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Paradigms, Methods, and Tools for Multicriteria Decision Models in Sustainable Industry 4.0 Oriented Manufacturing Systems

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Abstract: The rise of Industry 4.0 tools transforms the way production plants are planned, controlled, and monitored, allowing organizations to achieve greater flexibility, efficiency, and cost reduction. This way, the use of emerging technologies provides a new look at the industrial sector, particularly concerning sustainability issues in a society that suffers worsening effects from climate change. On the other hand, the degree of success when implementing Industry 4.0 practices in sustainable-oriented manufacturing systems is closely related to hard decision-making, which involves, in practice, multiple and even conflicting criteria to model multidimensional problems. For that reason, it is worth recognizing the importance of the multi-criteria decision-making/aid (MCDM/A) approach to support decision modeling and application so that this research field can be better explored to enhance Industry 4.0 implementation and innovative advances in operations management. Given this backdrop, this paper undertakes a systematic literature review (SLR) of 118 papers, thereby combining a set of predefined keywords with several exclusion criteria to detect the literature that is related to sustainable decisions in manufacturing systems that introduced Industry 4.0 practices in the Web of Science (Clarivate Analytics) database. Cross-matching important research metrics from these papers encourages this work to provide readers with two axes of discussion with the aid of five research questions: a bibliometric analysis and a content analysis. Among many findings, some guidelines for decision-making are put forward to share insights and provide decision-makers, scholars, experts, stakeholders, and other professionals with an overall managerial background when applying sustainable-oriented multicriteria models in manufacturing systems.

Keywords: multicriteria; Industry 4.0; sustainability; manufacturing system; systematic literature review

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1. Introduction

In light of the new century, the concept of sustainability has become increasingly prominent, even becoming an essential criterion for consumers' purchasing decisions in society [1]. Consequently, the industrial sector, from manufacturing to services, is adopting increasingly sustainable practices in its production processes in order to minimize the negative impacts caused by the development of its potential polluter's activities, thereby including environmental issues to be evaluated in terms of that life quality and cleaner production systems. This way, the implementation of sustainable practices might bring not only environmental benefits but also opportunities for enhancing production efficiency, competitiveness, and profitability from a strategic perspective [2].

However, the adoption of sustainable practices is a challenging task for many companies. Additionally, the internal resistance to changing organizational planning processes and operations management due to cultural reasons, as well as the allocation of financial, material, and human resources for this purpose, illustrates some barriers to implementing sustainable manufacturing systems [3]. In fact, many structured actions for guiding sustainable development in an organization imply high financial investments in a limited environment in terms of budgetary constraints. Moreover, the emergence of new technologies to cover managerial gaps and enhance production efficiency introduces new paradigms and tools to the decision-making process, and they do not always have an attractive financial return over a short-term horizon. For that reason, the implementation of sustainable practices with the aid of new technologies may reshape the relationship of public and private entities with suppliers or stakeholders since it is necessary, for example, for companies to adopt different criteria in the selection of suppliers and in the choice of sustainable products.

In this sense, Industry 4.0 has brought a transformation in production process optimization, allowing greater flexibility, efficiency, and cost reduction through the use of enabling technologies such as systems integration, additive manufacturing, the Internet of Things (IoT), artificial intelligence (AI), and big data. These technologies also have the potential to contribute to cleaner production, thereby promoting sustainability from social, financial, and environmental perspectives [4]. For instance, using sensors and data analysis, it is possible to identify different wastes in productive systems and then reduce both costs and environmental impacts. Bearing this in mind, it might be possible to assume that the application of digital technologies allows manufacturing systems to become more agile and integrated.

Thus, the emergence of Industry 4.0 tools seeks to improve systems' control and monitoring, with the aim of providing a more efficient decision-making process. On the other hand, the complexity behind the conception and implementation of these tools in manufacturing systems implies the urge for techniques to consolidate the structuring and resolution of decision problems since they can have negative environmental impacts if they are poorly managed in the process [5]. For that reason, there is a growing concern about energy consumption and the generation of electronic waste, which certainly impacts operations management's ability to overcome technological paradigms that exist in daily operations [6].

On considering what has been exposed, it is worth noting the importance of the Multi-Criteria Decision Making/Aiding (MCDM/A) approach, which is useful in complex contexts that involve many alternatives to be evaluated against several criteria/attributes, often conflicting with each other [7]. The principles of MCDM/A can be employed in several contexts, as demonstrated in the application of Roselli et al. (2020) in the health area, with the study on triage of patients during the COVID-19 pandemic [8], as well as in the study in the environmental area, with the research of Monte and Morais (2019) on the water supply system [9], and in the study by Da Silva et al. (2020) on prioritizing flood risk in urban areas [10].

Particularly in the context of Industry 4.0, MCDM/A methods can be used in various applications in sustainable manufacturing systems, such as supplier selection, portfolio definition, inventory management, equipment allocation, and the choice of technologies, among others. From analyzing the state-of-the-art in this field, therefore, it is evident that there is a wide range of benefits when applying the multicriteria method, assuming that decision-makers (DMs) are able to deal with decisions involving multiple criteria, thereby mathematically inserting their preferences over a set of consequences. In a complex situation, it is expected that DMs might consider several other criteria when building the preliminary assumptions of a multicriteria model, seeking not only profit but also sustainability and life quality in terms of social equity.

Thus, this paper undertakes a systematic literature review (SLR) on multicriteria methods in sustainable operations management, with a particular focus on the context of Industry 4.0-oriented manufacturing systems. The SLR includes a critical analysis of the use of MCDM/A methods in this context, as well as the key challenges and opportunities associated with the adoption of these methods to support strategic issues in Industry 4.0 manufacturing systems. For this, about 118 peer-reviewed articles identified in the Web of Science (Main Collection) were analyzed through bibliometric and content analysis. Therefore, by exploring technological and decision-making paradigms, tools, and methods, this article also aims to provide the academic community and organizational sectors with useful guidelines and important insights about decision-making problems in the real world through the proposition, application, and methodological advances in the light of the multicriteria approach.

This paper is structured as follows: An overview of MCDM/A methods to support problem structuring and strategic decisions is presented in Section 2, as is Section 3, which is the theoretical background related to sustainable manufacturing systems with views to understanding the further discussion and formulating the research questions (RQs). In Section 4, the search strategies and criteria to compose the systematic literature review are described, as well as in Section 5, which provides analyses and discussions of the results, considering the issues raised by the RQs. Finally, in Section 6, some final remarks are made, and some open issues and opportunities for future research are indicated.

2. A Theoretical Background on MCDM/A Methods in Supporting Strategic Decisions

In this section, an overview of multicriteria decision methods will be presented. Some ways of classifying these methods will also be addressed, with the aim of providing an understanding of how they work and how they can be applied to support multi-criteria decision problems.

Many decisions are made on a daily basis, both personal and professional. A multicriteria decision context is represented by problems that have at least two alternatives that must meet multiple objectives, which is the focus of this SLR [11]. Given this context, it should be noted that there is a need to develop models that formally represent the problem and are supported by multicriteria methods. The models can assist in visualizing the alternatives to the problem as well as finding the best solution according to the decision-makers preferences while maintaining the rationality of the process. Here, the decision-maker (DM) is a central actor in multicriteria decision problems, since this differentiates MCDM/A problems from operational research (OR) optimization problems. It is the DM—or even a group of DMs, in the case of a group decision approach—who takes responsibility for the consequences assumed by his/her decisions. In addition, other actors can be part of the process in order to support DMs, such as analysts, specialists, experts, and stakeholders, among others.

In a decision-making context in an organization, MCDM/A methods are generally used with the active participation of a manager or executive who assumes DM responsibility. In this sense, it must be remarked that the decision-making intends to incorporate subjective aspects, which are inherent to the problem context and the DM's relative preferences and which should be dealt with during the process of choosing, ranking, and sorting from a set of alternatives [7]. To achieve this goal, it is important that the DM understand the criteria involved in the decision problem so that it can properly establish value judgments with regard to his/her relative preferences over different criteria and alternatives in order to obtain an effective decision.

Formally, there are many methods reported in the literature that deal with a multicriteria approach and that can be classified in different ways. The classification allows a better understanding of the conceptual assumptions made in those methods, allowing the DM to make the appropriate choice of method to conduct the decision process and solve the problem faced.

