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Review

Advancing Sustainable Decision Making in Additive Manufacturing: A Comprehensive Review of Multi-Criteria Decision Making Approaches

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Abstract: Additive manufacturing (AM) is one of the technologies of Industry 4.0 that has been contributing to the development of different manufacturing industries. The integration of sustainability concepts into additive manufacturing has been gaining attention among researchers. This integration is essential in the development of AM technologies and can be a significant asset in terms of decision making for organizations. This work aims to present a concise literature review on the integration of decision making, especially multi-criteria decision making, and sustainability into the AM environment. The literature on this topic currently possesses a total of fifteen documents, which were analyzed in this work. Some developments on this topic have been achieved in domains such as material selection, process selection and challenges, and drivers' analysis of sustainable AM. This review shows that even though there has been an effort in recent years to integrate sustainability into additive manufacturing, there is still a long road to the development of this topic for the future, and so some recommendations for future research paths are presented.

Keywords: additive manufacturing; 3D printing; MCDM; decision making; sustainability

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1. Introduction

With the introduction of Industry 4.0, the manufacturing industries are experiencing advanced technical developments [1]. Additive manufacturing (AM) is one of the technologies of Industry 4.0. AM has been revolutionary in the manufacturing industry in recent years due to its possibility of creating complex parts that can be very difficult or impossible to produce through conventional manufacturing processes. AM has garnered significant importance in a wide range of industries due to its transformative capabilities. One prominent sector where AM has made substantial inroads is aerospace and aviation, where it has been utilized for prototyping, lightweight component production, and even manufacturing complex geometries unachievable through traditional methods [2]. The automotive industry has embraced AM for rapid prototyping, tooling, and customization of vehicle parts, leading to streamlined production processes and enhanced design flexibility [3]. AM has also been applied in unconventional approaches, such as in the use of nanoparticles in the material and integration with electronics [4]. In healthcare, AM has also been applied [5]. AM can help create a decentralized, adaptable, and agile production environment that successfully adjusts to the constantly shifting customers' needs [6]. Considering the changes in the world that we are all witnessing, interest in Industry 4.0's sustainability implications and potential benefits for social, environmental, and economic advancement is growing [6]. The current manufacturing trend in Industry 4.0 offers new key technologies like cyber-physical systems, Internet of things (IoT), AM, and big data analytics that are contributing to sustainability directly or indirectly [7]. More sustainable manufacturing practices must be developed and adopted to reduce the environmental emissions of the manufacturing sector [8]. Sustainable manufacturing is producing items in a way that minimizes adverse environmental effects while maintaining economic viability and preserving natural resources and energy [9]. Sustainable manufacturing positively impacts the environment, the economy, and society [10]. Any organization that ignores sustainability issues risks significant financial losses as well as a negative reputation in the marketplace [7]. Energy reduction approaches and manufacturing energy consumption calculations have gained significant attention in the context of sustainable development [11]. Sustainability in AM or sustainable additive manufacturing (SAM) is becoming more popular, given its advantages, which include enhancing design freedom, increased product functionality, and recycling potential [12]. AM techniques can be crucial for reducing material waste and saving energy in the era of sustainable development [13]. Even though sustainability is a big concern nowadays and SAM is gaining more attention, not many studies have been conducted on the incorporation and analysis of sustainability into the AM processes. The incorporation of the sustainability concept into AM is essential to decision making. This paper aims to conduct a short literature review on the integration of decision making and multi-criteria decision making (MCDM) with sustainability into the AM universe.

Multi-criteria decision making (MCDM) and multi-criteria decision analysis (MCDA) are different names for the same concept. MCDM and MCDA are generic terms that encompass various methods that aim to help individuals make decisions according to their preferences, where there is more than one decision criterion [14]. MCDM is an area of operational research to find optimal results in complex scenarios where some objectives and criteria may be conflicting. These methods help in decision making and can be used in different areas such as management, engineering, science, health, and other areas where there is human interaction in the decision. These techniques have been developed in response to real-world problems that require consideration of multiple criteria as well as decision makers' desire to incorporate the most recent developments in computer technology, scientific computing, and mathematical optimization into their decision-making processes [14]. MCDM can be a valuable asset for AM from several perspectives. It can aid the AM industry in material selection [15]; the most suitable material for specific applications can be chosen considering multiple criteria, such as mechanical properties, cost, and environmental impact, for example. It can also aid in process selection, considering criteria like accuracy, cost, and energy consumption [16]. MCDM can also be used to evaluate the sustainability of AM processes or materials. The integration of MCDM into the AM environment can aid in its development and in bringing other concerns that have been evaluated in other manufacturing settings, such as sustainability evaluation, that are not yet established for AM, turning this integration innovative and ground-breaking for this specific industry. Nevertheless, the integration of MCDM into the AM world is not yet significant, and so there is a long way to go in this integration. When considering technology development, decision making and tools that enable it are essential to its growth, and AM is no different. This work intends to identify and analyze the studies that have been conducted that integrate decision making, especially MCDM methods and sustainability aspects, into the AM atmosphere. So, the specific goals of this small review are as follows: (1) identify and analyze the existing studies that integrate MCDM, sustainability, and AM; (2) provide a discussion on the founded studies and identify how these studies have contributed to the integration of sustainability into the AM world; and (3) identify possible research paths upon which more development can be performed on integrating sustainability concepts and MCDM that can positively impact the AM industry. This paper is structured as follows. After this introductory section, Section 2 presents the research methodology used to perform the research. Section 3 describes the results of the conducted review. In Section 4, a critical analysis is performed on the obtained results. To finish, in Section 5, a conclusion is presented.

