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Multi-criteria decision-making for equipment selection: A review focused on the triple bottom line

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Abstract
The selection of equipment is a fundamental decision for the business's future. Several methodologies have been proposed to assist in this kind of decision, one of them being the Multiple Criteria Decision-Making (MCDM) methods. However, over the years, new themes have gained strength such as Environmental, Social, and Governance (ESG), and Circular Economy (CE). This study's objective to identify the main multicriteria methods that are applied in equipment selection, and to recognize how researchers incorporate sustainability concepts are incorporated in decision-making regarding equipment selection. A systematic review of the literature was conducted using the Methodi Ordinatio to rank the articles. The Bibliometrix tool was used for bibliometric analysis. The results demonstrate low concern with sustainability in the decision-making process in equipment selection. It was identified that the Analytic Hierarchy Process (AHP) method was the most used method in equipment selection, appearing in more than half of the analyzed articles (24 studies). To better integrate MCDM decisions, the authors intend to study a multicriteria model through the sustainable approach.

Keywords: Equipment selection. Decision-making. MCDM. Sustainability. Environment.

Resumo
A seleção de equipamentos é uma decisão fundamental para o futuro do negócio. Várias metodologias foram propostas para auxiliar nesse tipo de decisão, sendo uma delas os métodos de Tomada de Decisão Multicritério (MCDM, na sigla em inglês). No entanto, ao longo dos anos, novos temas ganharam força, como Meio Ambiente, Social e Governança (ESG, na sigla em inglês) e Economia Circular (CE). O objetivo deste estudo é duplo: identificar os principais métodos multicritério aplicados na seleção de equipamentos, bem como suas variações e disseminação, e identificar como os pesquisadores incorporam conceitos de sustentabilidade na tomada de decisão em relação à seleção de equipamentos. Foi realizada uma revisão sistemática da literatura usando o Método de Ordenação (Methodi Ordinatio) para classificar os artigos. A ferramenta Bibliometrix foi utilizada para análise bibliométrica. Os resultados demonstram que não há preocupação com a sustentabilidade no processo de tomada de decisão na seleção de equipamentos. Para integrar melhor as decisões do MCDM, os autores pretendem estudar um modelo multicritério com abordagem sustentável.

Palavras-chave: Seleção de equipamento. Tomada de decisão. MCDM. Sustantabilidade. Meio-ambiente.

1. Introduction.

Nowadays, efficiency improvement depends on quantitative and qualitative data. In this sense, equipment selection and acquisition are indispensable in any business since the equipment is critical to a company's success (PALANISAMY *et al.,* 2020). The selection of oversized equipment puts the company's cash flow at risk, generates excessive inventory, and possibly leads to equipment idleness. In contrast, the selection of undersized equipment risks the quality levels required by consumers (SITORUS *et al.,* 2019).

Many data and factors as well as multiple conflicting criteria must be considered in order to generate an better solution with respect to a proper decision-making process. Moreover, acquiring equipment is a complex decision because it requires a significant investment and has many alternatives and criteria; and an accountable amount of data must be analyzed (SAHIN; AYDEMIR, 2022). Selecting the most suitable equipment avoids extra costs and has a significant impact on costs and benefits (SITORUS; BRITO-PARADA, 2020).

In addition to the technical and economic characteristics of equipment selection, sustainability is emerging as one of the requirements and factors to be considered in this decision-making process, including social, economic, and environmental aspects. In this way, decision-makers and analysts must consider economic, technical, and other sustainable aspects in their algorithms and decision-making procedures (KAMISSOKO *et al.,* 2014; WARIS *et al.,* 2019; PATCHARACHAVALIT *et al.,* 2023). Also, to being concerned with technical and economic aspects in selecting equipment, companies must also consider environmental and social issues. It is highlighted the use of life cycle thinking, which includes designing proper disposal for equipment and consumables (ABDELKAREEM *et al.,* 2021).

In this regard, several frameworks have been proposed over time to handle the equipment selection problem, as Multiobjective Optimization (PATCHARACHAVALIT *et al.,* 2023) and multicriteria (MCDM) methods integration (HAFEZALKOTOB *et al.,* 2018). However, MCDM are the most suitable (ULUTAS; CENGIZ, 2018). They are appropriate to handle several alternatives evaluated and compared between their performance in some attributes. These methods can support subjective and objective assessments, as well as the combination of those with mathematical and computational tools (KUMAR *et al.,* 2017).

The MCDM methods are extensively used for sustainability evaluation (PAGSUYOIN *et al.,* 2015; OPON; HENRY, 2020) or equipment selection problems (PATYK; BODZIONY, 2022). Concepts such as sustainability, Life Cycle Assessment (LCA) and Circular Economy (CE) are becoming more evident (RAZA *et al.,* 2023). Hence, organizations have been seeking to implement a few norms and initiatives that consider these concepts (ONAT; KUCUKVAR, 2022). LCA is an important tool for evaluating and comparing different technologies, assessing the main impacts, outputs, and inputs of the entire life cycle of a product (HUARACHI *et al.,* 2020), having great use for evaluating products and processes in the industrial sector (SALVADOR *et al.,* 2018; OTT *et al.,* 2022). The concept of CE is based on a regenerative loop that facilitates and implements techniques for recirculating and reusing products and materials, promoting savings in financial resources and environmental degradation with the disposal of materials (JABBOUR *et al.,* 2020). However, this type of initiative depends on a commitment and effective adoption of circular practices, which has been part of targets of private and state-owned companies in recent years (BAG *et al.,* 2020; PURWANDANI *et al.,* 2021).

Current laws and financial incentives for sustainable companies and the consideration of sustainable aspects are essential issues for the positioning of companies in various stock exchange rankings, since environmental and social responsibility are demanded by organizations (WANG; XU, 2021).

The relevance and importance of conducting investigation and research into sustainable materials and equipment rests mainly on the environmental aspect. There is a growing number of studies that report the problems caused to humans. Those include the ingestion of polluting particles from industrial equipment, since the presence of air pollutants derived from carbon was found to negatively interfere with people's diets (GARCÍA *et al.,* 2023), and increased risk of cardiovascular disease (SALVARAJI *et al.,* 2023). On the social dimension, it is essential to assess the impact of ergonomics on workers, which can cause health problems and economic risks for the company. The weight and geometry of the equipment can influence whether it can be carried by the worker (KASOVIĆ *et al.,* 2023), equipment noise generation (KHARLAMOV *et al.*, 2023) and the working position, as well as ergonomics in general (PANDIT *et al.*, 2023).

The current literature shows solidity and clarity about multicriteria decision-making in equipment selection. However, to the best of our knowledge, there is no study that reviewed the sustainability role in multicriteria decisions for equipment selection, even when sustainability must be at the core of the decision process for purchasing industrial equipment. Hence, adopting more comprehensive methods, harmonizing economic, technical, social, and environmental criteria is crucial. It ensures that different aspects are scored and evaluated according to their importance in the decision-making process.

This manuscript's aim is twofold: (i) to identify the main multicriteria methods (MCDM) that are applied in equipment selection, as well as their variations and integrations; and (ii) to identify how sustainability concepts are incorporated in decision-making regarding equipment selection.