A first distinction can be made with regard to the nature of the set of alternatives to the problem: a discrete set of alternatives or a continuous set of alternatives [7]. When a predefined, discrete set of alternatives is considered, a wide range of multicriteria (or multiattribute) decision methods can be used to choose, rank, or sort those alternatives according to the decision problem being dealt with [12]. On the other hand, a continuous set of alternatives means that the objectives considered in the modeling can assume any value as long as they satisfy a set of constraints imposed in the model. In this sense, optimization techniques are applied to what we call multiobjective decision methods.

Another classification is related to the rationality with which that are able to deal with the consequences of the decision problem [7]. A compensatory rationality is considered when the DM is willing to allow a low level in one criterion to be compensated by a higher level in another criterion, considering tradeoffs between them. On the other hand, a non-compensatory rationality is considered when such a compensation mechanism is not present in the preference structure of the DM. This is essential to undertaking a proper elicitation procedure that deals with the DM's rationality, making the decision recommendation credible.

Other classifications consider the three main types of methods [12]: single-criterion synthesis, outranking, and interactive methods. Methods classified as single criteria of synthesis use additive aggregation techniques to obtain a global score for each alternative, permitting comparison between them. The best alternative is the one with the highest global value. The methods classified in this category are in the context of multi-attribute value theory (MAVT) and multi-attribute utility theory (MAUT) [7]. On the other hand, outranking methods consider pairwise comparisons between alternatives in order to obtain those that fit better in a higher number of criteria (considering a coalition of criteria).

Keeney & Raiffa (1976) define the most traditional methods among multidimensional decision models as those based on multi-attribute value theory (MAVT) and multi-attribute utility theory (MAUT) [11]. In both MAVT and MAUT models, one of the highest challenges faced is the establishment of the criteria scaling constants k_i, which are usually called weights but do not represent only the level of importance of the criterion. These additive models assume that the DM is willing to elicit, from his/her preference structure, the weights or scale constants that represent the inter-criteria evaluation. By eliciting these parameters, one can aggregate them into a global value or utility. Elicitation procedures have been developed to support the elicitation of scaling constants, such as the classical tradeoff [11] and the swing procedure [13]. This way, through additive aggregation, one can obtain the recommendation for DM according to the decision problem (choice, ranking, portfolio selection, or even sorting from a set of alternatives). As mentioned in [14], the evolution of MCDM/A methods implies new paradigms of decision-making to extract from the DM its personal value judgments in terms of intra- and inter-criteria evaluation, whether by adopting holistic evaluation or even elicitation by decomposition of alternatives. In fact, many MCDM/A methods introduce in their elicitation procedures innovative approaches for ensuring reliable decisions, i.e., resulting in less cognitive effort and fewer inconsistency rates. It will be discussed better in this SLR.

Additionally, the methods of the ELECTRE family and the PROMETHEE family are the main representatives of outranking methods [12,15]. Despite MAVT- and MAUT-based methods assuming an additive aggregation model to compose a unique global value, outranking methods are based on pairwise comparisons of alternatives, seeking to establish relationships and use them to reach a final decision. In this method, two phases are used to model the problem: the first phase involves the creation of an outranking relationship, aggregating information between the alternatives and criteria, while the second phase aims to explore this relationship to support the decision. They present some difficulties for DM when applying this methodology. At first, it might be cited as the amount of information that the DM needs to provide, such as weights, agreement and disagreement indexes, indifference and preference thresholds, as well as veto values or intermediate values between preference and indifference thresholds. This information is specific to each method, and sometimes it is considered difficult for DMs to define it. In addition, these methods permit DMs to express their preferences without hesitation [7].

Hence, Table 1 presents methods with a discrete set of alternatives that deal with a compensatory rationality (AHP, MACBETH, FITradeoff, SMARTS, SMARTER, and BWM) and non-compensatory rationality (outranking methods—ELECTRE and PROMETHEE).

Table 1. Summary of some recurrent MCDM/A methods in the literature.

Method	Principles and Description	Types of Problems	Reference
AHP (Analytic Hierarchy Process) method	It is one of the most well-known methods used in multicriteria problems. It allows DM to perform paired comparisons of alternatives, considering the relative importance of each of the criteria. Initially, DM performs a qualitative judgment (nominal scale) and then transforms it to the verbal scale defined by Saaty, with values ranging from 1 to 9. With this, peer-by-pair comparison matrices are generated that reflect the DM preferences for each alternative in relation to each criterion. Further studies such as [16] pointed out some important remarks when applying AHP: once it might be difficult to treat problems with more than seven alternatives and the possibility of inconsistent DM judgments, the range of consequences of each alternative and criterion is not considered, and the importance scale is predetermined and arbitrary.	Choice, Ranking.	[17]
SMARTS/SMARTER	SMARTS and SMARTER are additive methods that have been proposed to incorporate the swing procedure to elicit the scaling constants. Those methods consider additive aggregation to obtain the global values of alternatives. The SMARTER also incorporates the ROC weights instead of performing the second step of the swing procedure.	Choice, Ranking.	[18]
MACBETH	The MACBETH method is an additive aggregation method that works based on pairwise comparisons performed by decision-makers comparing elements (criteria and/or alternatives) based on a linguistic scale in terms of attractiveness. Such linguistic judgments are converted into a numeric scale based on linear programming models in order to provide a recommendation for the DM.	Choice, ranking	[19]
Best-Worst Method (BWM) and Best-Worst Tradeoff (BWT)	It is a multicriteria aggregation method that has the advantage of requiring fewer comparisons compared to other matrix-based methods. The BWM seeks to minimize the greatest discrepancy between the weight ratios and the preferences declared by the DM. The method uses the consistency index to evaluate the reliability of the results and can be used to derive independent weights or combined with other methods. However, as in the AHP method, the BWM uses the Saaty subjective scale, which can introduce inconsistencies in the DM judgments. It should be noted that further studies have detected that the addition or removal of an alternative can lead to a reversal of order and distort all comparisons made since BWM is based on paired comparisons. Further advances include the tradeoff elicitation procedure in BWM, namely BWT.	Choice, Ranking.	[20,21]

Table 1. *Cont.*

Method	Principles and Description	Types of Problems	Reference
FITradeoff method	Is used to elicit the scale constants in the context of MAVT and presents the same axiomatic structure as the traditional tradeoff [11], but incorporates partial information concepts. To provide its preferences, DM can make use of two paradigms: decomposition elicitation and holistic evaluation. In decomposition elicitation, pairs of consequences are presented, where for each pair of adjacent criteria, the best consequence for the worst criterion is compared with an intermediate value for the criterion that is best placed in the ordered ranking. With this, an inequality is obtained that is inserted in the linear programming problem (LPP) of the model. At the end of the process, the space of weights is obtained. In the holistic evaluation, the DM has a joint view of the alternatives to the problem, expressing dominant relations between them with the support of graphical and tabular visualizations. The DM can choose to select the best alternative from the set or eliminate the worst among them. This preference information is included in the LPP or can be used to end the decision-making process.	Choice, Ranking, Portfolio, Sorting.	[22]
ELECTRE	This family of methods is based on agreement and disagreement indexes, as well as on weak and strong outranking relations and preference and indifference thresholds. These methods use the kernel concept, which represents the solution to the choice problem by being the subset of alternatives that is not outranked by any other kernel. ELECTRE allows DMs to make adjustments in preference and indifference thresholds according to their preferences.	Choice, Ranking, and Sorting.	[23]
PROMETHEE	PROMETHEE methods work with overclassification flows, which allow the analysis of the advantages and disadvantages of each alternative in relation to the others in terms of each criterion.	Choice, Ranking, Sorting, and Portfolio.	[15]
VIP analysis method	Is a multicriteria decision method that is based on the additive aggregation of partial information. One of the main characteristics of this method is the use of inequalities to establish the relationships of dominance and potential optimality between the alternatives. Another important feature is the possibility of obtaining a graphical visualization that represents the domains of the alternatives. It is important to emphasize that VIP analysis does not present a structured form for the elicitation of preferences, which can be considered a limitation in relation to other methods.	Choice, Ranking.	[24]

Table 1 summarizes a set of the most recurrent MCDM/A with notable applicability in many organizational contexts, including problems related to Industry 4.0, when dealing with a discrete set of alternatives. They differ according to some particular characteristics, such as the elicitation procedure, rationality, the type of decision problem, and even the decision paradigms involved in the mathematical modeling of DM's preferences.

