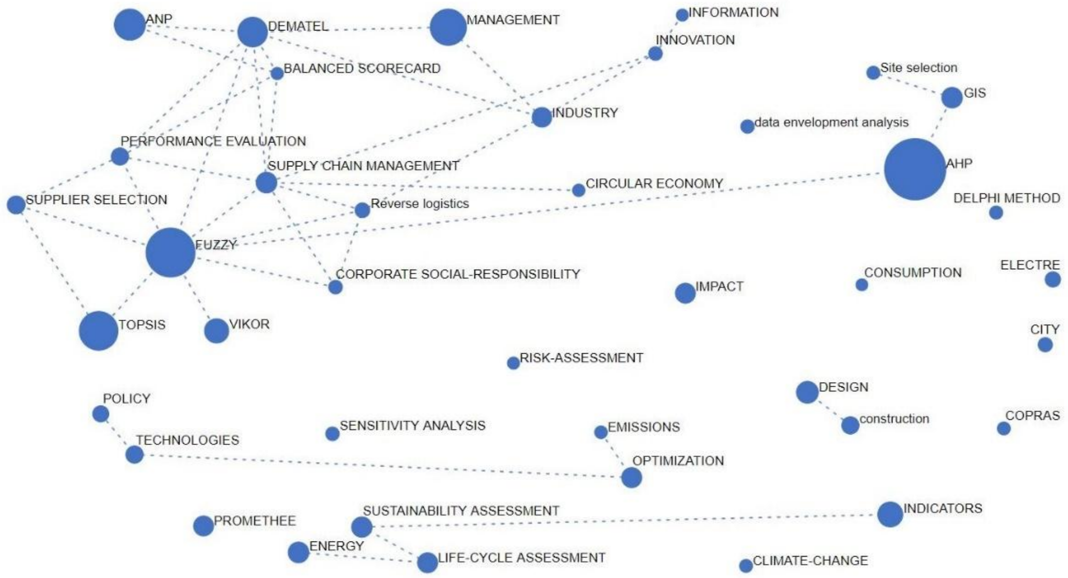

Figure 5.8 – Auto-correlation map of keywords

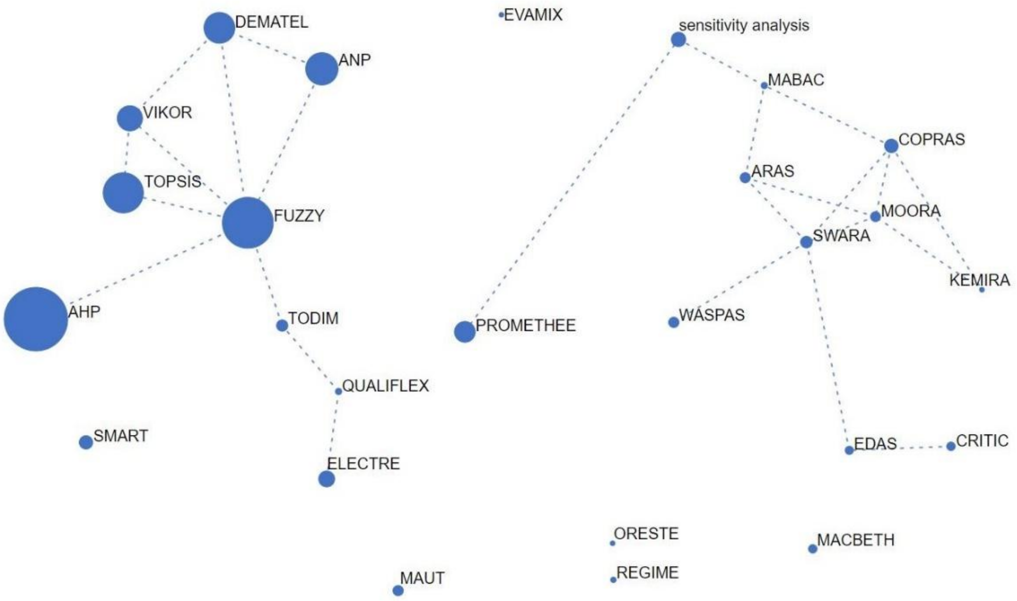

Figure 5.9 – Auto-correlation map of MCDM/A methods applied in SD issues

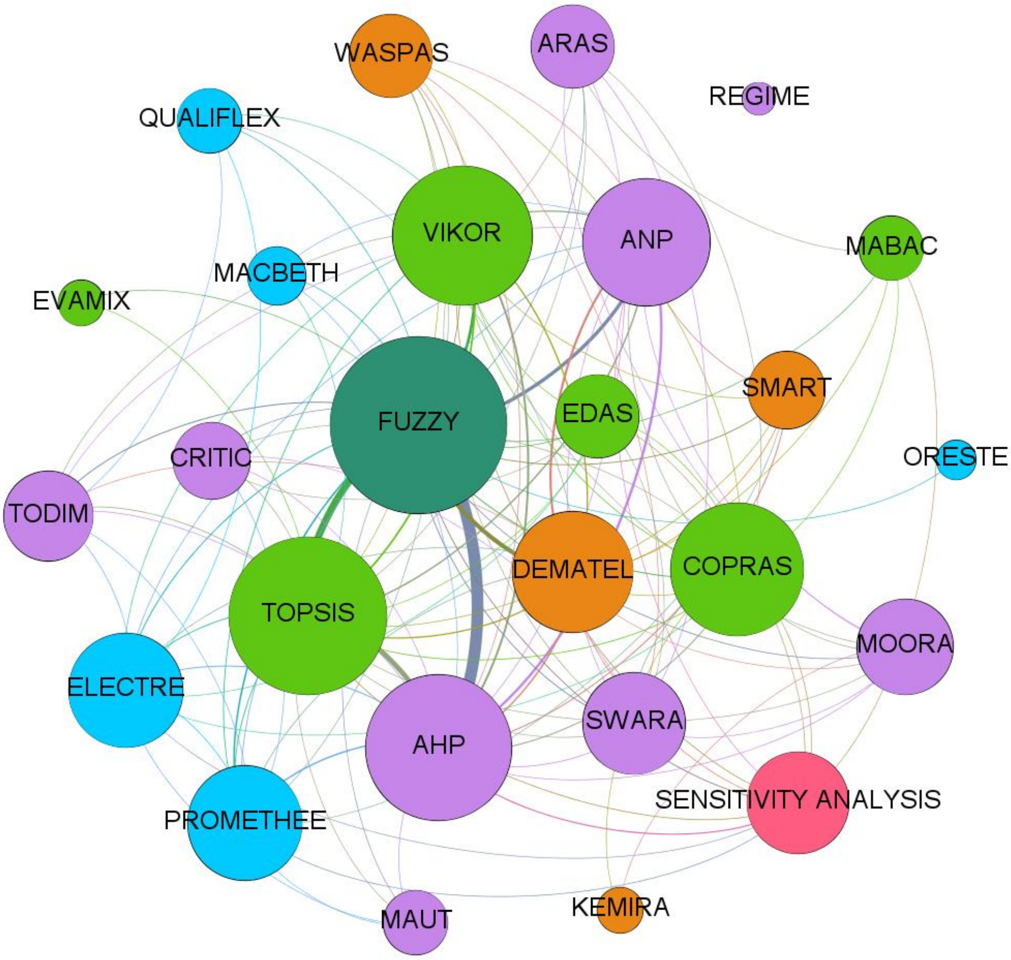

Figure 5.10 – Co-occurrence network of MCDM/A methods applied in SD issues

Continuing to analyze the autocorrelation between the terms corresponding to the methods of MCDM/A, use of fuzzy logic and use of sensitivity analysis of keywords plus and author's keywords were isolated, and the autocorrelation between them was verified. At first, the map represented in figure 5.9 was generated, which visualizes the most important connections between the MCDM/A methods. It is essential to understand that the link between two MCDM/A terms may be related to some hybridization of the methods or, generally in a smaller number, to the use of different methods in the same study to compare their performance.

It is possible to verify in figure 5.9 the presence of two clusters, the first revolving around the use of fuzzy logic and containing methods such as AHP, TOPSIS, VIKOR and DEMATEL, while the second revolves around sensitivity analysis, with methods such as PROMETHEE, ARAS and MABAC. It is interesting to note that some MCDM/A methods already uses fuzzy set in their process, like ELECTRE and PROMETHEE, so these methods does not appears as strongly connected in the network showed in figure 5.9.

Some methods do not belong to any of these clusters: SMART, MAUT, ORESTE, REGIME, MACBETH, and EVAMIX. This means that, in the sample, their connections with the use of fuzzy logic, sensitivity analysis, or hybridization did not prove to be significantly robust.

It is also possible to analyze these relationships using the Gephi® software to check all the correlations between the themes, including the weak correlations in figure 5.10. The size of the nodes is directly proportional to the number of documents using the MCDM/A method, the size of the edges is also directly associated with the strength of the connection between the methods, and the color is related to the grouping according to the taxonomy of the MCDM/A methods adopted for this study. As expected, the fuzzy relationship permeates mostly methods, while the use of sensitivity analysis was less frequent. Even observing the weak relationships, the REGIME method is never used with any other method, and the AHP, TOPSIS, ANP, VIKOR, and DEMATEL methods have the most significant amount of most robust connections that is, they are methods generally used together, both in hybrid approaches and in comparative analysis.