The remainder of this manuscript is categorized as follows: The second section reviews the relevant literature on the topic. The third section describes the methods used to review the literature. The fourth section focuses on the MCDM applied in equipment selection, the sectors where studies are applied, the mapping of sustainability in the articles with Multiple Criteria Decision-Making (MCDM) methods, and the discussion of these results. The final section presents the conclusions and final remarks of this manuscript.

2. Theoretical background.

2.1. Equipment selection.

The selection of new equipment is a complex process that consumes much time and requires advanced knowledge and extensive experience. Therefore, this decision-making process is difficult for engineers, managers, the industry that produces the equipment, and salespeople. Thus, for an adequate evaluation, decision-makers need to have a large amount of data available to be evaluated, in addition to other factors that must be considered in the process (AYAG; OZDEMIR, 2006).

The correct selection of equipment is essential for any organization, both the selection of direct and indirect equipment because the selection of equipment that is not suitable for the company or the process can negatively affect performance and productivity, especially in a highly competitive scenario (DAGDEVIREN, 2008).

The standard procedure for selecting equipment is to identify the requirements (such as size, function, and robustness) against the equipment available for purchase that meets the requirements presented and select the one with the lowest acquisition and maintenance costs, since this is one of the main criteria in equipment selection (TABUCANON *et al.*, 1994; LIU *et al.*, 2021). Therefore, the selection of the correct type of equipment can provide a reduction of investment costs, as well as maintenance and operation costs, increase equipment utilization, improve the production layout, and still increase company efficiency and productivity (TABUCANON *et al.*, 1994; KRSTIĆ *et al.*, 2019).

In addition to the factors aforementioned, the selection of equipment has a direct effect on the companies' global competitiveness since the use of the correct and optimized equipment helps to increase production, enables the effective and flexible use of human labor, besides improving the flexibility of the system. This fact does not mean that equipment must be oversized, and the importance of the equipment selection process cannot be overlooked. In summary, the equipment selection directly influences the company's performance, thus this type of decision should be considered strategic and essential (TUZKAYA *et al.*, 2010). Therefore, with a high supply of several types of equipment available, determining the best alternative for a given context is not a simple task (CHAN *et al.*, 2001).

In cases such as the selection of equipment for the manufacturing or material handling sector, the crucial characteristics of each piece of equipment are defined, and the most suitable equipment should be selected (TABUCANON *et al.*, 1994; SAPUTRO; ROUYENDEGH, 2016). In addition to financial and technical aspects, environmental impacts and energy consumption can be considered when defining the criteria for characterizing the decision problem (PATYK; BODZIONY, 2022).

Decisions regarding the purchase of equipment affect several criteria that are often conflicting. (ULUTAS *et al.*, 2020). In this way, a decision based on only one or a few criteria, as well as a decision based only on previous experiences or intuition, might not lead to a rational decision or good quality.

Using techniques based on statistics or mathematics increases the reliability of the decision and contributes to its safety. The MCDM methods can be an excellent way to facilitate the decision-making process of equipment selection and offer robustness (ULUTAS *et al.*, 2020).

2.2. Multi-criteria decision making.

Multi-criteria optimization is the process of determining the best possible solutions according to the different established criteria. Several conflicting and non-measurable criteria often characterize practical problems, and no solution satisfies all criteria simultaneously. Therefore, the solution is often a compromise solution according to the decision-maker's preferences (BAZZAZI *et al.*, 2011; DALIC *et al.*, 2020). An example of this is that human judgments are often vague, and the decision-maker cannot always estimate his preference with exact numerical values. In these situations, determining the exact value of attributes is difficult or even impossible. Hence, fuzzy approaches with linguistic terms are often used to describe and deal with these imprecisions and uncertain elements in a decision problem (BAZZAZI *et al.*, 2011).

The greater the number of possible solutions to the problems, the greater the complexity of resolution, since the objective, its criteria, and alternatives have limitations that in greater or lesser numbers, can limit the freedom of judgment (POPOVIC *et al.*, 2019; KARABACEVIC *et al.*, 2018; JENKINS; KEISLER, 2022). MCDM was developed as part of Operations Research (OR) to create mathematical tools that could help the subjective evaluation of criteria by decision-makers (YATSALO *et al.*, 2016; STANUJKIC *et al.*, 2017). In this way, the MCDM facilitates the selection of the most suitable alternative, classifying the alternatives into smaller numbers of categories and ranking these alternatives according to subjective requirements (POPOVIC *et al.*, 2019; MARDANI *et al.*, 2015).

Some recent reviews indicate that the MCDMs have significantly increased their use, development, and application. The study of YANNIS *et al.*, (2020), focused on the review of MCDM applied to decision problems in the transport sector. KUMAR *et al.*, (2017) reviewed the application of the MCDM to the sustainable development of renewable energies, and STOJCIC *et al.* (2019), investigated the MCDM applied to decision problems in sustainability engineering. The three studies found the Analytic Hierarchy Process (AHP) as the most used procedure for multi-criteria decision-making.

3. Materials and methods.

A systematic review of the literature was developed in five steps to achieve the objective of the article: (I) eligibility criteria, (II) selection of database and definition of search strategies, (III) data collection and selection process, (IV) application of the *InOrdinatio* method, (V) application of the bibliometrix and systemic review of the final portfolio. The flow diagram in Figure 1 illustrates the process and the result obtained from each research phase.

