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Decision Models for Supplier Selection in Industry 4.0 Era: A Systematic Literature Review

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Abstract

Industry 4.0 comprises the application of different technological solutions so that business processes throughout the production chain are integrated. The supplier's selection, considering the industry 4.0 requirements, is essential in promoting collaborative strategies between suppliers and manufacturers. In this context, this study presents a systematic literature review about quantitative models to support supplier selection in the industry 4.0 era. Fourteen studies were reviewed and characterized in different perspectives such as modelling, application, and validation of the decision model. The results revealed that most of the decision models were developed combining multicriteria decision-making (MCDM) with Artificial Intelligence (AI). Among the criteria related to the Industry 4.0 environment, the most frequent ones were information sharing, technological capacity, digital collaboration and engagement. The gathered results can be useful to guide researchers and managers in the development of computational tools to assist decision-making processes for supplier selection in Industry 4.0 era.

Keywords: Supplier Selection; Industry 4.0; Systematic Review; Decision Models; Multicriteria Decision-Making

1. Introduction

Globalization compelled several industrial sectors to face adaptations to meet markets with high requirements levels [1]. In this context, Industry 4.0 emerges, which represents the paradigm of fourth stage of industrialization and comprises the integration and application of different technological solutions in the establishment of the Internet of Things and Cyber-Physical Systems, so that business objects and processes are integrated promoting an intelligent environment [2]. Industry 4.0 is defined by [3] as "the sum of all disruptive innovations derived and implemented in a value chain to address the trends of digitalization, automation, transparency, mobility, modularization, network-collaboration and socializing of products and processes".

The emergence of Supply Chain 4.0 concept represents the use of technologies characteristic of Industry 4.0, to facilitate the management of several activities, such as scheduling and task management, inventory management, warehouse and transport strategy throughout the production chain [4]. The supply chain 4.0 definition presented by [5] corresponds to "a transformational and holistic approach to supply chain management utilizes industry 4.0 disruptive technologies to streamline supply chain processes, activities and relationships in order to generate significant strategic benefits for all supply chain stakeholders".

Integration between the links in the supply chain has become essential, as it promotes the development of collaborative and synchronized strategies between suppliers and manufacturers [6]. This integration is highly relevant in improving member companies' performance since individual planning without taking into account partnerships with suppliers can result in goods and service levels with non-competitive costs, which can affect long-term profitability [7]. Therefore, competitive pressures can be minimized through the development of supply

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base management strategies, in which suppliers can assist in the improvement of critical areas of the manufacturer [8].

Supplier selection is one of the most important decisions in the supply chain management context. The main objective is to find the right supplier who can provide the customer with the right quality products or services at the right price, in the right quantities, and at the right time [9]. As reported by [10, 11], several stages of decision-making comprise the process of selecting suppliers. Firstly, it is necessary to define what is to be achieved through supplier selection, and decision-makers must identify purchasing needs and what alternatives are available. Then, it is necessary to formulate the criteria, which can be quantitative or qualitative. In the qualification stage, the objective is to eliminate inefficient candidates. Finally, one or more suppliers are selected and orders are allocated between them.

The literature presents several studies that propose quantitative decision models to support supplier selection. Given the relevance of this research topic, there are also several review studies on existing models. In the bibliographic survey conducted by this study, 15 systematic reviews on this topic were found. As shown in Table 1, these studies characterized different aspects related to the modelling, application, and validation of decision models, in addition to bibliometric aspects. However, no previous review studies are focused on the characterization of decision models for supplier selection in Industry 4.0 Era. In general, these models are geared towards digital supply chains and incorporate metrics from the context of Industry 4.0 to the decision-making process for selecting suppliers.

Given the need to better characterize the studies and map the state of the art on the subject, the objective of this article is to present a systematic review of studies that proposed quantitative decision models to support supplier selection in the Industry 4.0 era. To achieve the proposed objective 14 studies were collected from IEEEXplore®, Emerald Insight, Science Direct, Scopus, Springer Nature, Taylor & Francis, and Scholar Google databases and then analyzed. The characterization of these studies included the following aspects: year of publication, origin country, techniques and decision metrics used, type of model, the approach used for modeling uncertainty, supply chain strategy, application sector, the data source for application, and validation approach.

This paper is organized as follows. In section 2, the methodological procedures for studies selection are detailed and the aspects considered for analysis and classification of studies. Section 3 presents the characterization of the studies and the discussion of the results. In section 4, several opportunities for further studies are identified. Finally, section 5 presents the conclusion and contributions of this study.