Likewise, it is possible to verify the autocorrelation relationships between the MCDM/A applications by research area. In figure 5.11, one can observe two groups. The first involves the most considerable amount of research areas and concentrates the highest percentage of documents, highlighting a solid link between ‘Urban Studies’ and ‘Public Administration’ research areas, as well as a strong link between ‘Environmental Sciences & Ecology’ and ‘Science & Technology’, in addition to other science mappings between research fields. The second cluster reveals a strong link between ‘Water Resources’, ‘Meteorology & ‘Atmospheric Sciences’ and ‘Geology’. Two research areas have no connections to other nodes - ‘Telecommunication’s, and ‘Transportation’.

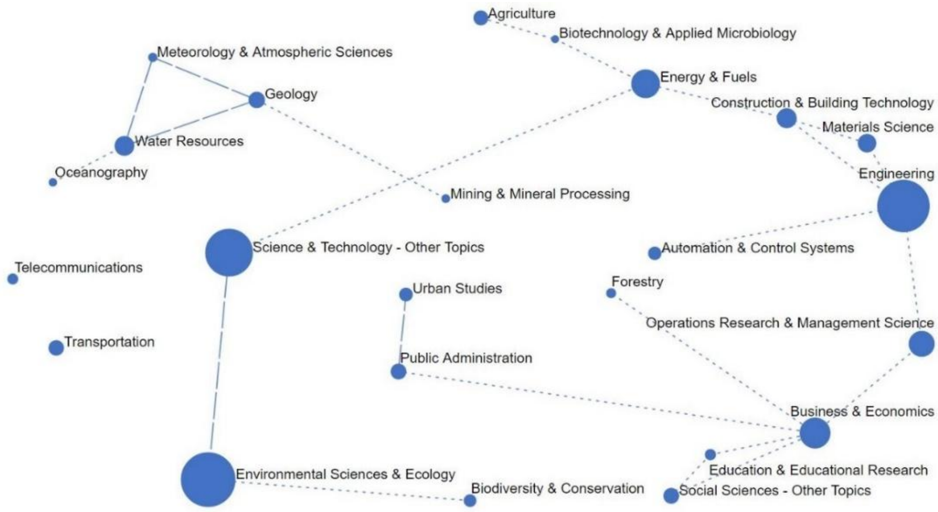

Figure 5.11 – Auto-correlation map of MCDM/A applications in SD issues by research area

The bivariate analysis combines dimensions previously analyzed to verify the correlation between terms of different dimensions to simplify the interpretation of the phenomenon being studied. The first relationship was between the MCDM/A applications by research area concerning the applied MCDM/A method, as show in figure 5.12.

From this figure, it is possible to verify the most used MCDM/A methods in the twenty-four applications by research areas. The AHP method assumes the leadership in all research areas, since it is the only method that appears in all areas. Also, the AHP method has been applied in the largest number of publications, concentrated in ‘Engineering’, ‘Environmental Science and Ecology’, and ‘Science and Technology’. These areas also account for the highest use of ANP, DEMATEL, TOPSIS, and VIKOR.

On the other hand, KEMIRA did not register any use in these areas, and EVAMIX and MABAC were only used in ‘Operations Research’ and ‘Management Science’.

Figure 5.12 – Correlation between MCDM/A methods applied in SD issues by research area

Continuing to analyze the MCDM/A applications by research area, the correlation between them and the top 10 countries (in terms of number of publications) obtained by the authors affiliation could be obtained using the VantagePoint®. The results are shown in figure 5.13.