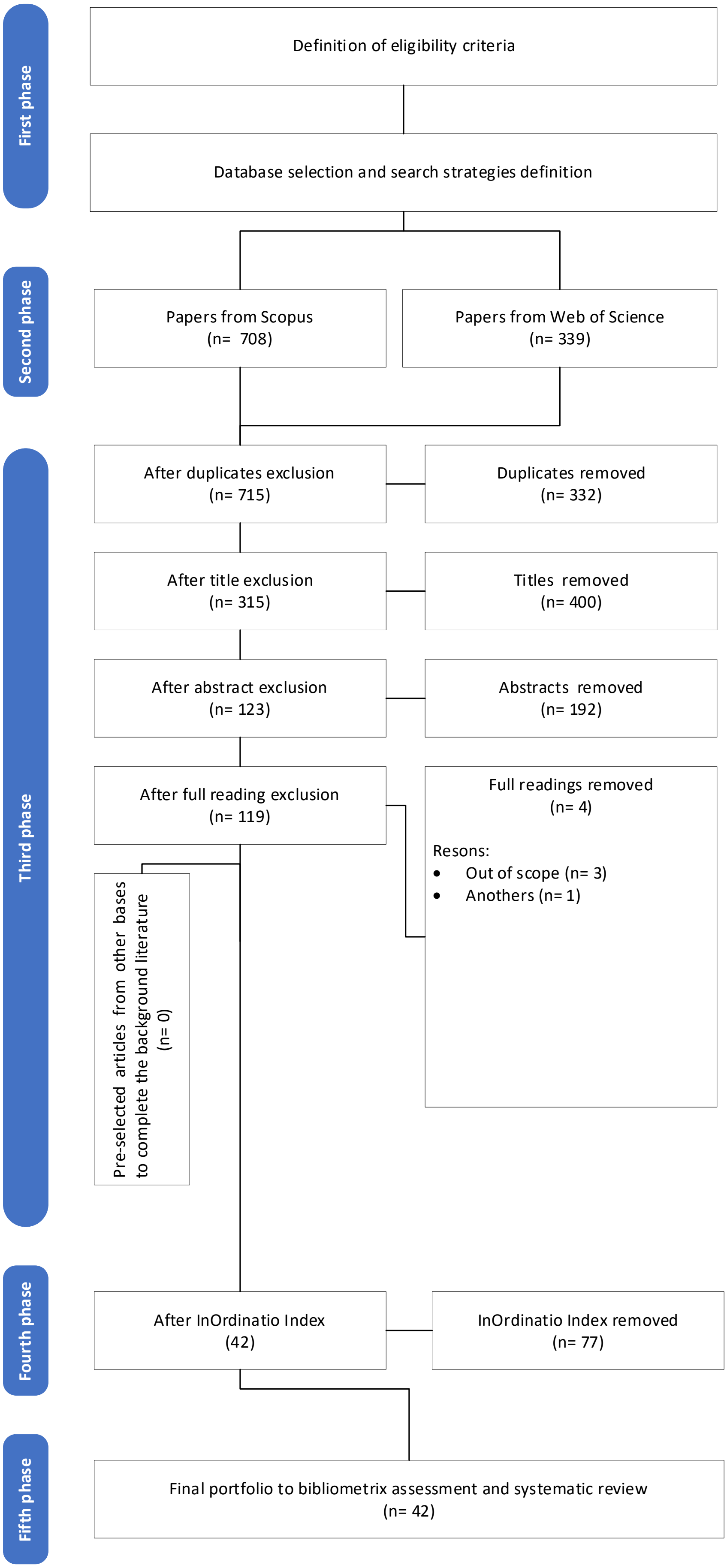

Figure 1 – Overview of Research Methods.

3.1. Eligibility criteria.

To obtain the final portfolio, inclusion and exclusion criteria were defined to be applied during the selection process, as shown in Figure 1. The eligibility criteria ensure a higher consistency assisting the screening of the studies and decreasing the number of studies outside the scope of the study.

Table 1 - Eligibility criteria.

Item	Description
Inclusion criteria (IC)	
IC 1	Multicriteria equipment selection
IC 2	Using one or more MCDM tool
IC 3	Use of sustainable criteria during the equipment selection
Exclusion criteria (EC)	
EC 1	Duplicate studies
EC 2	InOrdinatio Index <= 0

3.2. Selection of database and search strategy.

Scopus and Web of Science are the most significant databases with the most relevant sources about different themes (MONGEON; PAUL-HUS, 2016). Therefore, these databases were chosen to obtain the studies using the string search shown in Table 3 with the keywords and Boolean operators of Table 2 and considering the search strategy in Table 3.

Table 2 - Search Strings.

First axis	Boolean operator	Second axis
("machine select*" OR "equipment select*" OR "machine procure*" OR "equipment procure*" OR "machine purchas*" OR "equipment purchas*" OR "machine provi*" OR "equipment provi*" OR "machine suppl*" OR "equipment suppl*")	AND	("multicriteria" OR "multiattribute" OR "MCDM" OR "MCDA" OR "multi-criteria" OR "multi-attribute" OR "criteria" OR "attribute" OR "decision making" OR "decision-making")

After the search string, the results in each database are limited to (II) research article and review article, (III) simple search mode, and (IV) no time frame. As shown in the full strategy search in Table 3.

Table 3 - Search strategies.

Limitations	Scopus	Web of Science
Language	"English"	"English"
Type document	" Research article and Review article "	" Research article and review article "
Research field	"Article title, Abstract, Keywords"	"Topic"
Document Search mode	"Simple"	"Simple"
Time	"No time frame"	"No time frame"

3.3. Data collection and selection process.

The articles were filtered considering the eligibility criteria to ensure that all papers in the portfolio were relevant to this study. Duplicates in both databases were deleted using Mendeley software features and manually excluded by the authors. The data were collected in early June 2022.

3.4. Applying the *InOrdinatio* Index.

As the *Methodi Ordinatio* (PAGANI *et al.*, 2015) explains, each paper has an *InOrdinatio* index calculated by the formula shown in Eq. 1. Papers with *InOrdinatio* lower than "0" were excluded after the application of eligibility criteria to ensure that only the most relevant research is included in the portfolio.

$$InOrdinatio = \frac{IF}{1000} + a \times [10 - (Research\ Year - Publish\ Year)] + (\sum Ci) \ldots\ldots\ldots\ldots \quad \text{Eq. 1}$$

Where:
$\boldsymbol{IF}$: $Impact\ Factor.$
$\boldsymbol{a}$: $Weighting\ factor\ specified\ from\ 1\ to 10\ by\ the\ authors.$
$\boldsymbol{Research\ Year}$: $Year\ when\ the\ research\ was\ conducted.$
$\boldsymbol{Publish\ Year}$: $Year\ when\ the\ paper\ was\ published.$
$\boldsymbol{Ci}$: $Number\ of\ citations.$

3.5. Full reading of the final portfolio.

In the final phase, a bibliometric analysis was conducted to assess the robustness of the sample and the scientific contribution of the articles to the scientific knowledge on the topic of sustainability. For this purpose, the Bibliometrix package © analysis interface (ARIA; CUCCURULLO, 2017) from the Rstudio software © (CRAWLEY, 2012) was applied to perform bibliometric analyses. Specifically, the results related to the portfolio's co-citation network and collaboration network were considered. These insights provide a comprehensive understanding of the theme and aid in identifying the sustainability topic within the broader context of multicriteria selection equipment and identifying the authors influencing the subject.

Following the outcomes of the Bibliometrix package ©, all articles in the portfolio underwent a thorough analysis through full reading to complete a reading form. This process involved gathering relevant information to comprehend various aspects of the sustainability topic within the selected theme.

4. Results and discussion.

4.1. Bibliometric Analysis.

4.1.1. Co-citation.

The co-citation network of the bibliometrix software provides visual identification of the citation network of the studies in the portfolio. This output allows us to understand how citations are distributed among them, which pieces of work are pivotal, and which themes are concentrated. In the network of citations in the final portfolio, the most significant highlight is the author Saaty (1998), who has a centralized position and is of greater relevance considering the citations of his work in the network with applications of his Analytic Hierarchy Process (AHP) method used to assist in complex decision-making. Figure 2 demonstrates the configuration of the citation network found in the portfolio and the links between the thematic clusters represented by different colors that help to understand the positioning of each piece of research and its relationship with other studies. This output contributed to the identification of the position of each article in the citation network.