In addition, it should be highlighted that the SMARTER method and the FITradeoff method mentioned in Table 1 belong to a specific category of MCDM methods that work based on partial information about the decision makers' preferences. These methods seek to reduce the cognitive effort and the amount of information required by DMs when eliciting preferences [25,26]. Several partial information methods also use the swing elicitation procedure to guide the elicitation process, such as the PRIME method [27], the RICH method [28], and the interval SMART/SWING method [29]. The FITradeoff method is a widely known partial information method, with several applications presented in the literature [30]. This method is suitable for solving MCDM problems of choice problematic [22], ranking problematic [31], sorting problematic [32], and portfolio problematic [33,34]. Recently, De Almeida et al. (2021) incorporated the possibility of combining two preference modeling types—elicitation by decomposition and holistic evaluations—in FITradeoff, which can bring several benefits to the decision process [14].

When dealing with a continuous set of alternatives, objectives can be expressed as functions, and alternatives are possible values of variables integrating those functions. According to Antunes et al. (2016), multiobjective optimization includes explicitly multiple evaluation aspects that can be represented by different objective functions, and therefore, multiobjective optimization models aim to find a reasonable solution for the decision maker, which represents an acceptable compromise outcome [35]. In multiobjective optimization, a nondominated solution (in the space of objectives) or an efficient solution (in the space of decision variables) is a feasible solution for which no other feasible solution exists, simultaneously improving all objective function values [35]. The concept of a nondominated or efficient solution is extremely important in multiobjective optimization since the compromise solution chosen by the DM should be part of the set of nondominated solutions. In this sense, multiobjective optimization approaches focus their efforts on finding efficient solutions that represent a reasonable outcome for the decision-maker. A well-known procedure to find efficient solutions in multiobjective optimization models is to transform the original multiobjective problem into a single objective problem through scalarizing functions. There are three basic scalarizing techniques that are generally used to compute efficient solutions: (i) Selecting one of the objective functions to be optimized, considering all others as constraints; (ii) Optimization of a weighted sum of the objective functions; (iii) Minimizing a distance function to a reference point, such as the ideal solution.

In multiobjective optimization, the preferences of the decision makers can be incorporated into the decision models in three different ways [35]: a priori articulation, in which the preference parameters are fixed prior to computation of the model; a posterior articulation, when the whole set of nondominated solutions is obtained and then the preferences of the DM are expressed in face of this set; and progressive articulation of preferences, in which preference declarations are intercalated with computation of solution steps, which is done by interactive methods. There are several methods suitable for dealing with multiobjective decision problems, such as methods based on the optimization of a utility function [36], goal programming [36,37], and the multiobjective simplex method [38]. Several interactive methods for dealing with multiobjective problems have also been developed, such as the step method (STEM) [39] and the TRIMAP method [40].

Altogether, an in-depth analysis of the MCDM/A methods analyzed in this paper is important to understand, in light of the SLR scope, how this methodology can contribute to supporting strategic decisions for ensuring sustainable practices in the productive sector. To do so, it might be useful for manufacturing professionals to understand the underlying assumptions behind the use of the MCDM/A approach as well as the main issues to be addressed before conducting the decision-making process. This is the backdrop for proposing the SLR. As observed next, current papers related to Industry 4.0 put a spotlight on multifaceted aspects that encourage professionals to structure, apply, and model MCDM/A models.

3. The Role of Sustainable-Oriented Industry 4.0 Practices in Manufacturing Systems

In this section, the literature will explore the importance of adopting sustainable practices with the aid of Industry 4.0 tools to deal with typical problems in manufacturing systems. Afterward, the critical discussion revealed the main aspects to be investigated by this SLR, thereby reinforcing the potential contributions of this paper for the academy and practitioners in covering emerging topics on this matter.

3.1. Implications of Sustainability Management in Industrial Operations

The search for sustainable manufacturing systems has a growing interest, highlighting the literature on sustainability in Industry 4.0 with the emergence of new methods, tools, critical analysis, and comprehensive reviews in this research field. Thus, several review papers are available to investigate this relationship and address different aspects, such as the adoption of technologies and sensors, the use of intelligent systems, and sustainable systems. Through some key findings of these works, it is possible to have an overview of the theme with a view to identifying gaps for future planning, developing, and choosing MCDM/A methods. Despite the fact that the main discussion regarding this section is centered on emerging sustainable Industry 4.0 topics, it is not the focus of this paper to gather a comprehensive analysis of the key findings of review papers related to Industry 4.0.

As illustrated in Figure 1, it is worth noting that, despite some review papers that deal with sustainable Industry 4.0 manufacturing systems, this work aims to investigate, in the light of the MCDM/A approach, how decision models can be improved from methodological and strategic perspectives.

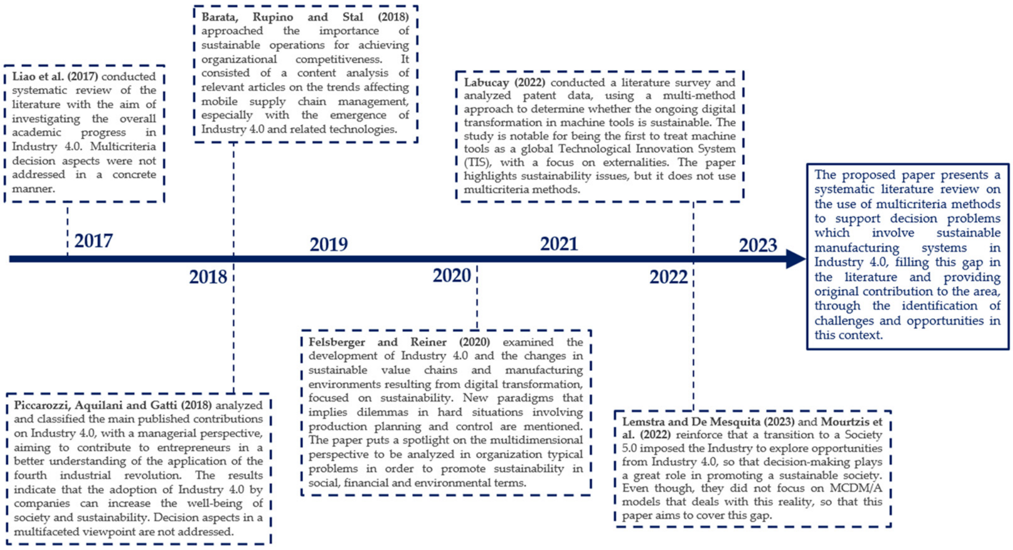

Figure 1. Timeline of review papers on sustainable-oriented Industry 4.0 systems: evidencing the contributions of this SLR [41–47].

From a generic perspective, Liao et al. (2017) conducted a systematic review of the literature with the aim of investigating the overall academic progress in Industry 4.0. In the study, four research sub-questions were raised, and the results of the analysis of the articles summarized the current research activities in the area as well as highlighted existing deficiencies and directions for future research. The authors state that the results obtained in the review can be used as a basis for future research in Industry 4.0. However, as in other reviews mentioned earlier, multicriteria decision aspects were not addressed in a concrete manner [41].

The importance of sustainable operations for achieving organizational competitiveness was already discussed by Barata, Rupino, and Stal (2018) in their contributions. It consisted of a content analysis of relevant articles on the trends affecting mobile supply chain management, especially with the emergence of Industry 4.0 and related technologies [42]. Similarly, Piccarozzi, Aquilani, and Gatti (2018) aimed to analyze and classify the main published contributions on Industry 4.0 from a managerial perspective, aiming to contribute to entrepreneurs' better understanding of the application of the fourth industrial revolution [43]. For this, 68 articles were selected for reading and classification. The results indicate that the adoption of Industry 4.0 by companies can increase the well-being of society and sustainability. Thus, despite having a focus on Industry 4.0 and highlighting sustainable aspects, this research does not address decision-making aspects from a multifaceted viewpoint.

On the other hand, Felsberger and Reiner (2020) conducted an analysis of approximately 90 articles with the aim of examining the development of Industry 4.0 and the changes in sustainable value chains and manufacturing environments resulting from digital transformation [44]. The analysis had a specific focus on sustainability, and the results indicated that the combination of information technologies and manufacturing equipment can drive global sustainable competitiveness. However, the authors already mentioned that it introduced new paradigms that imply dilemmas in hard situations involving production planning and control. Despite the fact that this study does not address the gap that our paper aims to fill, it puts a spotlight on the multidimensional perspective to be analyzed in typical organizational problems in order to promote sustainability in social, financial, and environmental terms.