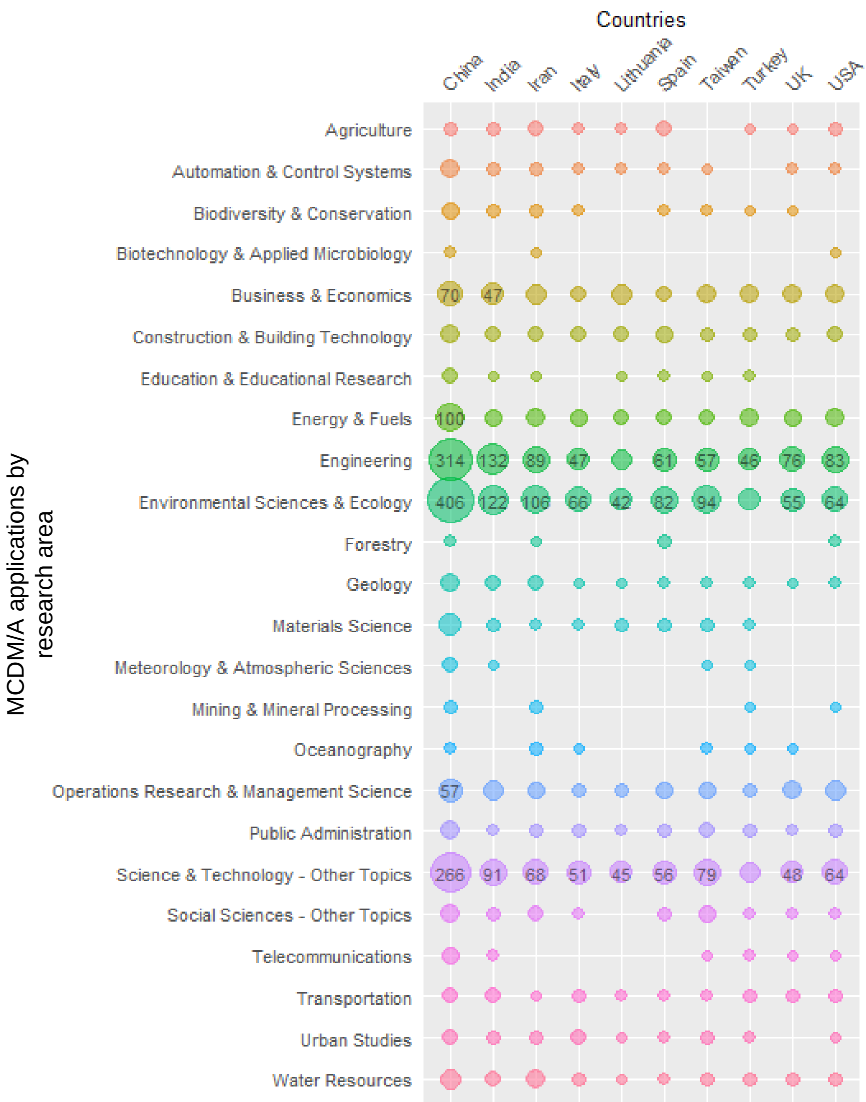

Figure 5.13 – Correlation between research areas of MCDM/A applications for SD and countries

China was the only country that has published in all analyzed areas and maintained the leadership in all of them. Some research areas such as ‘Business and Economics’, ‘Construction and Building Technology’, ‘Energy and Fuels’, ‘Engineering, Environmental Sciences and Ecology’, ‘Geology’, ‘Operations Research and Management Science’, ‘Public Administration’, ‘Science and Technology’, ‘Transportation’, and ‘Water Resource’s were researched by all countries. Going in the opposite direction, ‘Biotechnology and Applied Microbiology’ has studies published only by China, Italy, and the USA.

No country has used all methods in its studies. Meanwhile, the AHP, ANP, DEMATEL, PROMETHEE, TOPSIS, and VIKOR methods have been used in studies from all countries. Unlike the previous analyzes, China, the country with the largest bibliographic production, does not take the lead in some methods, namely ARAS, COPRAS, MOORA, SWARA, and WASPAS, are more employed by Lithuania, while India leads in the use of PROMETHEE method.

Finally, in figure 5.14, the top 10 countries are listed in terms of quantity of publications and the MCDM/A methods analyzed.

Countries

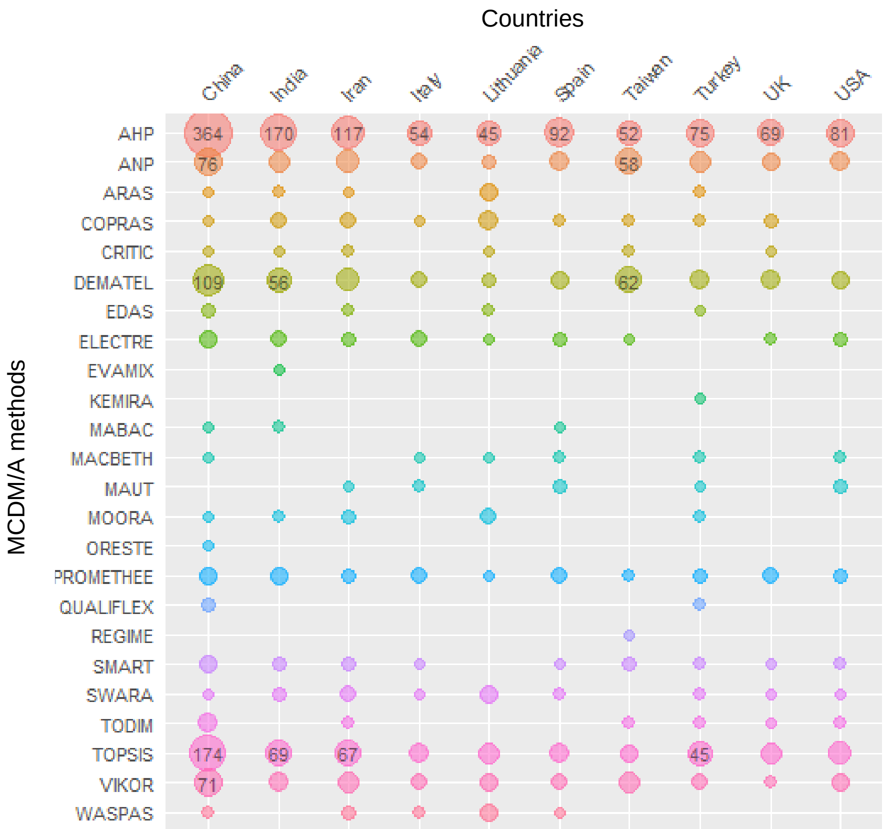

Figure 5.14 – Correlation between MCDM/A methods applied in SD issues and countries

Figure 5.15 shows the correlation between the publication sources and the research areas, so it is possible to verify which sources dominate each publication areas. Although they are highly relevant for research on sustainability and sustainable development, the areas of ‘Agriculture, Automation and Control

Systems’, ‘Biotechnology & Applied Microbiology’, ‘Business & Economy’, ‘Education & Educational Research’, ‘Forestry’, ‘Geology’, ‘Material Science’, ‘Meteorology & Atmospheric Science’, ‘Mining & Mineral Processing’, ‘Oceanography’, ‘Social Sciences’, ‘Telecommunications’, ‘Transportation’, ‘Urban Studies’, and ‘Water Resources’ did not present publishing sources in the 'core sources' zone under Bradford law. Furthermore, it is possible to verify a greater differentiation between the sources based on their publication profile, such as Sustainability dominating the areas of ‘Environmental Sciences & Ecology’ and ‘Science & Technology’. Simultaneously, the Journal of Cleaner Production also advances to the Engineering area.