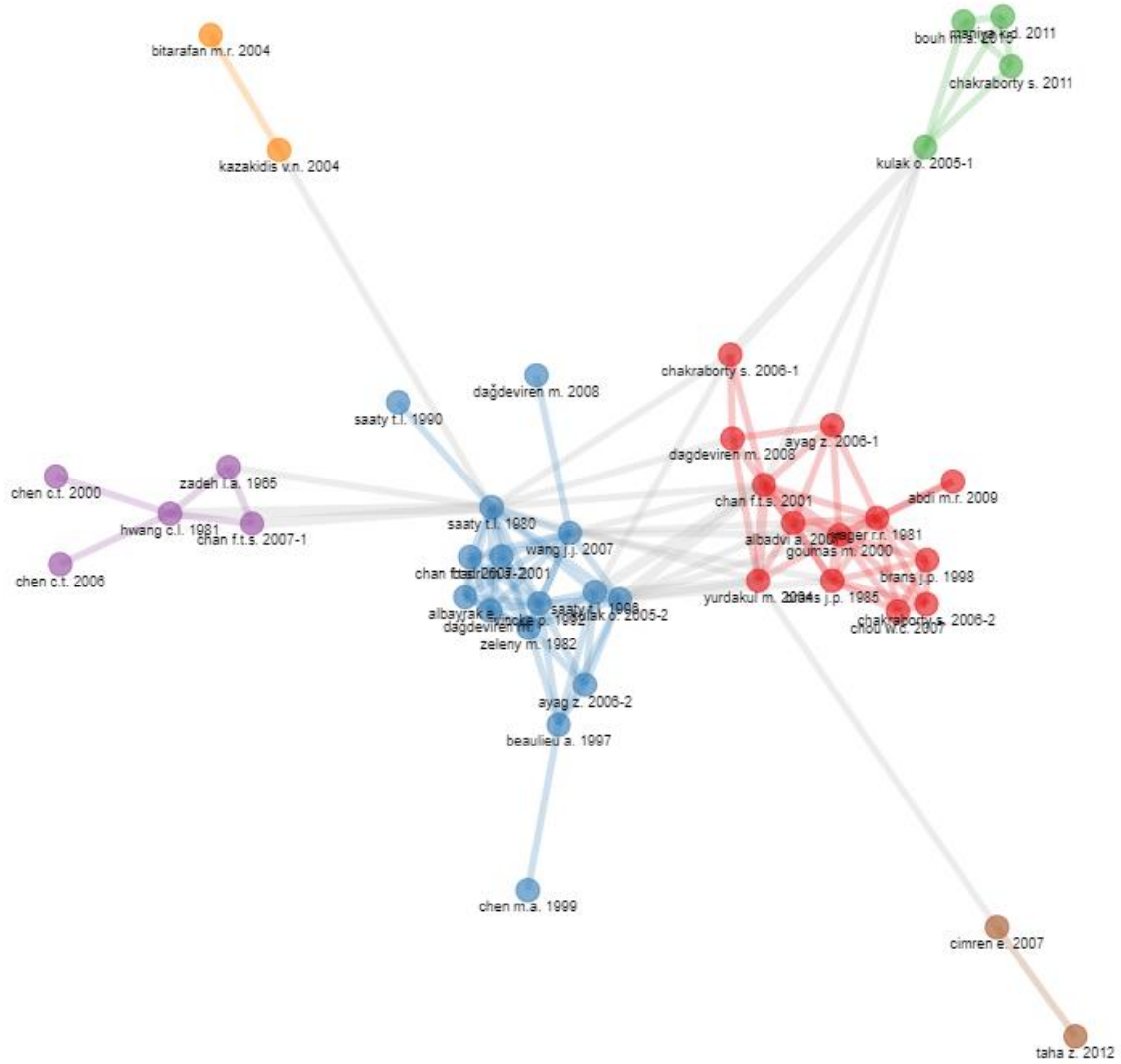

Figure 2 – Co-citation diagram.

In addition, two other papers that stand out and appear in the same grouping or are cited together are Chan *et al.*, (2000) and Goumas and Lygerou (2000). The authors Chan *et al.*, (2000) evaluated alternative solutions in selecting fuzzy methodologies for technology selection. At the same time, Goumas and Lygerou (2000) explored a fuzzy environment approach integrated with the Preference Ranking Organization for Enrichment Evaluation (PROMETHEE) method for ranking alternative energy projects. The PROMETHEE both works are references in fuzzy integration to the MCDM method; this explains his frequent appearance in the citation network. Also, the PROMETHEE consists in a group of different approaches (with the same principles) to obtain a ranking of alternatives, whether partial or total ranking, for example. Finally, the most centralized groups in the figure are those that used the AHP method in a simple way and relate to the articles at the ends that used other methods besides AHP. The left-wing group also utilized fuzzy methods combined with multicriteria. These results will be better addressed in topic 4.3.

4.1.2. Collaboration network.

According to the diagram of collaboration networks (Figure 3), three groups deserve to be highlighted. One of the groups (green in Figure 3) is formed by researchers and professors from Slovakia, and they have several research papers published together. The group's principal papers applied the AHP method in selecting appropriate material handling equipment in selected industrial companies (HORŇÁKOVÁ *et al.*, 2021).

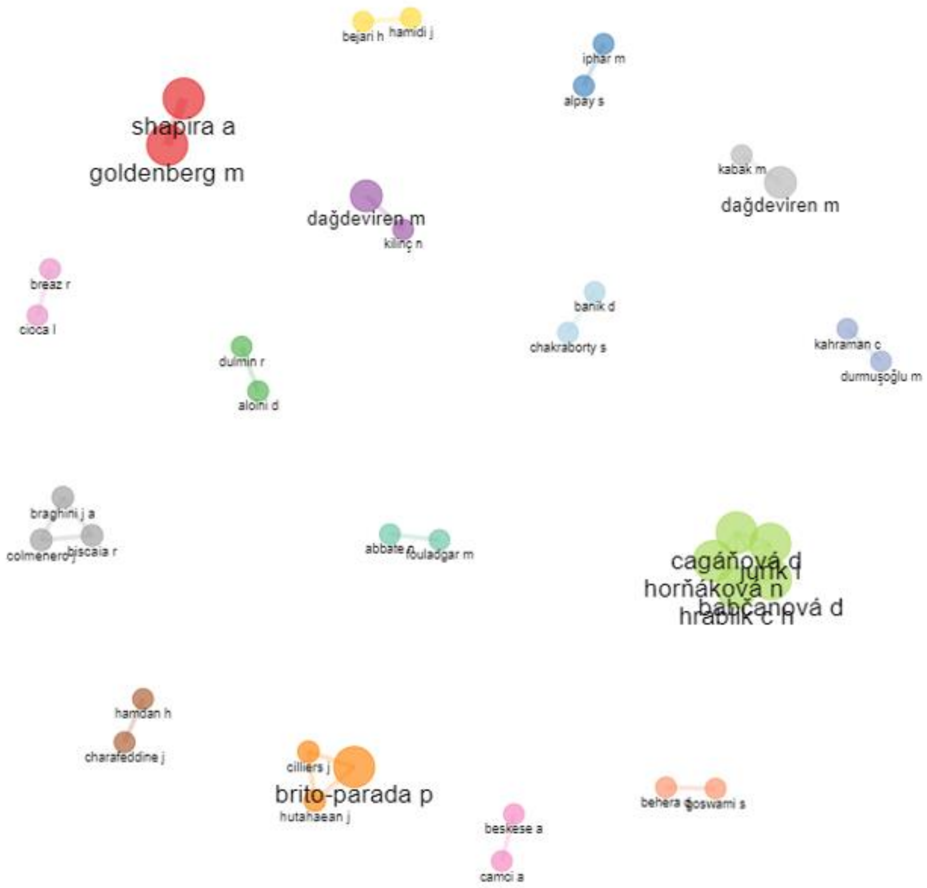

Figure 3 – Collaboration network.