Labucay (2022) points out that only one-third of current studies examining the relationship between Industry 4.0 and sustainability focus on manufacturing [45]. To fill this gap, the author conducted a literature survey and analyzed patent data using a multi-method approach to determine whether the ongoing digital transformation in machine tools is sustainable. The study is notable for being the first to treat machine tools as a global technological innovation system (TIS), with a focus on externalities. Although the focus of the study is on Industry 4.0 manufacturing systems, the literature review also highlights sustainability. However, it differs from the scope of this article in that it does not use multicriteria methods in its search and does not suggest the use of decision models for future research.

Moreover, recent studies such as Lemstra and De Mesquita (2023) and Mourtzis et al. (2022) reinforce in their findings that a transition to a society 5.0 imposed the industry to overcome issues and explore opportunities from industry 4.0, so that decision-making plays a great role in promoting a sustainable society [46,47]. Even though they did not focus on MCDM/A models that deal with this reality, this paper aims to cover this gap.

When considering the above, it becomes evident the lack of research on the use of multicriteria methods, deeply discussed in the previous section, to support decision problems that involve sustainable manufacturing systems in Industry 4.0. This field represents a significant gap in the literature. Thus, the present study seeks to fill this gap by providing an original contribution to the area and identifying challenges and opportunities in this context. This was the backdrop for proposing the research questions (RQs) that this SLR aims to answer.

3.2. Formulating Research Questions

An integrated overview of multicriteria methods and sustainable manufacturing systems enabled us to draw up five strategic research questions (RQs) with a view to designing the SLR in the next section (see Table 2).

Table 2. Research questions to be investigated by the SLR.

Code	Question
RQ1	How have MCDM/A methods historically evolved in terms of improving decisions on sustainable-oriented manufacturing operations from scholars, other professionals, and the whole community?
RQ2	Which multicriteria problems and methods were taken into account by professionals when enhancing cleaner production systems?
RQ3	Which criteria, rationality, indicators, and other parameters are usually taken into account by decision-makers when structuring multicriteria problems in sustainable operations?
RQ4	How are Industry 4.0 tools and paradigms tackled by decision-makers in multicriteria problems?
RQ5	What are the main challenges and trends when structuring and modeling multicriteria methods in sustainable manufacturing systems for future lines of research?

From RQ1, this SRL intends to provide historical background and the applicability of MCDM/A approaches in order to analyze the relationship between their benefits in real sustainable manufacturing systems. The keyword network also aids this analysis by establishing patterns of interest among scholars. The second research question (RQ2) evaluates the state-of-the-art by classifying the different decision problems that practitioners typically deal with in terms of preference modeling from a multicriteria perspective. In considering RQ3, all the parameters involved in the decision problem are vital to guarantee the effectiveness of future MCDM/A applications. By investigating whether these are taken into account, the SLR reveals some trends and important challenges for future research. Otherwise, RQ4 is important because it could reveal how the multicriteria approach can be used to break paradigms in sustainable operations as well as integrate Industry 4.0 tools into the decision-making process, from the conception to the implementation of strategic decisions. Finally, in RQ5, some trends and open issues can be listed by cross-checking the data collected that was used to answer the previous RQs. Considering this, the design of the SLR seeks to help answer, through critical analysis, all these RQs.

4. A Systematic Literature Review on Sustainability Issues with MCDM/A Methods and Industry 4.0

In this section, the SLR research design is carefully designed in order to investigate, in light of Industry 4.0, the main aspects to be considered as trends, emerging topics, and even gaps when building multicriteria models. Afterward, a comprehensive discussion of bibliometric tools and the content analysis of a set of eligible papers make it clear how to properly answer the RQs presented in the previous section.

4.1. Methodology: Designing the SLR Structure

From the wide discussion that emerges from the set of research questions (RQs) such as those above in Section 3, it is important to implement an appropriate methodology in order to detect and investigate publications in the literature regarding this field. From this perspective, Kitchenham et al. (2009) preconized the use of a systematic literature review (SLR) as a solid approach to mapping the state-of-the-art related to a specific scope, thereby defining an intervention strategy for searching articles in scientific databases with a systemic view [48]. This way, the SLR undertakes a systematic search method for comprehensive analysis, critical appraisal, and synthesizing of the information selected.

Moreover, the use of bibliometrics tools comprises a helpful strategy to detect trends, hot topics, and patterns of scientific development as outlined by formal studies held in databanks [49,50]. Altogether, such methods seek to add not only objectivity to SLR analysis but also to support critical discussions that might be insightful for the academy, industry, and professionals related to Industry 4.0. Broadly speaking, the SLR has the potential to gather multiple researchers' findings, limitations, and essential contributions in the same field of knowledge, adopting bibliometric methods that could potentially increase rigor and mitigate bias in literature reviews.

Even though SLR and bibliometric analysis are usually implemented in many fields to evidence patterns of research, they are being used in multidimensional methods and Industry 4.0. This paper sets out to summarize important information from recent research regarding sustainability management issues that have a strong impact with the support of the MCDM/A approach in the context of Industry 4.0. There is clearly a gap in the literature about the prominence of manufacturing systems to promote cleaner production in the light of a changing climate that impacts, from many perspectives, the quality of life and operations management. Additionally, this SLR aims to put a spotlight on the integration of methods and tools related to sustainable manufacturing operations decision-making, thereby fostering collaboration between public and private institutions, such as the academy and industrial sectors, to provide future funding about how to plan the best ways to tackle the challenges of achieving a cleaner production in a complex context affected by global warming and its impacts [51].

Therefore, this paper undertakes a systematic literature review to detect, investigate, and critically analyze peer-reviewed papers that purposefully apply or even replicate MCDM/A methodologies in the context of problems related to sustainable management of manufacturing systems in the light of Industry 4.0 in a structured and transparent manner. On considering the SLR guidelines proposed by [48,49], the materials and methods used for structuring this paper can be structured, for didactic purposes, into three steps: detailing (i) data source and search strategy, in which the overall scope of the SLR is delimited; (ii) exclusion criteria, in which some filters are applied systematically for achieving the SLR scope; and (iii) data extraction, collection, and visualization. It should be noted that the previous section was the backdrop for establishing the research questions (RQs) that model this SLR. The use of the combined approach of [48,49] is potentialized since the study is didactic, replicable, and endeavors to reduce biases when compared to traditional narrative and meta-analysis-based reviews. Furthermore, Figure 2 outlines the SLR design and structure, considering the underlying assumptions that are described below.