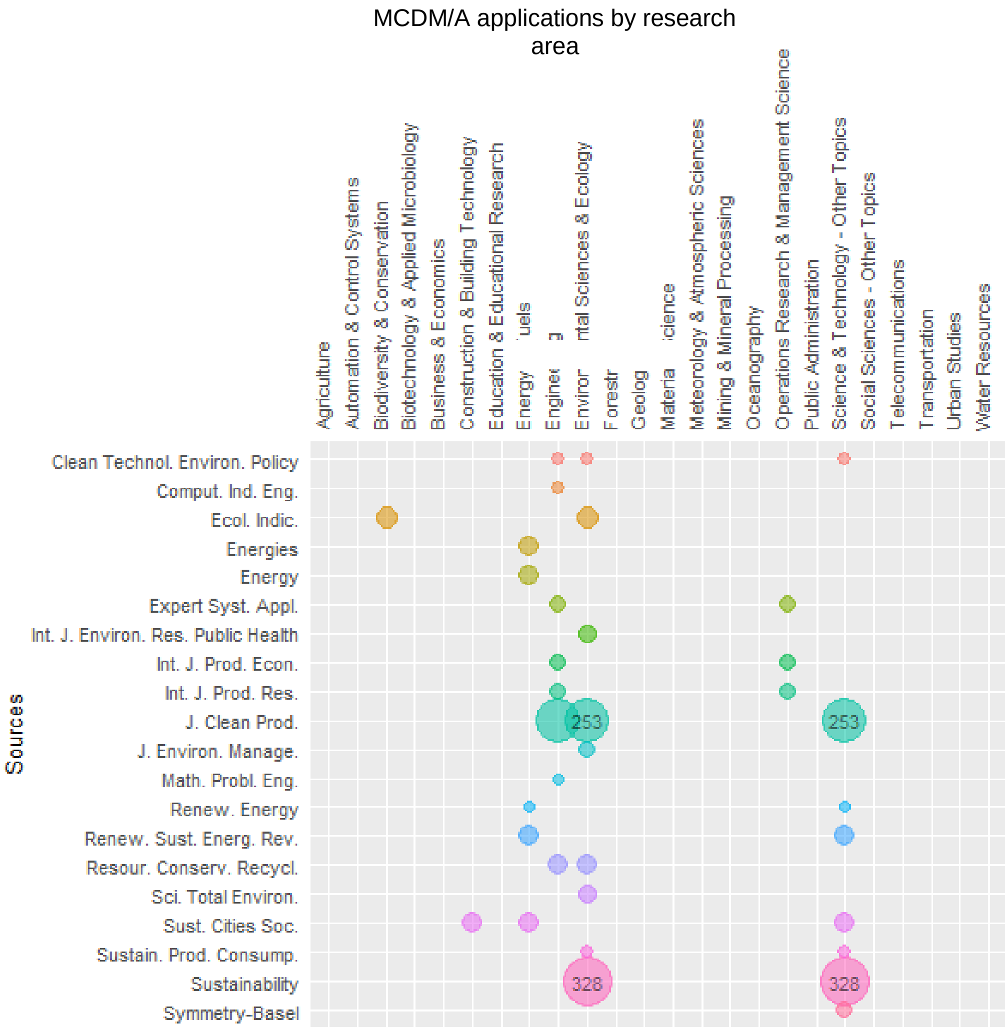

Figure 5.15 – Correlation between sources and research areas of MCDM/A applications for SD

The co-occurrences between the sources of publication and the methods of MCDM/A or with the authors' affiliation countries were also analyzed, but they did not return relevant results in the same way as the previous results. The sources' behavior follows the same pattern as the occurrence of the MCDM/A methods or the countries alone.

Visualization techniques were used here to represent a longitudinal science map and strategic diagrams, as proposed by Cobo et al. (2011b) and Callon et al. (1991). The thematic evolution analysis reveals the interaction between keywords (concerning the MCDM/A methods' application research areas). It identifies shifts in the boundaries of the focused areas, exploiting their interactions and convergence by two techniques using a longitudinal map analysis and strategic diagrams concerning different time-slices.

For this research, the following time-slices were defined: (i) 2010-2013; (ii) 2014-2017; and (iii) 2018-2020. Figure 5.16 presents the longitudinal science map of the MCDM/A methods applications in sustainable development or sustainability research fields using 'thematicEvolution' function in Bibliometrix.

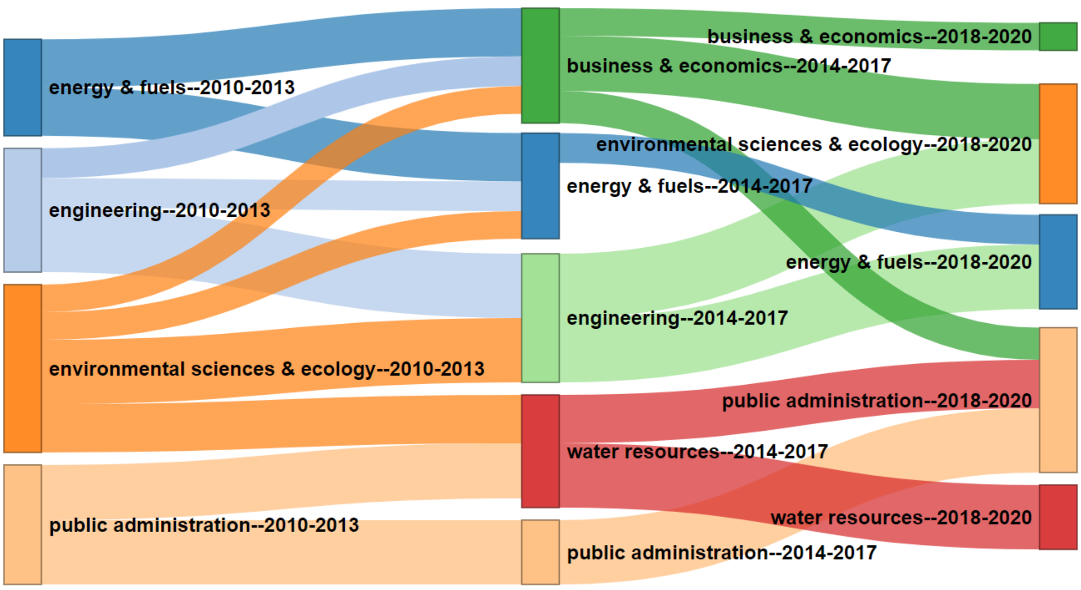

Figure 5.16 – Thematic evolution: a systemic and longitudinal science map analysis

From a systemic perspective, all of the broader areas are presented in this science map. The line thickness is proportional to the inclusion index, and the size of the node is proportional to the number of documents published. As can be seen, in the first period (2010-2013), four significant areas of research stand out from the others, while in the other periods one can identify the presence of five areas. This longitudinal map allows verifying the transformation of the applications of MCDM/A methods in these areas. For instance, applications in 'Environmental Sciences & Ecology' were deployed in further studies of MCDM/A applications on 'Business & Economics' 'Energy & Fuels', 'Engineering', and 'Water Resources'.