2. Methodological Procedures

2.1. Selection procedure of studies

The selection of the studies was based on the guidelines for conducting systematic reviews proposed by [12-14]. Initially, searches for studies were performed using the string “(supplier OR vendor OR partner) AND (selection OR evaluation) AND ("supply chain 4.0" OR "industry 4.0" OR "digital supply chain" OR “smart supply chain”)”. The studies were collected from Science Direct, Emerald Insight, IEEE Xplore®, Scopus,

Table 1: Review studies related to supplier selection

Proposed by	Time horizon	Reviewed studies	Characterized aspects
Ho et al. [16]	2000-2008	78	Decision techniques and performance metrics;
Wu and Barnes [17]	2001-2011	140	Countries, decision techniques, educational institutions, journals and phases of the supplier selection process;
Chai et al. [18]	2008-2012	123	Decision techniques and journals;
Genovese et al. [19]	1987-2010	28	Countries, decision techniques, journals, performance metrics and type of application;
Igarashi et al. [20]	1991-2011	60	Performance metrics, phases of the supplier selection process, theoretical perspective and type of research
Govindan et al. [21]	1997-2011	33	Application sector, decision techniques and performance metrics;
Zimmer et al. [14]	1997-2014	143	Application sector, countries, decision situation, decision techniques, data type, dimensions of sustainability, journals, performance metrics, phases of sustainable supplier management, sourcing, type of application and validation approach;
Nallusamy et al. [22]	2004-2014	52	Application sector, decision techniques and performance metrics;
Yildiz and Yayla [23]	2001-2014	91	Application sector, decision techniques and performance metrics;
Wetzstein et al. [24]	1990-2015	221	Countries, decision techniques, environmental strategy, journals, operational approach, performance metrics, supplier selection strategies and stages of the R&D process;
Araújo et al. [25]	1973-2015	119	Decision techniques, journals, methodology, performance metrics, phases of the supplier selection process and project sector;
Simić et al. [26]	1966-2016	54	Decision techniques;
Ocampo et al. [27]	2006-2016	244	Decision techniques, journals and theme;
Zhang et al. [28]	2009-2020	193	Application sector, countries, decision techniques, journals and performance metrics;
Chai and Ngai [29]	2013-2018	95	Decision techniques;

Springer Nature and Taylor & Francis. Then, an additional search was performed using the Google Scholar tool. Based on [13], the bibliographic search followed the following procedure:

1) Inserting the search string in each database;
2) Use of a filter to select only studies published from 2011 onwards. The search for studies will be carried out from that date because the term "industry 4.0" first appeared in 2011 [15];
3) Use of another filter to select only studies published in scientific journals, books, book chapters, and conference proceedings. In the case of the Google Scholar tool and the Taylor & Francis database, as they do not have this filter, this step was performed manually;
4) Sorting the studies by relevance based on criteria contained on each database (except of Google Scholar, which does not have this feature);
5) Selecting the first 300 results listed;
6) Analyzing the title, abstract, keywords and, in some cases the content of studies to eliminate those that did not include quantitative models to support decision-making for supplier selection in the context of industry 4.0;

Deleting copies of repeated studies, that is, those that were listed and selected in more than one database. As shown in Table 2, 14 studies were selected and analyzed.

Table 2: Search results and selection of studies in the databases

	Steps						
	1	2	3	4	5	6	7
Emerald Insight	31,938	18,784	16,467	16,467	300	0	0
IEEE Xplore®	18,769	10,703	10,100	10,100	300	2	1
Science Direct	584,679	282,338	235,276	235,276	300	3	3
Scopus	65	65	65	65	65	9	4
Springer Nature	37,263	27,001	12,177	12,177	300	1	1
Scholar Google	14,700	14,200	14,200	14,200	300	14	5
Taylor & Francis	1,149,988	380,904	380,904	380,904	300	0	0
Total							14

2.2. Aspects for studies analysis and classification

The selected studies were analyzed holistically from some structural dimensions. Initially, data related to the year of publication and study origin country were collected. Then, the studies were characterized according to a set of 10 aspects related to the modeling, application, and validation of decision models. The aspects were based on other systematic reviews of the literature on topics related to supply chain management [12-14].