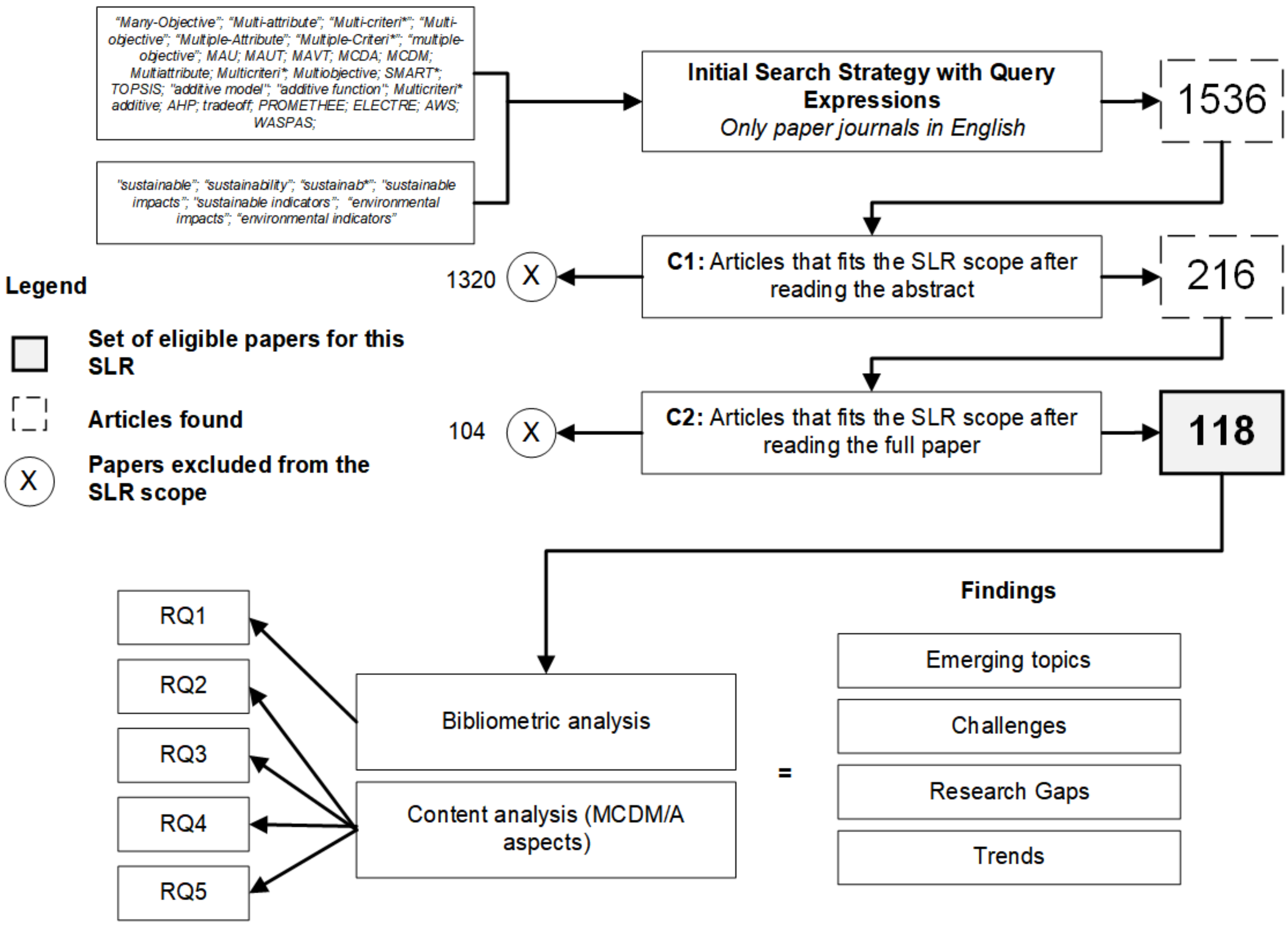

Figure 2. Flowchart of applying the SLR methodology.

4.2. Data Source and Search Strategy

At first, the scope of the SLR must be defined, which keeps in focus all the research questions listed at the end of Section 3. Using papers published (at least early access) between 1945 and March 2023 that were identified by searching on a highly respected database—the Web of Science (Main Collection—Clarivate Analytics), compiled by the Institute of Scientific Information (ISI)—bibliometric analysis, strategic, and managerial discussions have been performed in an in-depth searching process to investigate a set of eligible papers regarding the SLR scope.

The design of SLR was structured in such a way that it might be possible to investigate and map the state-of-the-art regarding: (i) publications and related citations per year; (ii) co-authorship of relevant publications, co-citation, and bibliographic matching with possible relationships between them; and (iii) a network of research concerning the main keywords addressed over the years. Moreover, the comprehensive analysis is based on the classification of typical aspects in which decision-makers tackle MCDM/A problems [7]: decision problems; types of multicriteria methods and their integration with Industry 4.0 tools; criteria/indicators; rationality in the decision process; and common alternatives.

It is worth noting that this SLR aims to analyze, in particular, approaches that deal with multicriteria methods applied to sustainable manufacturing systems, differing from approaches, procedures, and methods that model or design sustainability impacts in other non-applied contexts. That is why we disregard papers that deal purely with sustainability assessment and impacts when building the overall scope. However, many papers published recently in the Web of Science database do not clearly state the context of application to industry or manufacturing systems, whether in the title, abstract, or keywords. Considering this, this study adapts the initial search strategy to a more open scope so that the exclusion criteria are focused on detecting which papers are adequate for the SLR scope. Thus, these baseline assumptions permit the formulation of the initial search strategy by combining the sets of multicriteria and sustainable management keywords, as shown in Table 3.

Table 3. Sets of keywords used to delimit an initial search strategy.

Set of MCDM/A Methods Keywords	Set of Sustainable Management Keywords
"Many-Objective"; "Multi-attribute"; "Multi-criteri*"; "Multi-objective"; "Multiple-Attribute"; "Multiple-Criteri*"; "multiple-objective"; MAU; MAUT; MAVT; MCDA; MCDM; Multiattribute; Multicriteri*; Multiobjective; SMART*; TOPSIS; "additive model"; "additive function"; Multicriteri* additive; AHP; tradeoff; PROMETHEE; ELECTRE; AWS; WASPAS;	"sustainable"; "sustainability"; "sustainab*"; "sustainable impacts"; "sustainable indicators"; "environmental impacts"; "environmental indicators"

The combined search strategies as schemed in Table 2 were implemented in a progressive analysis of the article's content, which means from the title/keywords to the abstracts and, consequently, to the main text. This occurs because it is possible for the initial search strategy (Table 3) to make an in-depth search for some of these applications in the context of sustainable-oriented Industry 4.0 systems.

4.3. Exclusion Criteria

At this stage, the initial search strategy (in terms of query expressions in paper titles and abstracts) is the key point for selecting eligible papers and compiling the bibliometric database. Thus, the initial search found 1536 peer-reviewed papers, which are candidates for eligibility under the SLR scope. To do so, the entire process was carefully revised with the aid of the exclusion criteria. They were implemented to validate the initial search so that the SLR might verify if all papers fit the delimited scope, excluding false-positive papers. Additionally, this SLR disregards its strategies articles not available in English and published in other languages, as well as works published in scientific journals that were not taken into account.

Apart from initial results, research protocols were refined using exclusion criteria C1 and C2. These represent pre-selected articles that do not fit the main scope (see Figure 2).

C1: articles that fit the scope, in general—here, only papers that mention the use of multicriteria methods, procedures, or models in the manufacturing context were admitted to this SLR after reading the abstract. Considering that some papers did not fit within the scope of this research, some of them might cover other methodologies that do not meet the scope requirements. For example, some comparative studies from managerial perspectives, exploratory/qualitative papers, or even purely environmental/sustainability assessment applications were excluded.

C2: papers with MCDM/A modeling contributions within the scope of the SLR, after reading the full paper. This second exclusion criterion was incorporated with the aim of collecting papers that clearly introduced multicriteria methodologies for dealing with DM's preferences in manufacturing systems. After reading the full paper, this led to some papers being disregarded, where appropriate, due to some articles mainly discussing previous applications or even focusing on descriptive analysis of previous works as a learning process. Thus, applying these criteria simultaneously, we found 118 eligible articles.

4.4. Data Extraction, Collection, and Visualization

Assuming that the initial search strategy combined with the exclusion criteria are enough to select the set of eligible papers, it should be noted that this work makes use of computational tools for enhancing bibliometric analysis and data visualization [52]. This way, important bibliometric indexes, such as the number of publications, number of citations, citations per year, co-citation, and keywords, were extracted from the ISI database and gathered by using Minitab and the VOS viewer, for example.

By crossing these data in a strategic manner, the SLR results and discussion use the technical evaluation of research metrics to enhance the state-of-the-art analysis. The parameters justified with the RQs seek to highlight the main interests of academics, which include the degree of interdisciplinarity of the theme and possible trends for the complex problem of supporting sustainable operations systems. Additionally, the critical discussion of the 118 peer-reviewed papers regarding multicriteria methods in sustainable-oriented Industry 4.0 systems reveals challenges and suggestions for future research. Therefore, the applicability of these methods makes decision-making more effective and well-founded.

5. Results and Discussion

This section discusses the main findings obtained by extracting, collecting, and analyzing the eligible papers found previously. Here, bibliometric and critical analysis enable us to answer the research questions directly.

5.1. RQ1: How Have MCDM/A Methods Evolved Historically in Terms of Improving Decisions on Sustainable Oriented Manufacturing Operations from Scholars, Other Professionals, and the Whole Community?

On considering the publications and citation reports from the database, it is clear that there is increasing interest in scientific research on this matter. The search strategies implemented in the SLR scope, although investigating eight decades of scientific advances recorded in the Web of Science (Clarivate Analytics) database (from 1945 to 2023), should be noted that papers that implement MCDM/A methods in sustainable-oriented Industry 4.0 systems are dated from the end of the 2000s only. So, the research was focused on studies from the 2010s, which shows how recent this area of application is in managerial practices, although climatic effects, even incipient ones, have been the center of discussions since the end of the last century.

Moreover, it must be pointed out that approximately 50% of the papers published in this area are concentrated in the past decade (2007–2023), that is, 61 of the 118 articles. Figure 3 shows the frequency of publication concerning this SLR scope, both per year and in accumulated papers since the second half of the 2000s.