Besides, the strategic diagrams are graphical plots that highlight the different themes of the sample and shows their importance in the entire research field. These plots are formed by four quadrants, as described by Cobo et al. (2011b): (i) upper-right quadrant: motor-themes; (ii) lower-right quadrant: basic themes; (iii) lower-left quadrant: emerging or disappearing themes; (iv) upper-left quadrant: very specialized/niche themes. In synthesis, the themes are clustered and classified by their centrality, which represents the importance of the theme to the research field and by their density, representing their stage of development.

Figures 5.17 represents the strategic diagram of the analyzed research field in light of applications of MCDM/A methods in different contexts of decisions.

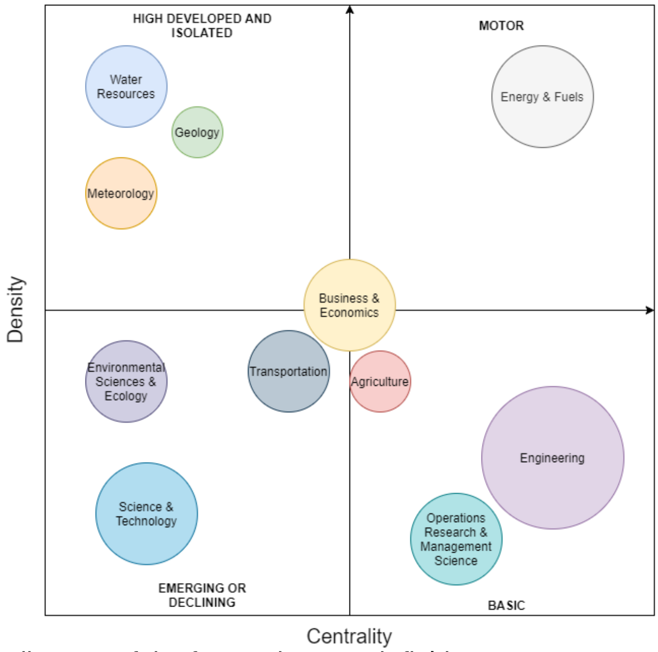

Figure 5.17 – Strategic diagram of the focused research field

Initially, two strategic diagrams (2010-2013 and 2014-2017) were analyzed by period according to the longitudinal map of figure 5.16. However, they did not return relevant results. Therefore, the period from 2010 to 2020 was used for this analysis. Analyzing the results obtained from this visualization (figure 5.17), it is possible to check the primary research areas associated with SD and sustainability studies that applied MCDM/A methods, such as ‘Engineering’. On the other hand, studies related to ‘Energy & Fuels’ are classified as drivers for the focused field. Applications of MCDM/A methods on ‘Water’, ‘Geology’ and ‘Meteorology’ are isolated from the others, which may indicate their high development. Finally, MCDM/A applications in ‘Business & Economic’, ‘Transportation’, and ‘Agriculture’ appear in the center of the quadrant, so it is impossible to group them in any of these stages of development. The size of the nodes is related to the number of articles included in this theme.

Figure 5.18 shows the use of MCDM/A methods over the examined timeframe, where it is verified that the AHP method, the most used in the sample, has a regularly growth over time, maintaining the leadership in all years and with a peak of production in 2019.

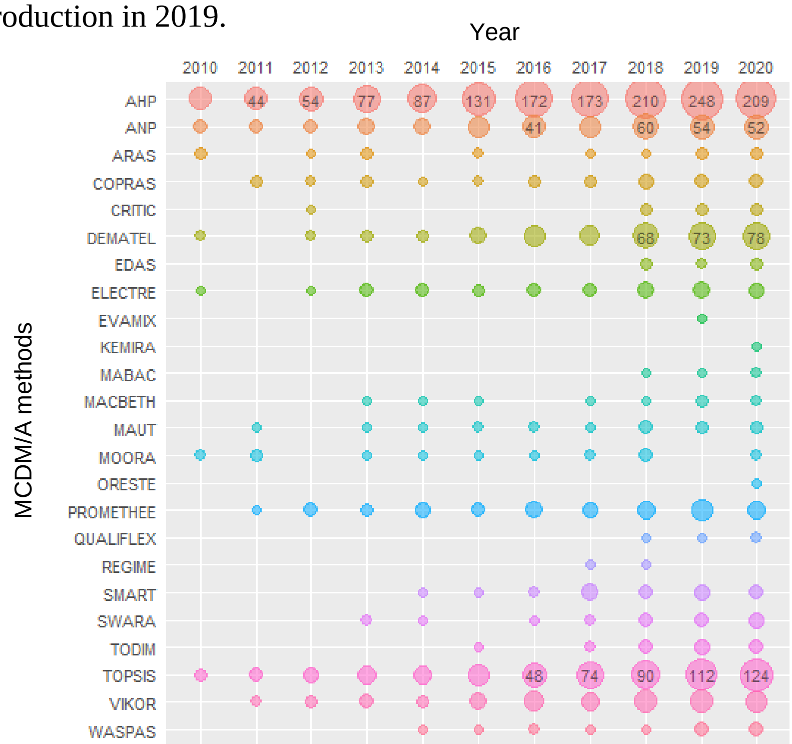

Figure 5.18 – MCDM/A methods applied in SD issues per year

Finally, figure 5.19 shows the use of the MCDM/A applications by research area over the investigated years, where it is verified that ‘Engineering’, ‘Environmental Sciences & Ecology’, and ‘Science & Technology - Other Topics’ show sustainable growth over time. Other areas appeared steadily or not significantly during the analyzed timeframe.

Figure 5.19 – Research areas of MCDM/A applications in SD issues per year

The use of the TOPSIS, DEMATEL, and VIKOR methods has increased considerably over the years, assuming the peak of production in 2020 for both methods. It is also interesting to note that the annual production of studies using DEMATEL has surpassed the use of ANP since 2018 and has shown an upward behavior since then. Another important recent evolution happened with the PROMETHEE and TODIM methods, which practically doubled their uses from 2018 to 2019, but were greatly affected by the low bibliographic production in 2020. EVAMIX and KEMIRA, according to figure 5.18, have been only used in a document in 2019 and 2020, respectively. Other methods appeared steadily or not significantly during the evaluated timeframe.

5.3.2.
Intellectual structure of knowledge

The intellectual structure shows relationship between nodes with represent references by citation and co-citation analysis in a network form. Although citation analysis in the documents or authors form are the most common analysis in bibliometrics to get the intellectual structure, the co-citation analysis (Small, 1973) is helpful in a detecting a shift in paradigms and schools of thought.

Co-citation is the connection between two documents that cite a third document (reference) and can be represented in a co-occurrence matrix and, consequently, in the form of a network. With this, some clusters can be revealed, observing how the software classified the articles and drawing relationships between them to interpret the results and analyze the proximity and location of these clusters.