a) Decision technique(s): lists the quantitative decision technique(s) used by each model. It also classifies in single technique (composed of only one decision technique) or combined techniques (which applies two or more techniques sequentially) [12, 14];
b) Model type: groups the models according to the nature of the decision techniques used, such as MCDM, mathematical programming, and AI techniques [13];
c) Modeling uncertainty: verifies whether the model adopts any approach to deal with decisions in uncertain environments, which are characterized by use of inaccurate data, qualitative assessments and/or subjective judgments [13]. It also classifies studies according to the approach adopted to deal with uncertainty, such as fuzzy set theory, pairwise comparison, among others;
d) Performance metrics: identifies the most common metrics used by models to assess supplier performance [14];
e) Supply chain strategy: identifies the competitive strategy adopted by the supply chain in which the buyer and its supplier(s) are inserted. Some types of supply chain strategy discussed in the literature are green, sustainable, resilient, lean and agile [13];
f) Choice of metrics: identifies how the metrics were chosen [13]. While some studies define metrics based on literature studies, others are based on the opinion of experts' opinion or the authors themselves;
g) Type of application: considers whether the application was made based on real data or simulated numerical examples [14];
h) Application sector: identifies the sector in which the purchasing company participating in the application operates, taking into account only applications based on real data [12];
i) Source of the data for application: analyzes the source of the data used to assess supplier performance [14]. It identifies whether they were obtained through historical data, experts' judgments, simulated data or combinations between them;
j) Validation approach: Examines whether any procedure was applied to validate the results of the study [13], such as sensitivity analysis or statistical technique.

3. Studies Characterization and Results Discussions

Figure 1 shows the distribution of studies over the years. Among the studies analyzed, 12 (85%) were published in the last two years (from 2019). This shows that interest in the research topic under study is recent and is on the rise. The distribution of studies according to the authors' origin country is shown in Figure 2. As some studies were developed by two or more authors from different countries, the frequencies sum is greater than 14. The countries that most published studies are Turkey, India, United Kingdom, and United States, respectively.

Table 3 summarizes some characteristics of the decision models proposed by each study, including the decision techniques employed and the type of model according to the nature of the techniques. It is important to highlight that 9 (64%) of the studies combined two or more techniques in the decision models. Among these, fuzzy logic and its extensions were often used as a component of combination with other techniques, for example, Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Best Worst Method (BWM). Table 3 also

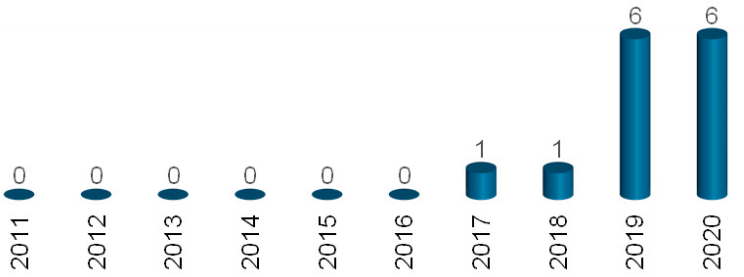

Fig. 1. Distribution of studies by publication year

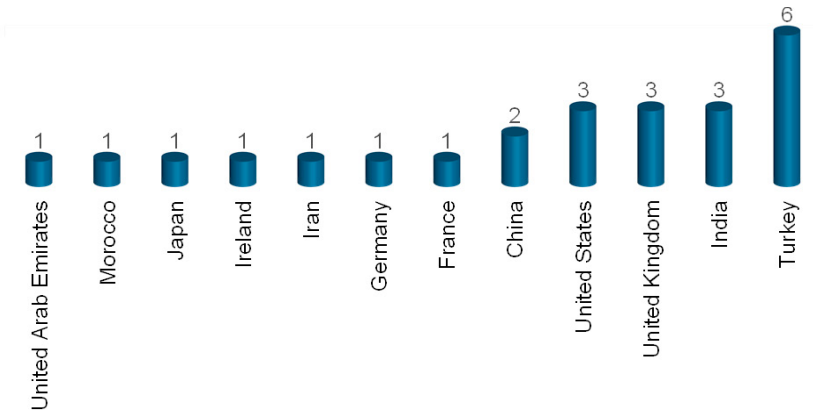

Fig. 2. Distribution of studies grouped by the authors' countries

identifies the most frequent types of models. The combination of MCDM techniques with AI techniques is the most frequent, totalizing 7 (50%) of the studies analyzed. Next are models based purely on AI (14.2%) or MCDM (14.2%) techniques. Figure 3 presents different approaches used in the studies to deal with decision-making processes under uncertainty.