The ascending rates evidence that these numbers are continually growing at considerable rates, given that this field of knowledge is an emerging topic for society.

Indeed, the degree of interest from the scientific community is perceived in terms of paper citations because the 118 papers were cited approximately 3700 times (31.57 citations per item) from multidisciplinary journals with great contributions and open issues to be discussed later. Indeed, the multidisciplinary nature reported by bibliometric analysis represents how the MCDM/A tools have the potential to impact the whole productive sector, thereby potentializing the Industry 4.0 policies in order to promote sustainable operations. This way, Table 4 highlights some high-impact and recognized journals that have published important advances in the subject.

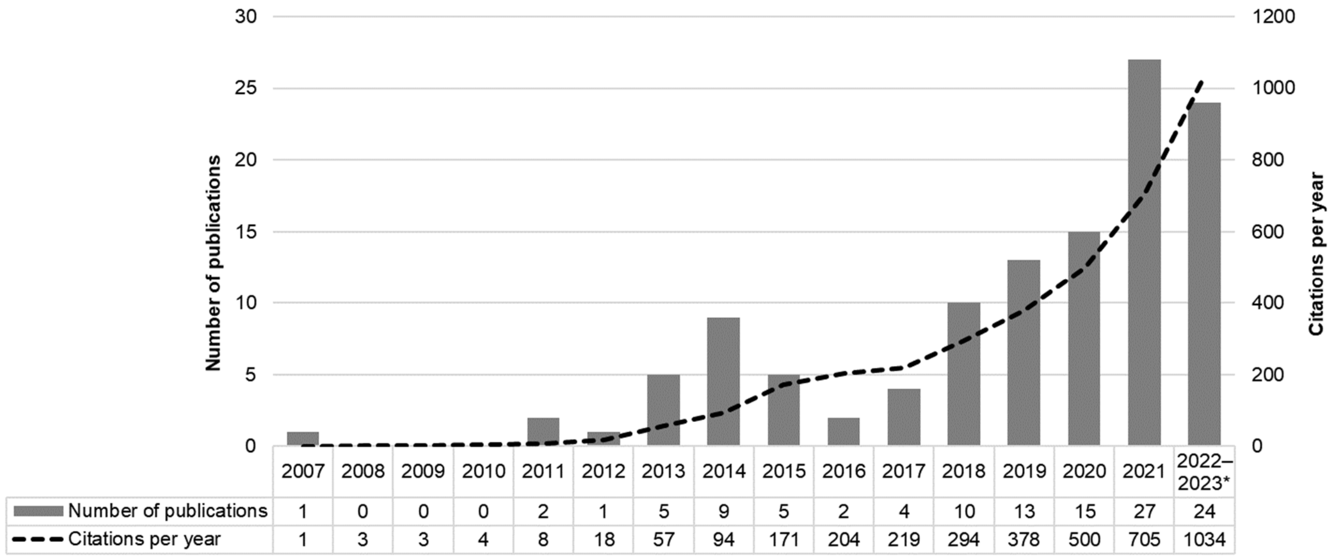

Figure 3. Historical evolution of citations and publications regarding the SLR scope (* until March 2023).

Table 4. Most relevant periodicals in which MCDM/A methods have contributed to this field.

Journal	Number of Articles	% of 118	2021 Impact Factor	References
Journal of Cleaner Production	16	13.559	11.072	[53–68]
Sustainability	16	13.559	3.889	[45,69–83]
Energy	8	6.780	8.857	[84–91]
Energies	6	5.085	3.252	[92–97]
Energy Conversion and Management	6	5.085	11.533	[98–103]
IEEE Access	6	5.085	3.476	[104–109]
International Journal of Production Research	4	3.390	9.018	[110–113]
Symmetry Basel	3	2.542	2.94	[114–116]
Applied Energy	3	2.542	11.446	[117–119]
Computers Industrial Engineering	3	2.542	7.18	[120–122]
Environmental Science and Pollution Research	3	2.542	5.19	[123–125]
International Journal of Environmental Research and Public Health	3	2.542	4.614	[126–128]
Mathematical Problems in Engineering	3	2.542	1.43	[129–131]
Sustainable Cities and Society	3	2.542	10.696	[132–134]
Sustainable Energy Technologies and Assessments	3	2.542	7.632	[135–137]
Others	32	27.119	-	[138–169]

Finally, bibliometric tools were implemented in the set of eligible papers in order to critically analyze the papers regarding the relationships between keywords in all documents [52]. In this sense, Figure 4 reveals the strategies and research scopes behind the co-occurring keywords that are closely related.

By answering this RQ with bibliometric analysis, this SLR allows readers to have a historical perspective of the literature review, from which some findings include detecting trends, challenges, and the development of multicriteria models on sustainable-oriented manufacturing systems for future studies.

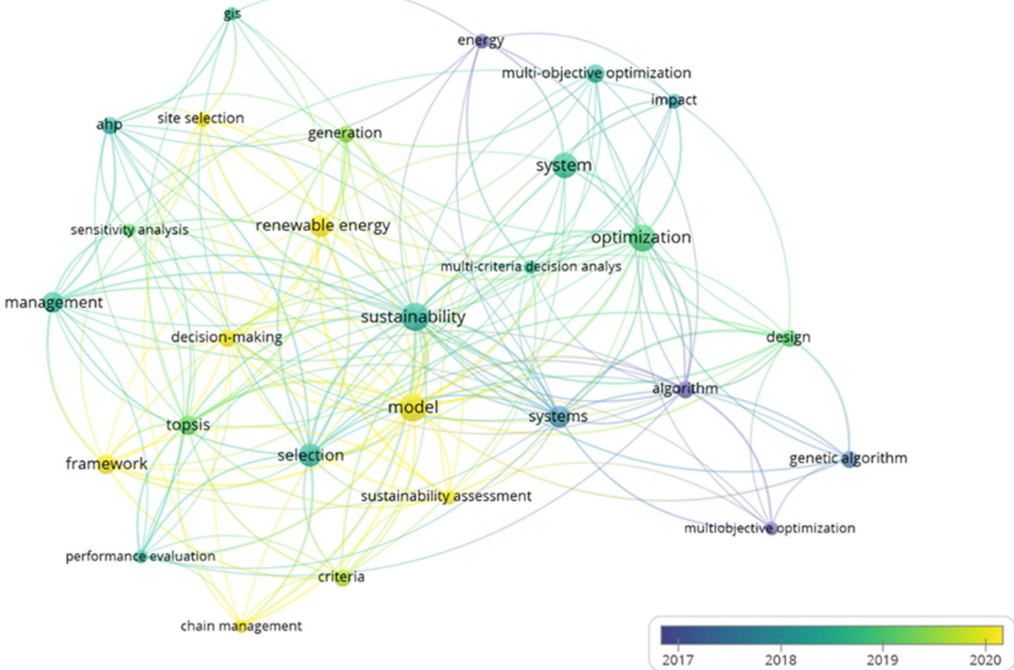

Figure 4. Keywords of the articles analyzed in this SLR.

5.2. RQ2: Which Multicriteria Problems and Methods Were Taken into Account by Professionals When Enhancing Cleaner Production Systems?