Figure 5.20 represents the sample's co-citation network, in which the VOSviewer® software identified some thematic clusters related to the previous results obtained during the data analysis stage. According to common characteristics like the central theme, one can interpret that the clusters, such as those related to ‘Ecosystem management’ (pink), have more recent papers, but they are distanced from the other areas and the cluster linked to Agriculture (light pink) for example. On the other hand, the 'Building & Transportation' clusters (yellow) and 'Energy-related studies' (red) are very closely, indicating exchanging information with a considerable amount and sharing the same source between them. The other three clusters identified are very close to each other, with the cluster with supply chain management studies (blue) being the division between corporate sustainability (green) and industry and logistics (purple).

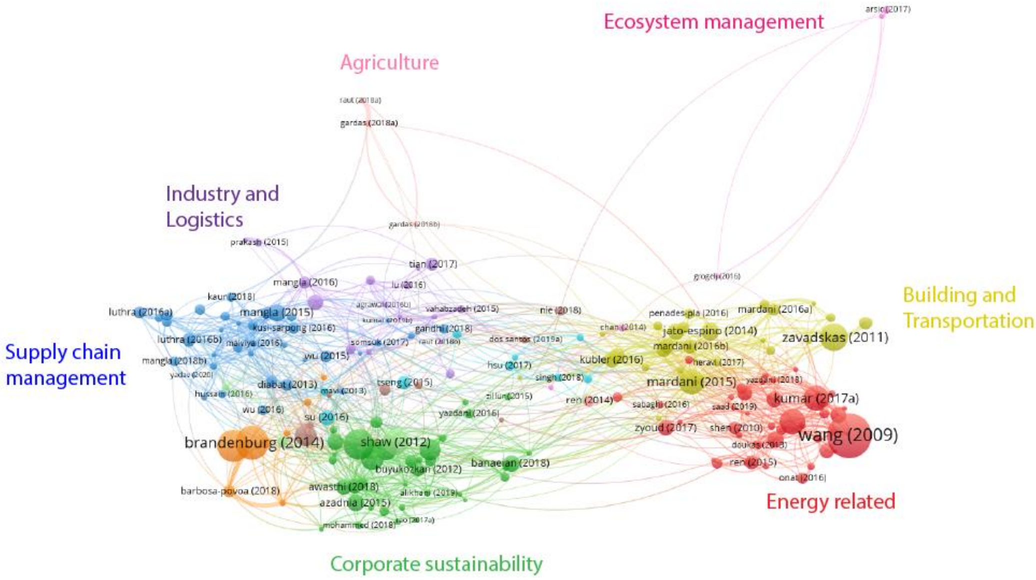

Figure 5.20 – Documents' co-citation network

Finally, figure 5.21 shows the relationship between the documents referenced by the articles in the sample, the prominent authors, and the methods related to their publications using the 'threeFieldsPlot' in Bibliometrix® package. In this way, it is possible to verify that most of the authors presented in this list have applied more than one method of MCDM/A concerning SD and sustainability issues in their publications.

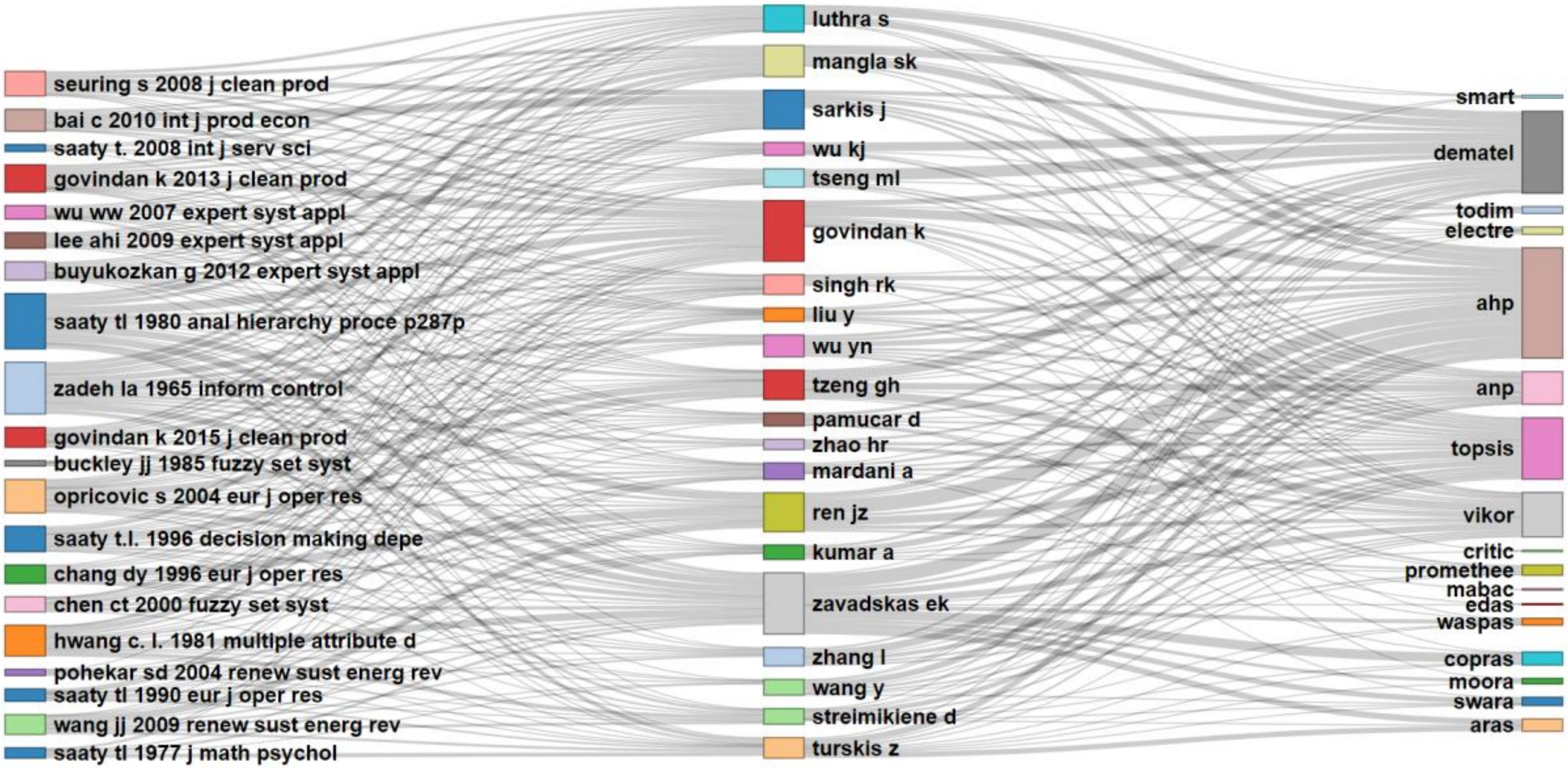

Figure 5.21 – Associations between references, top authors, and MCDM/A methods

5.3.3.
Social structure of knowledge

Social structure shows how authors or institutions relate to others in the field of scientific research, so in this research the co-authorship network structure as proposed by (Peters et al., 1991) was adopted. Thus, groups of authors, the most influent authors, hidden communities, and relevant institutions can be discovered and highlighted. So, if one gets the author's profile, he/she can also use the author's affiliation information (including country).