Another cluster to be considered is the duo Shapira and Goldenberg, represented in red in Figure 3. The Israeli researchers have four papers together. The two main papers proposed an AHP-based equipment selection model for construction projects (SHAPIRA AND GOLDENBERG, 2005) and an Integrative model for quantitative safety assessment on construction sites with tower cranes (SHAPIRA *et al.*, 2012).

Finally, the orange cluster in Figure 3 is formed by Brito-Parada, Cilliers, and Hutahaean. Their main research comprises a MCDM decision framework for the selection of biomass separation equipment (HUTAHAEAN *et al.*, 2018) and multicriteria decision-making for the choice problem in mining and mineral processing: applications and trends (SITORUS *et al.*, 2019).

4.2. A temporal Evolution of MCDM application in equipment selection.

Over time, the applications of MCDM in equipment selection have become more diversified, with a substantial increase in methods and sectors of the industry being studied. The evaluation period of articles began in 2005 with two studies. In that year, Shapira and Goldenberg (2005) published a study that used the AHP to make the selection of the construction model. Kulak *et al.*, (2005) applied the Axiomatic Design (AD) to the selection of industrial equipment. Figure 4 shows that annual publications involving MCDM and equipment selection growth are remarkable. The year 2022 has only one publication, perhaps because data were collected in early June. The peak of publications was in 2021, which makes sense if we start with a general analysis of publications involving MCDM methods, as there has been an exponential evolution in the number of publications in recent years (BASÍLIO *et al.*, 2022).

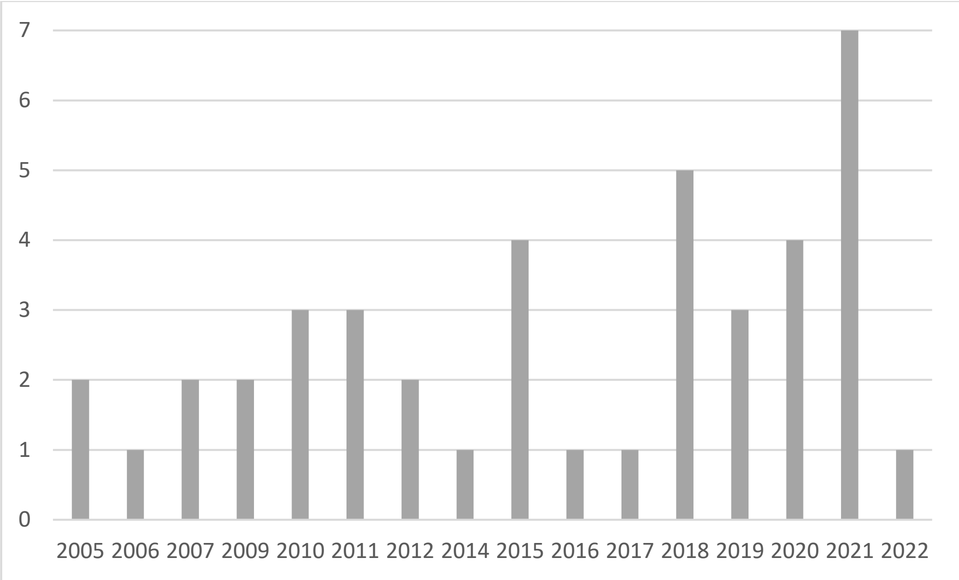

Figure 4 – Temporal evolution of MCDM application in equipment selection.

The popularization of MCDM is also due to the recent development of new methods, contributing to the literature and allowing new applications. In the last decade, some new methods have been highlighted in the literature, such as the Step-wise Weight Assesment Ratio Analysis (SWARA) (KERŠULIENE *et al.*, 2010), the Additive Ratio Assessment (ARAS) (ZAVADSKAS; TURKSIS, 2010), Evaluation based on Distance from Average Solution (EDAS) (GHORABAEE *et al.*, 2015), and Combinative distance-based assessment (CODAS) (GHORABAEE *et al.*, 2016). Therefore, the number of publications involving multicriteria and equipment selection increased over time, most likely due to the creation of new methods and the integration of different methodologies for decision-making. Finally, the difference between multicriteria methods is related to their applicability or their approach to problem-solving. While some methods accept only subjective languages, others require the analyst to provide objective data for the construction of the decision matrix and problem resolution.

4.3. MCDM Approaches Applied to Equipment Selection.

The methods found in the analysis vary to a large extent, ranging from complex applications of extensions and adaptations of fuzzy numbers (SITORUS; BRITO-PARADA, 2020) to the combination of several methods for comparison and sensitivity analysis. Moreover, multicriteria methods can gather and capture various attributes that are necessary for decision-making involving equipment selection, making the decision more robust.

Figure 5 shows the number of times each approach appears, remembering that the approaches can be used together, so the numbers added together exceed the value of articles evaluated by the study. The term “fuzzy approach” refers to papers that use some form of fuzzy numbers. The term “Combined approach” refers to papers using more than one method to solve a problem. The term “simple approach” refers to papers that formulated a methodology with only one method. Finally, within the “simple approach,” there is the term “simple approach with AHP or FAHP”, showing that more than half of the papers that used the “simple approach” used the AHP alone in its original or fuzzy version.

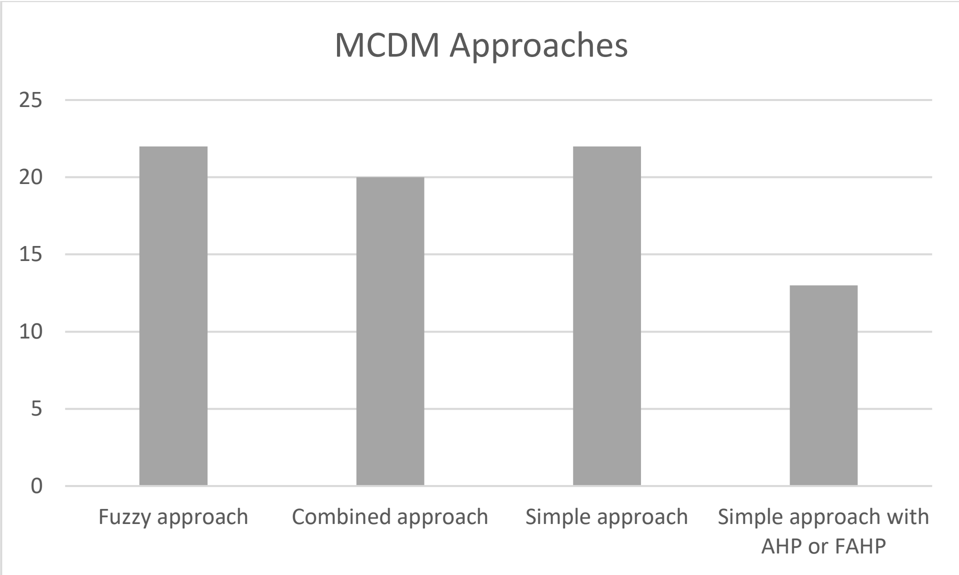

Figure 5 – Analysis of MCDM used in equipment selection.