The set of eligible papers analyzed by the SLR scope comprises various fields of application with recurring use of operations management expressions that, despite being quite different in their proposals, present similar definitions, applications, and settings for sustainable-oriented Industry 4.0 policies. However, to clarify the SLR findings and discussions arising from the content analysis, this paper aims to standardize the primary outcomes. Hence, in terms of typical decision problems faced by managers to deal with sustainable practices in manufacturing systems, the papers were classified based on the overall emphasis of the multicriteria modeling proposals. A summary of the five most recurrent types of MCDM/A applications and examples was identified as follows:

- Location of enterprises and manufacturing layout: it comprises multicriteria problems that take external and internal factors into consideration when replacing the industry layout in order to avoid multiple wastes (from logistics, worker interaction, and movements, stock planning, etc.). Moreover, it includes problems that rank or select green-oriented locations for achieving sustainable operations, thereby obeying environmental regulations and reducing production costs [115,119,135,154];
- Selection of sustainable (green) suppliers: the complexity behind the supply chain operation is the main motivation for restructuring the way managers deal with the evaluation and selection of suppliers. In terms of sustainable operations, green supplier selection is a common problem that includes multiple and conflicting criteria and has led to significant changes in the relationship between organizations and green suppliers [68,73,74,116,120,122,127–129,162,165];
- Machinery acquisition and maintenance for smart manufacturing: Industry 4.0 implies the need to transform the assets into smart elements in the production plants. This type of decision problem reveals the need for managers to prioritize, select, and decide which investments should be implemented in the organization to automate the manufacturing system with the aim of increasing system reliability. Thus, the sequencing of machines in business process management, the purchasing of assets to introduce this new paradigm, as well as the enhancement of maintenance planning, can be supported with MCDM/A models [45,64,109,153,156];

- Assessment of sustainable options for energy generation and distribution towards energy transition: in a changing climate, the risks with the potential to affect urban functioning put a spotlight on changing strategically the way Industry 4.0 managers take decisions in the energy context, more particularly. So, problems that fit into this scope are implemented under a sustainable-oriented perspective to establish planning, execution, and monitoring guidelines to promote cleaner and renewable energy production without disregarding the socioeconomic impact of these operations on the whole society [67,71,77,79,84,88,90,91,102,107,118,154,158,159]; and
- Socioeconomic and environmental impacts of Industry 4.0 tool implementation: from conception to implementation, new manufacturing tools have introduced new paradigms that managers must deal with. However, the effectiveness of Industry 4.0 tools can be affected by many barriers, such as social demand, financial constraints, and the personal knowledge and capacity of employees. From this perspective, some works bring into discussion the prioritization and selection of technological tools to support manufacturing interventions in a sustainable way [96,107,111,133,139,150,153].

Regarding the use of MCDM/A methods for dealing with at least one of the typical decision problems discussed previously, the majority of papers included traditional methods for selection and ranking alternatives, thereby using additive models (weighted sum and its variations), AHP (Analytic Hierarchy Process), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), MABAC (Multi-Attributive Border Approximation Area Comparison), WASPAS (Weighted Aggregated Sum-Product Assessment), and so on [58,72,74,87,93,95,99,104,115,119,120,123,126,127,129,134,157,162,165]. A considerable amount of paper includes the use of interactive methods, integrating metaheuristics from operations research into the traditional multi-objective linear programming (MOLP) approach [63,66,83,87,98,101,111–113,118,130,139,145,161].

In fact, the multicriteria perspective has required the subjective preferences of the DM to be incorporated into traditional MOLP problems in order to establish decision weights that represent a compromise solution between the multiple objective functions. Differing from single-criterion synthesis and outranking methods, the interactive ones assume interactive and successive mathematical formulations to elicit the DM's preferences, achieving alternatives that are clearly superior in all the established objectives. However, hybrid approaches, as schemed in [163], show how MOLP can be implemented using traditional multicriteria elicitation procedures; the authors illustrate it by combining MOLP and the rank-ordered centroid (ROC) procedure (for calculating surrogate weights under incomplete information).

Moreover, Fuzzy AHP, Fuzzy TOPSIS, PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation), and ELECTRE (Élimination Et Choix Traduisant la Realité) are reported in this SLR scope as common multicriteria methods applied to the sustainable-oriented manufacturing context [55,67,73,93,95,97,101,103,118,127,132,135,138,164,168]. It must be pointed out that many applications of fuzzy set theory illustrate methodological contributions from some articles to model the stochastic aspects of sustainable operations in practical terms. This is discussed strategically next. While these papers consider that DM has minimum expertise about the context, a trend for future research includes the design of group-based decision models, which can be useful when duties and responsibilities for decision-making are shared with multiple actors in the organization.

5.3. RQ3: Which Criteria, Rationality, Indicators, and Other Parameters Are Usually Taken into Account by Decision-Makers When Structuring Multicriteria Problems in Sustainable Operations?

From an in-depth analysis of the main characteristics that compose an MCDM/A model, the SLR outlines multifaceted indicators and parameters used by enterprises, managers, scholars, and the public administration for improving at least one of the main typical problems discussed in the previous RQ (see Section 4.2). From a multidimensional perspective, the SLR is able to detect five major types of criteria mentioned by the set of eligible papers: environmental, operational, financial, organizational, and other issues. In order to promote a didactical discussion regarding the main criteria modeled in the SLR papers, Figure 5 provides readers with a word cloud that was conceived according to their frequency of occurrence in all papers. For didactic purposes, many of the expressions related to these metrics have been standardized to clarify the findings presented in this paper.

Figure 5. Summary of the main criteria used in multicriteria models for sustainable-oriented manufacturing problems.

An interesting aspect related to future research regarding this field is the increasing incidence of social indicators that mention the impacts of Industry 4.0 technologies on life quality and community development. Consequently, manufacturing systems are incorporating in their sustainable practices the degree to which the technological tools and paradigms of Industry 4.0 imply social impacts after gathering financial and institutional efforts to adapt the local and global economies in terms of climate change effects. As an example of this evidence, [57] undertakes an interactive MCDM/A method with fuzzy logic to maximize social benefits from sustainable supply chain networks while minimizing economic costs and environmental impacts. Additionally, 12 district heating systems were evaluated under different MCDM/A methods [93]. The authors made a critical analysis in light of eight criteria, including the social impact of the heating system transition toward the fourth district heating generation and the implementation of the smart thermal grid concept, or the fifth district heating generation, considering the points of view of different stakeholders. This means there is a gap in current research, as the manufacturing system is now trying to incorporate external factors into its decisions that might influence sustainable practices from a strategic perspective. For this reason, this reinforces the need to consider simultaneously social, financial, operational, and environmental impacts [73].

Moreover, it means a great opportunity to encourage researchers to justify the use of a proper MCDM/A method, thereby dealing with the DM's rationality (i.e., the way DM establishes his/her preferences) used by a DM to quantify the relationship between the criteria [7]. From the set of eligible papers analyzed by this SLR, there was evidence of the prominence of compensatory models, which means the use of additive methods that aggregate multiple criteria evaluations into a global score. However, this matter was not discussed in the wide range of papers, so it is vital to estimate and justify properly, during the decision-making process, the extent to which the compensation between criteria can be considered so that mathematical modeling translates the DM's preferences. Actually, this means an open issue because there are no formal procedures to clearly investigate how the DM's rationality behaves.

Furthermore, it should be analyzed for future research to determine the influence of the correlation between criteria scales in order to evaluate, in the light of additive models (which comprise the most recurrent methods in this SLR scope), if the independence assumptions might be reasonably assumed. This is essential because the refereed independence assumptions must be checked to validate the linear additive form under a single criterion of synthesis methods [7]. Broadly speaking, if this formal validation is not verified in a given manufacturing problem, it might bring bias to the decision recommendation, so that the effectiveness of MCDM/A methods in supporting strategic decisions can be affected. This way, a general concern regarding the modeling and analysis of DM's rationality, the set of alternatives, and even the criteria indicators is to accredit the use of a proper multicriteria method for solving the case study.

In terms of a participatory approach to building the multicriteria models, a considerable number of the papers mention different stakeholders who engage in the multicriteria modeling process, such as operations managers and engineers from energy, textile, technology, and infrastructure companies; community representatives from commerce and services (trade, agriculture); and government officials.

5.4. RQ4: How Are Industry 4.0 Tools and Paradigms Tackled by Decision-Makers in Multicriteria Problems?

The multifaceted environment in industrial systems that suggests the adoption of Industry 4.0 tools implies the incorporation of new technological paradigms that reshape the way managers design, develop and take their decisions. As mentioned by Klingenberg et al. (2021), the emergence of new technologies and manufacturing tools plays a key role in promoting a new paradigm that promotes process automation and control, as well as providing clear information protocols that integrate workers, assets, and the production line in strategic terms [170].

It encompasses new concerns that are modeled in a multicriteria problem regarding the conception of Industry 4.0 practices, as mentioned by [163]. They introduced a multidimensional approach for prioritizing machine purchasing, thereby using financial (implementation and maintenance costs) and operational criteria (setup time, process time, etc.). This way, the authors affirmed that the MCDM/A approach was financially and sustainably justified for ensuring flexible and optimal job shop systems.