Table 3: Characterization of the models analyzed according to the decision techniques and model type.

	Proposed by	Techniques	Types of model
Single technique (5)	Büyüközkan and Göçer [30]	Interval Valued Intuitionistic Fuzzy Multi-Objective Optimization on the basis of Ratio Analysis (MOORA)	MCDM combined with AI
	Ghadimi et al. [31]	Multi-Agent System	AI
	Tozanli et al. [32]	Goal Programming	Mathematical programming
	Özek and Yildiz [33]	Interval Type-2 Fuzzy TOPSIS	MCDM combined with AI
	Zekhnini et al. [34]	Adaptive Neuro Fuzzy Inference System (ANFIS)	AI
Combined techniques (9)	Büyüközkan and Göçer [35]	Interval Valued Intuitionistic Fuzzy AHP and Interval Valued Intuitionistic Fuzzy Addial Ratio Assessment (ARAS)	MCDM combined with AI
	Büyüközkan and Göçer [36]	Pythagorean Fuzzy AHP and Pythagorean Fuzzy Complex Proportional Assessment (COPRAS)	MCDM combined with AI
	Hasan et al. [37]	Fuzzy TOPSIS e Multi-choice Goal Programming	MCDM combined with AI and Mathematical programing
	Kusi-Sarpong et al. [38]	BWM e VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)	MCDM
	Liao et al. [39]	Hesitant Fuzzy BWM and Hesitant Fuzzy ARAS	MCDM combined with AI
	Sachdeva et al. [40]	Intuitionistic Fuzzy Set TOPSIS and Shannon's Entropy Method	MCDM combined with AI
	Çalık [41]	Pythagorean Fuzzy AHP and Pythagorean Fuzzy TOPSIS	MCDM combined with AI
	Kaur and Singh [42]	Fuzzy AHP, TOPSIS and Data Envelopment Analysis (DEA)	MCDM combined with AI and Mathematical programing
	Torkayesh et al. [43]	BWM e Weighted Aggregated Sum Product Assessment (WASPAS)	MCDM

Initially, 12 (85.7%) of the studies proposed approaches for this purpose. It appears that the most recurrent approaches are fuzzy set theory (35.7%) and fuzzy set theory combined with pairwise comparison (35.7%). The widespread fuzzy set theory adoption may be due to the possibility that it allows the linguistic terms use quantified by fuzzy numbers to assess the weight of the metrics and the scores of the alternatives [44].

The metrics used in the assessment of suppliers are shown in Table 4. The metrics used by only one study were suppressed. The restrictions used by the mathematical programming models were not counted as metric. In summary, all studies contemplated the associated use of operational metrics with digital ones, that is, metrics aligned with the industry 4.0 environment. Otherwise, the grouping of digital metrics with environmental metrics was present in the studies by [31, 34, 36, 38, 41]. Besides, only the study by [36] used social metrics associated with digital metrics.

Table 4: Metrics adopted by the models for supplier selection

Metrics	Proposed by	Frequency
Information sharing	[30, 33, 35, 39, 42, 43]	6
Cost	[31, 34, 36, 37, 40]	5
Digital collaboration	[35, 36, 39, 43]	4
Digital engagement	[35, 36, 39, 43]	4
Flexibility	[35, 37, 39, 43]	4
Product quality	[31, 34-36, 41]	4
Technological capacity	[34-36, 40]	4
Service quality	[31, 39, 41, 43]	4
Supplier sustainability	[31, 34, 36, 41]	4
Use of analytical tools	[30, 35, 41, 42]	4
Cloud computing	[33, 41, 42]	3
Cybersecurity	[33, 37, 42]	3
Delivery	[31, 34, 40]	3
Financial stability	[35, 36, 43]	3
IoT Infrastructure	[33, 41, 42]	3
Privacity respect	[35, 36, 43]	3
Real time visibility	[30, 33, 35]	3
3D printing and augmented reality	[33, 41]	2
Automation	[33, 37]	2
Additive Manufacturing	[33, 42]	2
Collaboration level	[30, 37]	2
Digital customization and personalization	[35, 36]	2
Financing efficiency	[39, 43]	2
Information and communication technologies	[33, 37]	2
Smart logistics	[33, 42]	2
Reputation	[35, 36]	2
Robotics	[33, 41]	2
Security	[36, 43]	2
Support service	[35, 36]	2
Technological integration	[35, 36]	2