In this regard, Goswami and Behera (2021) integrated the Entropy, ARAS, and COMplex PRoportional Assessment (COPRAS) methods. Özcan and Çelik (2021) used Gray Relational Analysis (GRA), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and COPRAS. Ersoy (2021) used Entropy to generate the criteria weights and compared the performance of TOPSIS, CODAS, and EDAS.

Alpay and Iphar (2018) compared the fuzzy number version of the TOPSIS and VIšeKriterijska Optimizacija Kompromisno Rješenje (VIKOR) methods. Özgen *et al.*, (2011) compared PROMETHEE and TOPSIS. Ertuğrul and Öztaş (2015) used the Multi-Objective Optimization method based on Ratio Analysis (MOORA) and TOPSIS. Mathew and Sahu (2018) compared the CODAS, EDAS, MOORA, and weighted aggregated sum product assessment (WASPAS) methods. Lu *et al.*, (2022) used Entropy and Criteria Importance Through Intercriteria Correlation (CRITIC) to weigh the criteria and GRA-TOPSIS to rank the alternatives.

However, 24 articles use the AHP, a method created by Saaty (1988). About 57% of the articles used some methodology that includes AHP, whether alone or combined with other methods. This considerable number of papers using AHP is related to the great popularity of the method, being the most used and popular among MCDM, regardless of the application area (Basílio *et al.*, 2022). The AHP is considered interdisciplinary because its mathematics is not very complex. It is the only method that can be used both for weighting criteria and ranking alternatives.

Another frequently used approach is the fuzzy theory, developed by Zadeh (1965), which is still widely used with MCDM methods, having a series of extensions and adaptations which allow researchers to obtain better results and approaches.

Some fuzzy extensions and adaptations identified in the portfolio are the Fuzzy Axiomatic Design (FAD) used by Kulak *et al.*, (2005).

Efe (2019) used the Fuzzy Cognitive Map (FCM), formulated by Kosko (1986), with the integration of the Intuitionistic Fuzzy Numbers (IFN), which are also used by Aloini *et al.* (2014).

Sitorus and Brito-Parada (2020) used a stochastic fuzzy number formulated in a previous study (SITORUS *et al.*, 2019). Biscaia *et al.*, (2021) used a version of the bipolar trapezoidal fuzzy set integrated into the TOPSIS method, known as TrBF-TOPSIS. The bipolar trapezoidal fuzzy numbers were formulated by Akram and Arshad (2019).

Camci *et al.*, (2018) used Fuzzy Hesitant Numbers (FHN), Torra and Narukawa (2009) integrated into the AHP method. Most papers generally deal with AHP (for weighting the criteria) and some other tool for ranking alternatives.

Thirteen studies deal only with AHP or Fuzzy AHP (FAHP) for criteria weighting or ranking the alternatives, and six studies apply AHP or FAHP to weight the criteria and other tools like TOPSIS to rank the alternatives. To highlight the papers that applied these procedures, Dağdeviren *et al.*, (2009) used just the FAHP for weapon selection, and Dağdeviren and Yüksel (2008) applied AHP integrated with PROMETHEE to a machining equipment selection.

The AHP method is the most used MCDM in selecting equipment and decision-making in environmental sciences (CEGAN *et al.*, 2017; DELEPOSTE *et al.*, 2021; BASÍLIO *et al.*, 2022). This study corroborates this information because 24 articles with the AHP approach were found, integrating fuzzy numbers or not.

4.4. Sectors of Equipment Selection.

According to the analysis of the articles, the manufacturing sector is predominant in the applicability of MCDM for equipment selection. This fact is explained by the manufacturing sector, which employs several areas of engineering, such as management, mechanics, electrical, electronics, and others. Therefore, these professionals are more familiar with MCDM and other mathematical approaches to decision-making. All areas surveyed in the research and their participation in the portfolio of articles are shown in Figure 6. The category “other sectors” embraces education, technology, house, and defense, with just one occurrence each.

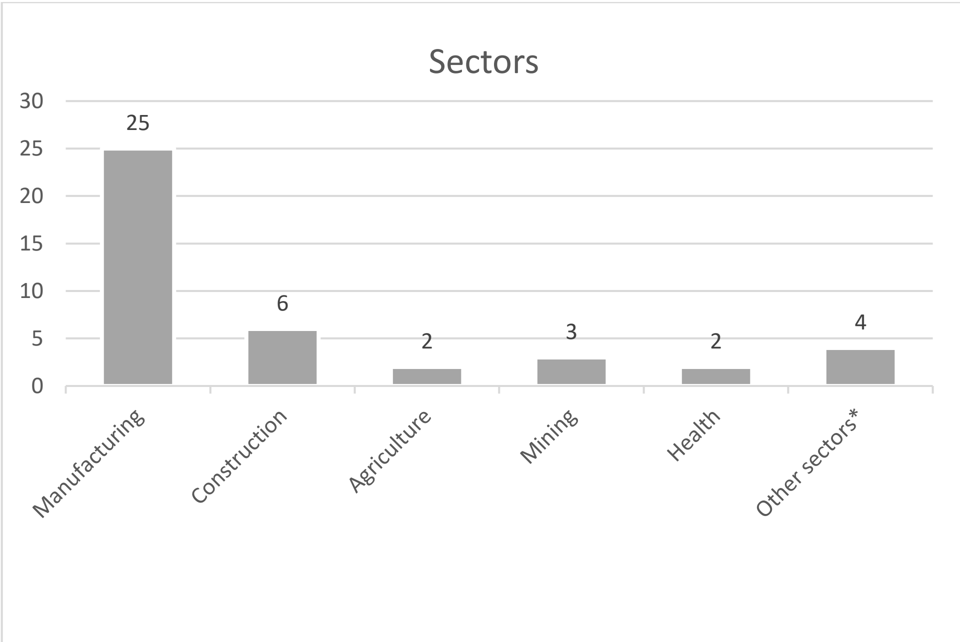

Figure 6 – Sectors of equipment selection.

4.5. Equipment in the Manufacturing Sector.

Focusing the analysis of the results on the manufacturing sector, which represents 60% of the analyzed articles (with 25 studies), two types of equipment deserve more attention because of their large number of occurrences within this sector. Although most research brings decision analysis to various pieces of industrial equipment, 40% of the studies (17) focus on two types of equipment to be selected: Machining Equipment and Material Handling Equipment (MHE).

Figure 7 shows a graph summarizing the types of manufacturing equipment that target decision-making processes involving MCDM.