Figure 5.22 shows the research sample's top 20 country collaboration in a network view (at the left-side) within four cluster proposed by the VOSViewer® software, and in an overlay view (at the right-side), where purple color indicates a majority of older papers (before 2015) while yellow nodes indicate newer documents (after 2017).

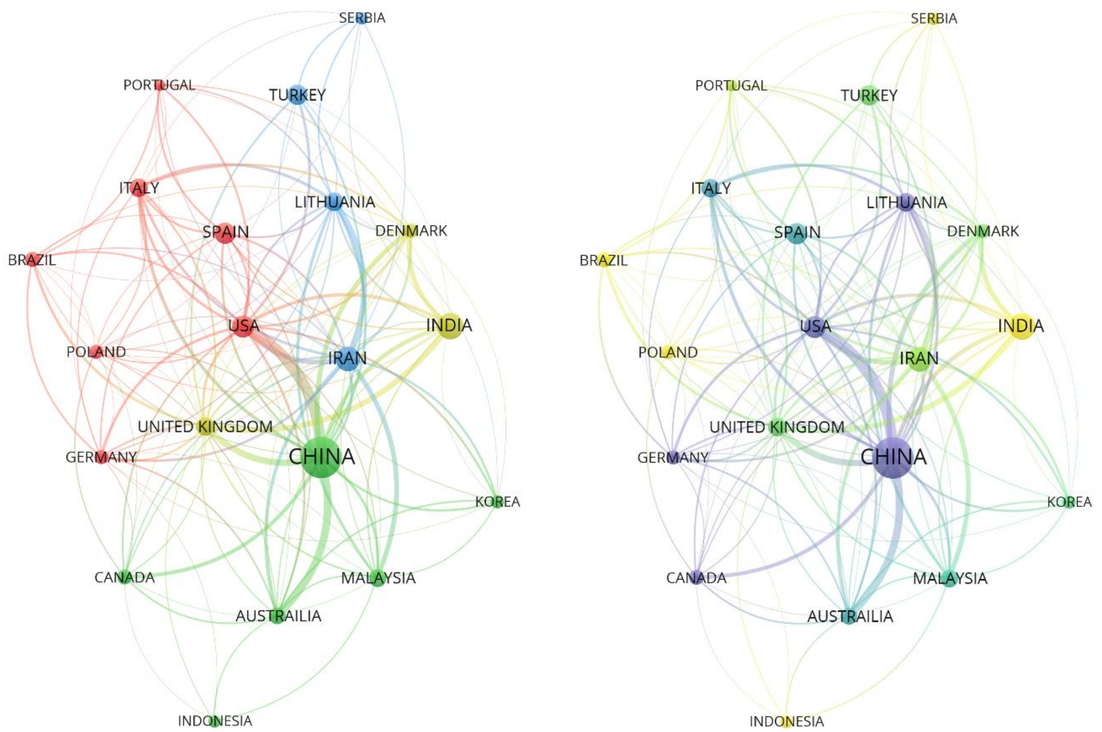

Figure 5.22 – Countries collaboration network in network view (left-side) and in overlay view (right-side)

As can be observed in figure 5.22, the nodes' size is related to the number of publications in each country, and the edges are proportional to the work done in partnership with other countries. The first cluster, in green, is led by China, which has strong links with all the countries in this cluster, as well as with the USA, which commands the red group with some countries in Europe and Brazil. The proximity between the nodes is also related to the countries' proximity (in cooperative work). That is, Indonesia and Serbia are the most distant countries in the whole analysis.

Another possible view to analyze the relationship between countries is through the countries collaboration map, as represented in figure 5.23.

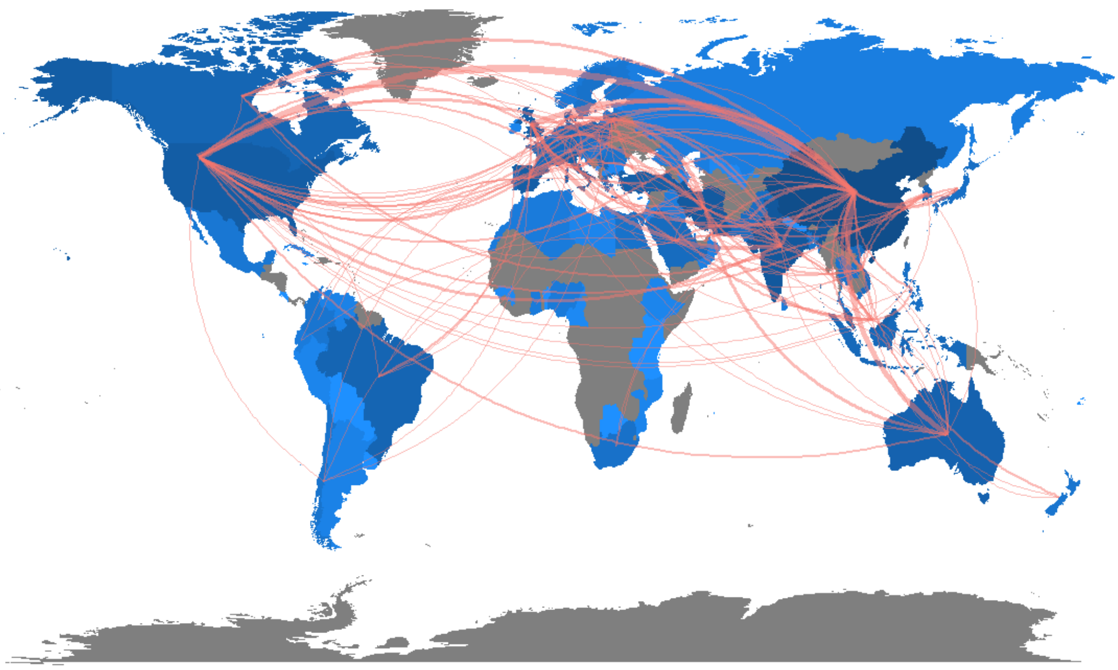

Figure 5.23 – Countries collaboration map

Although it is difficult to visualize the strength of cooperation between countries, visualization can quickly inform countries with more publications on the topic (in deep blue) and those with few publications (in light blue) or no publications on the topic (in gray). It is possible to see the lack of studies in most countries on the African continent and lower South American production. Looking at the edges that indicate international collaboration, it is possible to verify that European countries collaborate a lot among themselves, possibly due to the European Union's scientific cooperation agreements. China, the USA, England, and Australia also show good international cooperation compared to other countries. It is also likely to verify that geographical proximity is not necessarily related to greater cooperation between countries. In South America, for example, cooperation between countries on the same continent is very small or non-existent, and the same is true for the African continent.