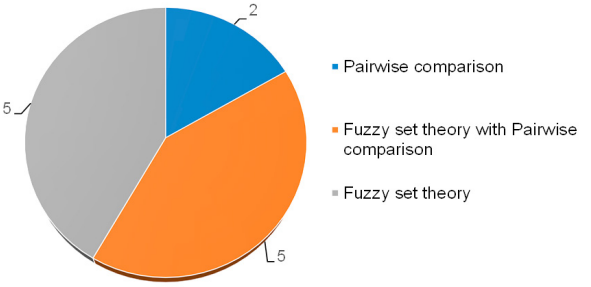

Fig. 3. Approaches for model uncertainty

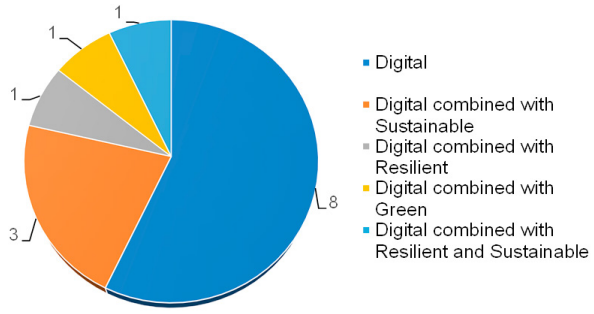

Fig. 4. Distribution of type of supply chain strategy

As shown in Table 4, metrics related to operations performance continue to be highly relevant, such as cost, flexibility, quality, and delivery. The most frequent metrics related to Industry 4.0 era are information sharing, technological capacity, digital collaboration, and engagement, cloud computing, respect for privacy, and cybersecurity. The development of these metrics reflects the advances of digital technology in the construction and implementation of Industry 4.0. Due to the incipience of the theme, attempts to develop metrics and investigate how to evaluate different aspects of the use of technology are still limited [45].

The metrics chosen by the analyzed studies are also related to competitive supply chain strategies. Although all models analyzed incorporate metrics from Industry 4.0, other types of supply chain strategies are also considered in some of the studies. As illustrated in Figure 4, the studies by [31, 34, 38] also focused on developing sustainable supply chains. [37] proposed a model aimed at resilient supply chains. [41] focused on green supply chains. Finally, [32] focused on resilient and sustainable supply chains.

Figure 5 presents the approach used by the authors to choose the metrics to use in the supplier selection process. In 6 (42.8%) studies, the metrics were defined by decision-makers based on a list extracted from previous studies. For 5 (35.7%) of the studies, the metrics were extracted based on previous studies. Less frequently, there are cases in which the metrics were defined by the study authors themselves.

Regarding the type of application, 72% (10) made the application in real cases. In contrast, 21% (3) applied the model

Fig. 5. Choice of the metrics used by the analyzed models

Fig. 6. Company sectors participating in real applications

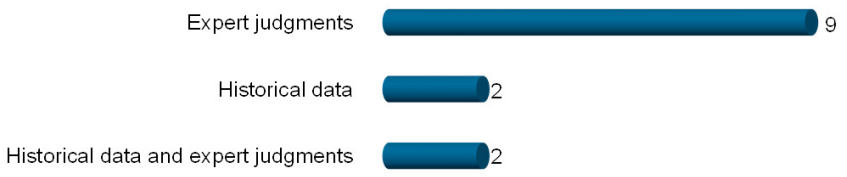

Fig. 7. Source of data used as inputs to the decision models

in illustrative cases. The model proposed by [34] was the only one not validated through the application of a real or illustrative case. Concerning real cases, Figure 6 reveals the application sector. It stands out in the automotive, aviation, and textile sectors. Applications were also identified in the food, agricultural, shipping, and retail sectors.

Figure 7 shows studies classification regarding the source of the input data used in the models' application. This data can be used to assess suppliers' performance. While 9 (64.2%) of the studies used judgments from experts to apply the model, 2 (14.2%) used historical data, and 2 (14.2%) used historical data combined with experts' judgment.

Finally, about the validation of the models analyzed, Figure 8 shows that 7 (50%) studies use some technique for this purpose. On the contrary, 6 (42.8%) of the studies only performed the real or simulated application of the model. Among the models that performed the validation of the results, 4 (28.5%) performed a sensitivity analysis to verify the impact of introducing small changes in the specific input parameters on the model results [46]. Furthermore, 2 (14.2%) analyzed the consistency of the results by comparing them with the results obtained in different techniques. Only 1 study performed the sensitivity analysis and the comparative analysis simultaneously.