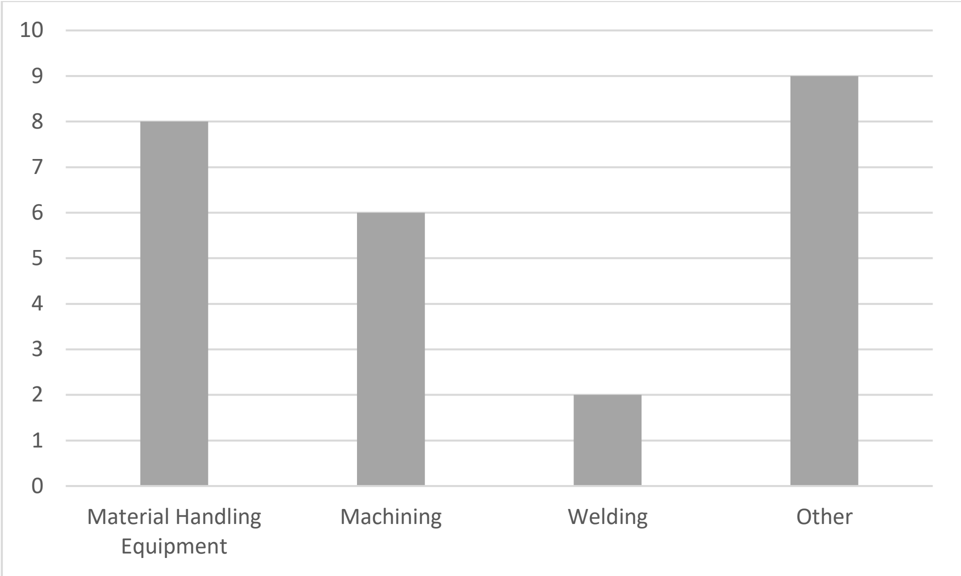

Figure 7 – Equipment selection in the manufacturing sector.
* Education, technology, house, and defense, with just one appearance each.

Considering the machining, Dağdeviren and Yüksel (2008) combined two methods, AHP and the PROMETHEE, for selecting milling machines to be purchased by an international company. Palanisamy *et al.,* (2020) proposed an approach based on the Best-Worst Method (BWM) to select an additive manufacturing machine.

Camci *et al.,* (2018) used the Hesitant FAHP for a CNC router selection in small and medium-sized enterprises (SMEs) in woodwork manufacturing. Cioca *et al.,* (2019) proposed an approach based on AHP and Fuzzy Inference Systems to reduce the risks of purchasing Five-Axis CNC Machining Centers.

Kabak and Dağdeviren (2017) ranked a set of CNC Router machines using the Analytic Network Process (ANP) and GRA.

Meanwhile, regarding the MHE selection problem: Mathew and Sahu (2018) solved two different MHEs problems in just one study; firstly, they applied CODAS method, EDAS method, WASPAS method and MOORA to the selection of a conveyor; secondly, they applied the same methods to an Automated Guided Vehicles (AGV) selection problem.

Horňáková *et al.*, (2021) applied the AHP to selecting a MHE in an industrial enterprise. Chakraborty and Banik, (2006) applied the AHP to select a MHE in a manufacturing industry. Goswami and Behera (2021) integrated three techniques for a AGV selection problem, namely ARAS, and COPRAS.

Ulutaş (2020) proposed an approach to the selection of a stacker based on the Weighted Euclidean Distance Based Approach (WEBDA) and performance selection index (PSI); this is the only study that used these tools. Yavuz (2015) integrated Yager's method and the AHP for a loader selection. Lashgari *et al.,* (2012) proposed a hybrid approach based on Fuzzy AHP and Fuzzy TOPSIS to select transport equipment at a mine. Finally, Onut *et al.,* (2009) proposed a framework for selecting a MHE based on Fuzzy ANP and Fuzzy TOPSIS.

The fact that the manufacturing sector is the primary area covered by this study is explained due to its great competitiveness with several companies with highly qualified human resources; it has grown with globalization (DAGDEVIREN; YUKSEL, 2008). It is evidenced by the fact that, mainly in machining, there is a diversity of processes and brands available and a diversity of services to be performed, involving large amounts of variables and existing geometries. The increasing competitiveness between several companies, explains the great use of decision models involving the selection of machining equipment, especially the MCDM, for being capable of handling a variety of options and being flexible to use.

Similar logic explains the great use of MCDM in selecting MHEs. Fixed and variable costs, size, the weight of the material to be transported, distance, and speed, are some of the attributes that can interfere with the purchase or not of an MHE (MATHEW; SAHU, 2018). The wide variety of tasks and actions that must be done in an industry may be preponderant factors for the existence of several articles proposing methodologies using MCDM for selecting MHEs.

Material handling equipment selection problem (MHESP) is an important area of decision-making for companies, as this decision directly affects productivity and manufacturing. This direct effect makes selecting appropriate equipment a strategic decision for today's manufacturing systems. MHESP is a complex problem with high time consumption due to several alternatives and conflicting objectives (TUZKAYA *et al.*, 2010). In addition, one of the main problems facing logistics is the proper selection of equipment to deal with material resources (ULUTAS *et al.*, 2020).

However, the category "other sectors" (Figure 6) is the most present in the portfolio, with nine appearances. Studies included in this category cover, e.g., the Machine selection problem in the food industry (ÖZCAN; ÇELIK, 2021); lead-free equipment selection (TANG; LIN, 2011); Occupational Safety Equipment selection (YILMAZ KAYA; DAĞDEVIREN, 2016); and selection of projects for automotive assembly structures (BISCAIA *et al.*, 2021).

4.6. Considerations About Sustainability and the Sustainable Triple Bottom Line in Equipment Selection.

Sustainability has been the target or tool of several papers involving MCDM and investigations in the industrial environment (SHARMA *et al.*, 2022; SHAH *et al.*, 2020). However, the articles analyzed for equipment selection diverge in regards with the extent of sustainability aspects that are taken into consideration during the decision-making process. Figure 8 depicts the data related to the consideration of sustainability and technical aspects.

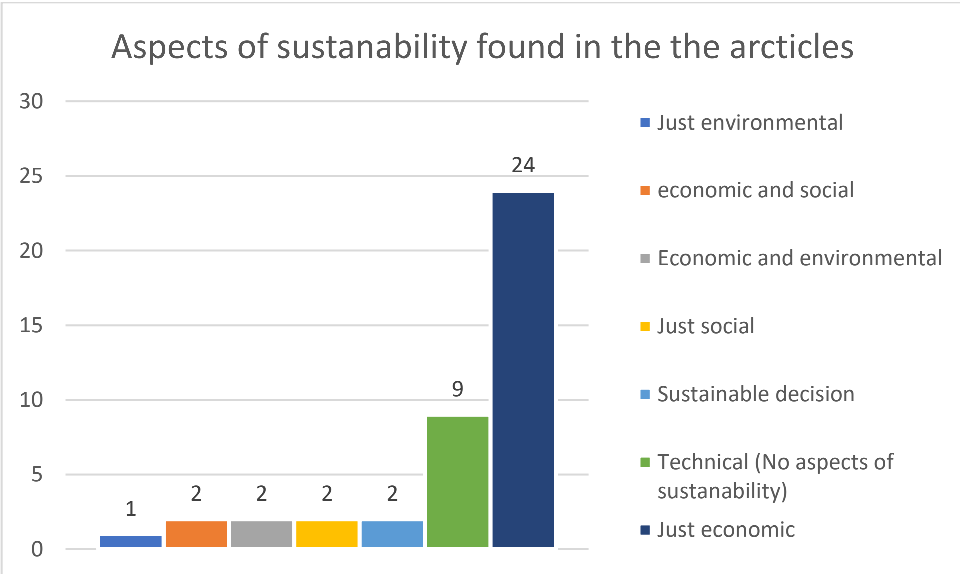

Figure 8 – Occurrence of sustainability and technical aspects in the articles in the final portfolio.