6
Conclusions

The rise of sustainable development as a field of applied research has been observed across various disciplines. Within the UN 2030 Agenda scope, the achievement of 17 Sustainable Development Goals (SDGs) requires decision-making considering multiple decision criteria usually complex and in conflict. In this research, an attempt was made to conduct a bibliometric analysis on the MCDM/A approaches in various contexts concerning sustainable development. In this regard, 3,473 published scientific articles from 2010 to 2020 were retrieved from the WoS database, selected, and reviewed.

The objectives of this study, to identify and visualize evolutionary pathways and build a scientific roadmap focusing on multicriteria decision-making methods applications for sustainable development issues by applying bibliometric analysis in various dimensions and levels (e,g., document level, authors' level, countries' level, MCDM/A methodological approaches, and application areas), were achieved, and the findings summarized in Section 5 make significant contributions to the state-of-the-art on MCDM/A approaches focusing sustainable development issues. In fact, the results shed light on the main MCDM/A applications to support decisions concerning the sustainable development, 2030 Agenda, and SDGs.

The bibliometric study was conducted following a recommended bibliometric workflow and the state-of-art of text-mining techniques, and employed three software for data pre-processing and analysis, as: (i) Bibliometrix® R’package; (ii) VOSViewer®; and (iii) The VantagePoint® software. The main conclusions associated with the research questions defined in the introductory chapter can be stated as follows.

The annual scientific production of the investigated research field presents an almost 20% compound annual growth rate (CAGR). However, it is interesting to note that after the 2030 agenda propose, in 2015, the annual growth rate of scientific production intensified, with this period accounting for almost 3/4 of the total publications.

Amongst the 28 MCDM/A methods applied to decision-problems regarding the SDGs' achievements, the most used is the AHP method (used in 1,445 studies), followed by TOPSIS (542 studies), ANP (337), DEMATEL (304), VIKOR (193), PROMETHEE (123), and ELECTRE (65). Following the taxonomy proposed by Danesh et al. (2017), the most used methods are utility-based (9 methods), followed by compromise (6 methods), and outranking (5 methods).

The results shown in figures 5.9 and 5.10 confirm two methodological trends observed in the MCDM/A literature, i.e., the integration of MCDM/A methods and the use of fuzzy set logic and sensitivity analysis. Concerning the integration of MCDM/A methods, the most common is the hybrid AHP-TOPSIS method. The integration of ANP and DEMATEL methods, in a D-ANP form, can also be highlighted. In turn, the favorite MCDM/A methods to combines with fuzzy set logic are FUZZY-AHP; FUZZY-TOPSIS; FUZZY-ANP; FUZZY-VIKOR; and FUZZY-DEMATEL. On the other hand, the sensitivity analysis was mostly used with PROMETHEE and MABAC methods. In terms of the higher incidence of MCDM/A applications by research area in sustainable development, the area with more MCDM/A applications is 'Environmental Sciences & Ecology', encompassing 1,214 studies. Following this area, 'Engineering' comprises 1,112 studies, while 'Science & Technology' 911 studies, and 'Business & Economics' 350 studies. It is also important to highlight the 'Energy & Fuels' area within 299 papers.

From the perspective of country contributions, China is the largest producer of papers, with 30% of all studies produced, three times than the second place, both in SCP and MCP. However, this country presents low international collaboration. The second and third places are India and Iran, with 8% and almost 7% of the sample, respectively. Despite being responsible for only 1% of the sample documents, Denmark has the highest internationalization ratio, with more than twice as many articles being produced in international cooperation. Another insightful result is shown in figure 5.13, concerning the MCDM/A applications in

SD issues by research area per country. For example, it is possible to infer that 'Biotechnology & Applied Microbiology' area has studies published only by China, Italy, and the USA.

It is interesting to note that the research trends analysis reveals that in 2020 the state-of-the-art topic was studies of air pollution and the use of hybrid MCDM/A methods. Hybrid MCDM/A methods are generated by combining different MCDM/A methods or a MCDM/A method with a non-MCDM/A method and show themselves as an evolution movement for the MCDM/A methods. Besides, the air pollution studies could be related to the Sars-Cov-2 pandemic and the imminent possibility of respiratory diseases, in addition to those caused by pollution.

When the correlation between the MCDM/A methods and MCDM/A applications by research area was presented, as expected, the AHP method assumes the leadership in all research areas, since it is the only method that appears in all areas. Also, AHP has the largest number of publications concentrated in 'Engineering', 'Environmental Science & Ecology', and 'Science & Technology'. These areas also account for the highest use of ANP, DEMATEL, TOPSIS, and VIKOR.

Finally, it is possible to verify that the primary themes for sustainability or sustainable development studies that applied MCDM/A methods, such as Engineering. On the other hand, studies related to Energy & Fuels are classified as drivers for the area. Applications of MCDM/A methods on Water, Geology and Meteorology are isolated from the others, which may indicate their high development. Finally, MCDM/A applications in 'Business & Economic', 'Transportation', and 'Agriculture' appear in the center of the quadrant, so it is impossible to group them in any of these stages of development.

Mapping and systemically analyzing the evolution of the research field covering applications of multicriteria decision making methods for sustainable development in the last two decades can help governments and organizations in sociotechnical transitions towards sustainability. Thus, MCDM/A for sustainable development is emerging as a recent study domain within management and public policy fields. The findings presented in this dissertation can help policymakers, researchers, and practitioners by providing directions about MCDM/A applications in various contexts concerning SDGs achievements within the 2030 Agenda framework or any generic SD framework.

Accordingly, further research suggestions can be summarized as follows:

- To conduct a systemic literature review (SLR) to improve the results of the bibliometric analysis by a hybrid approach in order to cover some gaps, how to understand the reason for applying the MCDM/A methods one by one the results achieved through them;
- To expands the bibliographic search on MCDM/A methods to verify possible combination of MCDM/A and non-MCDM/A methods aiming to explore the potential of artificial intelligence, sensitive analysis, and other advanced management tools to enhance the analytical accuracy of studies.

The findings presented in this dissertation can help policymakers, researchers, and practitioners by providing directions about MCDM/A applications in various contexts concerning sustainable development and SDGs achievements within the 2030 Agenda framework. Policymakers can better explore MCDM/A applications to prioritize projects and programs for SDGs achievement and define public policies addressed to the 2030 Agenda implementation in different contexts. Besides, public and private organizations from diverse sectors can replicate and improve existing MCDM/A models to enhance their strategic decision-making processes regarding resource allocation to corporate strategies associated with sustainable development.

7
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