Furthermore, the insertion of sustainable-oriented processes implies the need for interconnecting Industry 4.0 tools with the view to integrating smart systems that obey environmental regulations and then promoting cleaner production systems. For that reason, multicriteria problems focus on the innovative process, as mentioned by [92]. The authors make use of a hybrid-multicriteria method for prioritizing the infrastructure planning for autonomous electric vehicles, assuming safety, operational, and sustainability criteria while considering a macroeconomic scenario that led societies to an energy transition worldwide. Additionally, the complexity behind the supply chain has motivated [168] to propose an MCDM/A model for integrating different stakeholders for achieving sustainable reverse logistics. In fact, the circular economy puts a spotlight on the participatory approach taken by consumers, policymakers, and other stakeholders to gather multiple perspectives in order to achieve common goals.

Another focus of concern from policymakers is closely related to information systems safety, once the industrial sector has the challenging task of managing big data, and cloud computing, whose Industry 4.0 tools might ensure the organization's competitiveness and high-quality products and services. As detailed in [104], the use of blockchain technology for changing the existing infrastructure of information technology involved multiple DMs in a group decision context, so the authors proposed a multicriteria model for selecting a blockchain service provider, enriching blockchain to be better implemented in a reasonable way.

Similarly, augmented reality (AR) imposed on managers the need to deal with multidimensional dilemmas when implementing innovative tools, thereby with Internet-of-Things

(IoT) to reduce failure rates caused by human errors, as deeply investigated by [105]. Under a multidimensional perspective, including system effectiveness, user satisfaction, and information overload, AR and IoT can be better employed for enhancing quality in sustainable operations and providing competitiveness in a changing market.

Despite the fact that the set of eligible papers delimited by this SLR did not bring into discussion the implications of sustainable-oriented operations in terms of a new era, i.e., Industry 5.0, future research should tackle multicriteria decisions under the emergence of a new paradigm centered on sustainability, resilience, and human-machine relationships (sociocentric). Recent papers such as [47,171] revealed how this new paradigm has the potential to reshape strategic decisions in manufacturing systems; however, the authors revealed many concepts regarding the role of Industry 5.0, reinforcing this emerging topic for future works.

Therefore, the multicriteria approach has the potential to contribute to structuring strategic decisions, transforming both the economy and society in the light of sustainable development and value aggregation along the supply chain.

5.5. RQ5: What Are the Main Challenges and Trends When Structuring and Modeling Multicriteria Methods in Sustainable Manufacturing Systems for Future Lines of Research?

On considering what has been exposed in the previous RQs' discussions, some important remarks should be introduced as the starting point for overcoming open issues and following some trends in applying MCDM/A methods for supporting sustainable-related manufacturing problems. At first, it was not detected in all the eligible papers that the use of structured procedures for building multicriteria modeling and analysis from a strategic perspective. In this scenario, problem structuring methods (PSMs) are useful tools for supporting the whole decision-making process once the DM is encouraged to think about his values and preferences, which will be modeled consequently as criteria and alternatives to the problem [11]. This way, the main advantage of integrating PSMs in MCDM/A decision modeling is that they are accessible to non-specialized professionals on this matter, adopting easy-to-understand mathematical formulations with views to gather multiple perspectives of the context in a participatory approach [172].

Consequently, PSMs can support the decision actors in understanding their preferences, objectives, and common goals under complex industrial systems in the light of sustainable-oriented Industry 4.0. As illustrative examples of PSM's contributions, such as those mentioned in [172,173], multicriteria decision modeling can be enhanced in industry systems with a sustainable perspective, thereby attending to environmental rules without disregarding social and financial interests. Additionally, a lack of formal procedures suggests the use of framework propositions widely discussed in the literature with the aim of guiding DMs, analysts, experts, and stakeholders in taking credible decisions, as discussed by de Almeida et al. (2015) [7]. For example, the authors introduced a framework based on successive and recursive refinements to comprehend the process divided into three main stages: the preliminary phase, in order to clarify and define the set of alternatives and its criteria; the choice and conduct of a proper multicriteria method, which included the verification of the underlying assumptions that accredit the use of a chosen model in terms of intra-criterion and inter-criteria evaluation; and decision evaluation and recommendation, in which the results are strategically recommended for DMs.

After evidencing the most recurrent decision problems typically modeled with MCDM/A methods in sustainable-oriented manufacturing systems, another essential insight for future research is the lack of formal models that deal with risk assessment and management in the Industry 4.0 context. As outlined in de Almeida et al. (2017) [174], the complexity behind the conception, development, and even implementation of Industry 4.0 tools implies the need for assessing, from a probabilistic perspective, operations risk and reliability in sustainable systems. A variety of manufacturing systems can benefit from the evolution of these decision models, from commerce to services to the critical infrastructure of urban spaces. Recent trends in dealing with NATECH events in operations management [175]. For that reason, utility-based multicriteria methods are suggested for covering this issue once methods such as MAUT, rank-dependent utility (RDU), prospect theory, and its relatives are able to model DM's preferences under risky situations [10]. In fact, [4] contributions reveal that the implementation of Industry 4.0, despite introducing new technological paradigms, brings a new look to risk-reducing practices for achieving better performance with reliable and safe systems.

Regarding the use of group decision-making approaches, the SLR scope evidences another gap in the literature, so that few papers analyzed by this work gather multiple DM perspectives in order to support sustainable-oriented practices in manufacturing systems [116,119,128,165,166].

Moreover, the applicability of MCDM/A methods is concentrated on additive models, even in multiobjective approaches that comprise significant contributions in this field. This way, there might be a concern for researchers, managers, and professionals in facilitating the preference elicitation process, thereby adopting innovative methods that reduce the DM's cognitive effort and promote credible recommendations in practice. From this perspective, da Silva et al. (2022) put a spotlight on partial information-based models, in which elicitation procedures can be implemented during the decision process [176]. As mentioned in [14], behavioral studies on this matter reinforce the propositions of new decision paradigms to enhance the elicitation procedure and the decision-making process.

Finally, these suggestions for future research as well as the critical analysis of the SLR report can contribute effectively to structuring, proposing, and applying real-life problems concerning sustainable-oriented Industry 4.0 manufacturing systems.

6. Conclusions

Advances in manufacturing systems with the aid of Industry 4.0 technologies imply many problems that organizations must deal with in a multifaceted environment. It certainly evidences the need to take strategic decisions in a consolidated manner once these problems comprise non-trivial decisions because they might involve conflicting criteria. From this perspective, the MCDM/A methodology is suitable for managing complex decisions in which compromise solutions represent the DM's relative preferences regarding the criteria he/she tackles. This urge for new multicriteria methods and decision paradigms, as well as an increasing interest from society and the academy to apply this approach to real-life problems, suggests an in-depth analysis of the application of these tools to manufacturing systems that seek to achieve sustainable operations.

For that reason, among many findings, this SLR delineated the state-of-the-art in which the following matters are pointed out: how the historical evolution of multicriteria tools accredits this methodology to guide Industry 4.0 policies in practice; new concepts and different Industry 4.0 tools are used in modeling decisions, defining criteria, and shaping alternatives; and a considerable range of applications have been undertaken, from the conception to the implementation of manufacturing systems, mainly for ranking or choice problems.

Otherwise, the challenge of implementing multicriteria methods is focused on the building process of the decision model; in practical terms, a wide range of the eligible papers analyzed in this SLR lack formal procedures to structure, step by step, the multicriteria model. In general, the benefits of structured frameworks include the reduction of bias and inconsistencies in the DM's preference elicitation, especially when compared to non-structured procedures [7]. For example, different frameworks for multicriteria modeling consolidate the roles of the DM, specialists, stakeholders, and other actors involved in the process.

Moreover, it has the potential to reshape the way managers take strategic decisions in organizational contexts so that new Industry 4.0 paradigms can modify how he/she establish value judgments in sustainable-oriented situations. The comprehensive analysis with this SLR bases future research studies on key directions to cover the task of multicriteria decision-making issues, such as the extension of MCDM/A methods for a group decision context, the lack of risk-based multidimensional models that are easily replicable to operational environments, and the emergent of partial-information-based methods to facilitate the DM's cognitive effort in the preference elicitation process. In addition, a few sorting and portfolio selection problems fall within the scope of this research area, which therefore seems to be a gap in the literature. Hence, a broad range of information provided by this work outlines new practices that scholars, researchers, and other interested parties might implement to enhance the decision modeling of sustainable practices in the industry with the use of multicriteria methods in real decision-making. As a limitation of this paper, it might be considered that the SLR scope is centered on manufacturing systems that deal with Industry 4.0 tools and paradigms. Suggestions for future works include extending the scope, thereby adopting other query expressions and exclusion criteria, as well as expanding for other strategic contexts on industry systems.

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