4. Research Opportunities

From the mapping of the studies, some research opportunities on this topic were identified:

a) There is a lack of application of AI techniques with learning capacity. Although the application of ANFIS model has been identified, applications using artificial neural networks such as Multilayer perceptron, Kohonen, and Fuzzy Adaptive Resonance Theory (ART) have not been identified;
b) There are no applications of stochastic models for supplier selection in industry 4.0 era, which may be necessary to deal with probabilistic uncertainties;
c) There is an absence of models based on Fuzzy c-means, Fuzzy cognitive maps, Fuzzy neutrosophic sets, Hesitant fuzzy (VIKOR), Pythagorean fuzzy VIKOR, Fuzzy Analytic Network Process (ANP), Fuzzy cognitive maps, Fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL), Fuzzy NGT, ANP, ELimination Et Choice Translating REality (ELECTRE), Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH), Organization Rangement Et Synthese De Donnes Relationnelles (ORESTE), Preference Ranking Organization Method for Enrichment Evaluation

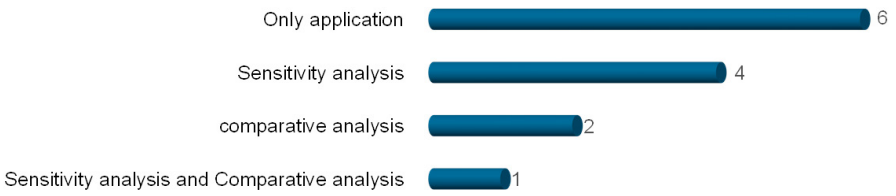

Fig. 8. Approaches used by the models analysed for validating results

(PROMETHEE), and Simple Multi Attribute Rating Technique (SMART). Therefore, the development of new models using such techniques has the potential to incorporate new functionalities into the decision models for supplier selection in the industry era 4.0.

d) There are no appropriate decision models to support decision-making in supplier selection in supply chains that combine digital strategy with lean and agile strategy;
e) Few decision models combine environmental and social metrics with metrics related to industry 4.0;
f) No applications were found in the sectors of civil construction, chemical, energy, metal-mechanical, pharmaceutical, footwear, and furniture;
g) There is a lack of quantitative decision models that support the choice of supplier evaluation metrics considering their interrelationships with industry 4.0 requirements;
h) There was also a lack of comparative studies between techniques that identify the advantages and disadvantages of use when applied to supplier selection in industry 4.0 era;
i) Besides, no study has proposed a procedure for validating the results using statistical techniques, such as hypothesis tests and Analysis Of Variance (ANOVA).

5. Conclusion

This study analyzed 14 studies that proposed quantitative models to support supplier selection in industry 4.0 era. This article characterized the studies according to 10 aspects related to the modeling, application, and validation of decision models. The results of this study confirm the growing academic interest in the development of decision models to support the supplier selection in the context of industry 4.0. Studies on this topic were identified only from 2017 and most models were developed combining MCDM with AI techniques. Fuzzy logic have been widely used in combination with other techniques, which is efficient when dealing with decision-making processes under uncertainty.

Among the criteria related to the industry 4.0 environment, the most frequent were information sharing, technological capacity, digital collaboration and engagement. It is worth to note that part of the studies chose to integrate digital supply chain strategies with sustainable, resilient and/or green strategies. More than half of the studies are based on real cases. Among these, applications in the automotive, aviation, and textile sectors stand out. Finally, half of the studies applied some technique to verify the validity of the results.

The development of this study has provided some contributions to the literature. Aspects previously ignored by previous systematic review studies on models for supplier selection were considered, including uncertainty modeling, choice of metrics, the data source for application, and validation approach. The results of this study allowed us to draw an overview of the state of the art regarding this research topic and to identify some opportunities for the development of future studies. Besides, the results presented can be useful to guide researchers and managers in the development of computational tools to assist in decision-making processes.

Finally, regarding the limitations of this study, although rigorous research procedures have been adopted for the selection and analysis of studies, it is possible that some studies have not been included in the sample. Therefore, this review can be complemented by new studies.

CRediT author statement

Carlos H. L. Resende: Conceptualization, Methodology, Investigation, Formal Analysis, Writing- Original draft preparation. Carla A. S. Geraldes: Supervision, Resources, Validation, Writing- Reviewing and Editing. Francisco Rodrigues Lima Junior: Conceptualization, Methodology, Supervision, Resources, Validation, Writing- Reviewing and Editing.

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