A highlight is that although the portfolio is comprised of studies that address sustainability in equipment selection, the consideration of sustainability is still weak in most studies, especially the environmental pillar of sustainability, since it is the pillar with the least emphasis in the papers. Manufacturing equipment is the most significant type of equipment analyzed in this study. This sector is responsible for most of the pollution and tailings found in nature (LU *et al.*, 2022; WANG *et al.*, 2022). In addition, this type of equipment produces a large amount of waste, and consumables are widely used in the manufacturing process (PALANIYAPPAN *et al.*, 2022). The sector is responsible for producing wastes that might serve as raw material for other processes or even be discarded correctly, or produced in smaller quantities if environmental aspects were to be established since the beginning of the equipment selection process (WEERDT *et al.*, 2020; TIAN *et al.*, 2022).

Equipment selection has a practical nature, which means that technical and usability aspects are the most important for this type of decision-making (WANG *et al.*, 2019). Therefore, technical aspects are considered in all the analyzed papers, whether integrated with sustainable aspects or not. Nine articles had only technical criteria, meaning that only the equipment's applied character was analyzed. However, most of the studies focused on the technical aspects and one of the pillars of sustainability, especially the economic pillar. Twenty-four of the analyzed studies include in the decision the technical and practical aspects of the equipment and economic aspects, including the purchase and maintenance value. The lack of awareness about the concept of sustainability and the triple bottom line may explain the lack of consideration of sustainability issues in equipment selection.

In two articles in the portfolio (YILMAZ; DAĞDEVIREN, 2016; KULAK *et al.*, 2005), the authors argued that only economic and technical aspects are suitable to be considered in the multicriteria analysis for equipment selection, leaving aside environmental or social issues. It can be explained because, at the time the articles were written, sustainability was growing topic, but without too many participations in the industries routine, with technical and mainly economic aspects considerations only. But inowadays, it needs to be reconsidered.

Regarding social aspects found in the literature, only two studies from the same authors (SHAPIRA; GOLDENBERG, 2005; GOLDENBERG; SHAPIRA, 2007) included social criteria. However, both studies barely consider aspects such as night shift work and ergonomic issues (strong winds and obstacles at the construction site), considering only the workers (as stakeholders). However, there is no real inclusion of other relevant stakeholders in the process except for a broad consideration of social aspects. In this sense, selecting equipment, even if addressing a few limited social aspects, cannot be considered fully socially responsible and sustainable.

On the environmental pillar of sustainability, only one study considered it without the other pillars but in combination with technical aspects. Ozfirat (2015) considered geological, soil, and environmental risks, as well as technical aspects of designing tunneling machines. However, the environmental aspects were not deeply explored since they were commented on and considered superficially, not contributing extensively to the decision-making addressed in the study.

About 10% of the articles consider two sustainability pillars besides the technical aspects. Half of these articles consider economic and social aspects, and the other half, economic and environmental aspects. The articles considering economic and social aspects propose decision-making based on the cost of equipment, safety, and ergonomics of workers (YILMAZ; DAĞDEVIREN, 2011; MARCHER *et al.*, 2021). However, there is no consideration of other social issues or stakeholders. Meanwhile, the articles considering economic and environmental aspects presented aspects such as equipment cost and issues relating to the energy consumption of packaging (ALOINI *et al.*, 2014) or sewing equipment (ERTUĞRUL; ÖZTAŞ, 2015).

Finally, only two studies (representing 5%) of the portfolio considered the economic, environmental, and social aspects in addition to technical aspects, appearing in the figure 8 as “Sustainable decision”. Owusu-Mensah and Musingwini (2011) used the AHP to evaluate the ore transport options at a mine in Ghana. They considered economic aspects such as energy and implementation costs; in social aspects, they considered safety and noise levels; and on the environmental dimension, they contemplated emission levels and topography. Tang and Lin (2011) applied the FAHP to select a lead-free welding machine. These authors considered costs of equipment and parts (economic), education and training of workers, occupational safety (social), pollution control, and environment assessment (environmental), aside from technical aspects.

In brief, in a general sense, sustainability and the triple bottom line are not considered in MCDM for selecting equipment. This is a concerns due to the increasing need for action towards a more sustainable development (SALVADOR *et al.*, 2018). The only two studies (OWUSU-MENSAH; MUSINGWINI, 2011; TANG; LIN, 2011) that considered the whole sustainable triple bottom line are from 2011, thus recent studies still lack the consideration of social and environmental aspects in their approaches to select equipment. It does not match current trends in other industrial and business research topics where sustainability is increasingly at the core, as well as the search for contributing to sustainable development and achieving the Sustainable Development Goals (SDG) (UN, 2015).

5. Conclusions.

This work developed a systematic and critical review of the literature about the selection of equipment through the MCDM, being able to contribute with authors who can seek information on the subject and propose the integration of the sustainability triple bottom line in the selection of equipment, especially the industrial ones. The most used MCDM for equipment selection is the AHP; this method is also intensively used in several areas. The primary area in these studies is the industrial sector, with machining and MHE problems.

Integrating sustainability and circular economy can contribute to resource conservation and reduce environmental impacts. The social pillar of sustainability can contribute to increasing work health and safety, such as by reducing accidents, improving ergonomics, and upgrading the workplace for workers. In general, the studies that proposed methodologies for machine selection do not consider sustainability. In fact, just two studies in the portfolio consider sustainable criteria for all three dimensions of the triple-bottom line. Although the use of MCDM for equipment selection has increased with several publications in recent years, recent studies are not considering sustainability approaches, such as Environmental, Social, and Governance (ESG), Circular Economy (CE), or Life Cycle Assessment (LCA).

Furthermore, the industrial community is expected to contribute to sustainable development and achieve the SDGs. In this sense, industries can contribute by manufacturing and selecting equipment that contributes to the triple bottom line, considering economic, social, and environmental aspects. Although we believe the results to be representative of the addressed body of literature, this study does not claim to be exhaustive, as the results reported here are based on the methodological steps presented in section 3, considering the specific keywords, search strings and databases shown. On this basis, future studies will focus on broadening the portfolio and adding sustainable (economic, environmental, and social) criteria into MCDM approaches for selecting equipment and comparing both results (sustainable criteria and only technical criteria).

A possible way to solve the problem of sustainable criteria absence pointed out by the results, would be creating a multi-criteria model based on ESG indicators that would allow a more structured analysis in decision-making during equipment acquisition, especially in large-scale industrial equipment. In this way, future studies are intended to carry out an empirical application to measure the model's effectiveness in solving the problem pointed out in the present study.

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