2. Research Methodology

2.1. Problem Formulation

This study aims to conduct a short literature review on the integration of multi-criteria decision making and sustainability into the additive manufacturing context. The relevance of this study is related to the lack of knowledge about this integration, and this work aims to structure the existing knowledge in the literature in a small literature review.

The literature review was developed following the approach presented in Figure 1. In the first phase, the problem to be addressed was formulated, and the aim of the research was identified. In the second phase, the databases to be consulted, the search strategies, and the criteria of exclusion were established. In the third phase, the defined criteria were applied to the search results, and the articles were selected. In the fourth phase, the selected articles were analyzed meticulously. In the last phase, the results of the research were presented, and this paper was written.

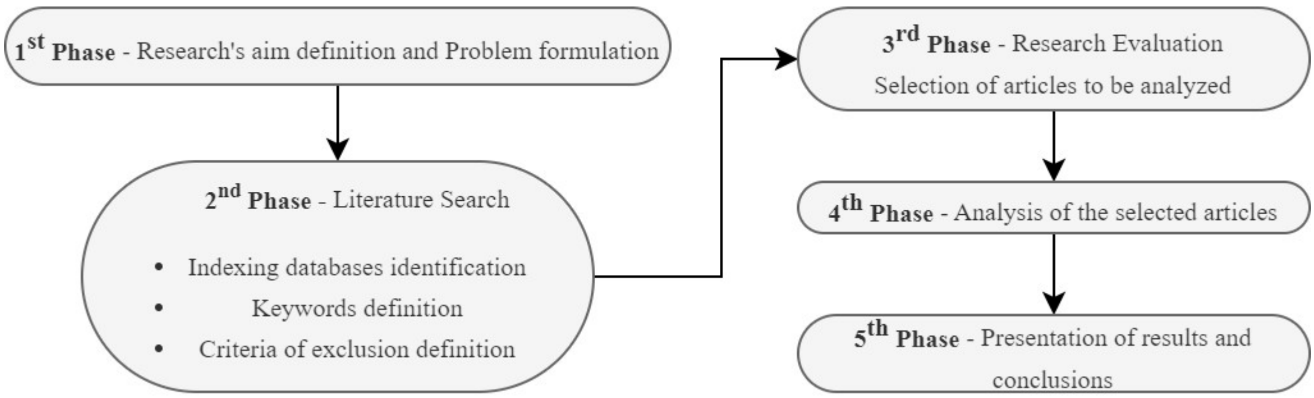

Figure 1. Literature Review Approach.

2.2. Literature Search

To start the search for relevant articles, the indexing databases "Scopus" and "Web of Science" (WoS) were chosen. These databases were chosen considering their coverage in terms of research articles. To define the keywords, several combinations were attempted so that all relevant articles would be found. So, the keywords that were used in combination in both indexing databases were "MCDM", "decision-making", "Additive Manufacturing", "3D-Printing", "Sustainability", "Triple Bottom Line", "Recycling", "Sustainable Manufacturing", and "Sustainable Practices". Most of the combinations used resulted in the intersection of articles. Considering that not many articles were found, the only applied criteria for rejection were that the articles must be written in English and that they could be accessed. The specific approach for the selection of the papers for this study is presented in Figure 2, and the number of articles found per combination of keywords is listed in Table 1.

Table 1. Quantity of articles per keyword combination.

Keywords	Results		
	Scopus	WoS	Scopus + WoS
"Additive manufacturing" AND "Triple bottom line" AND "MCDM"	7	6	9
"Additive Manufacturing" AND "Recycling" AND "MCDM"	2	1	2
"Additive Manufacturing" AND "Sustainable Manufacturing" AND "MCDM"	1	1	1
"3D printing" AND "Sustainability" AND "MCDM"	2	1	1
"MCDM" AND "Additive manufacturing" AND "Sustainability"	4	3	4
"Additive manufacturing" AND "Sustainable manufacturing" AND "decision-making"	19	11	21
Total	35	23	38

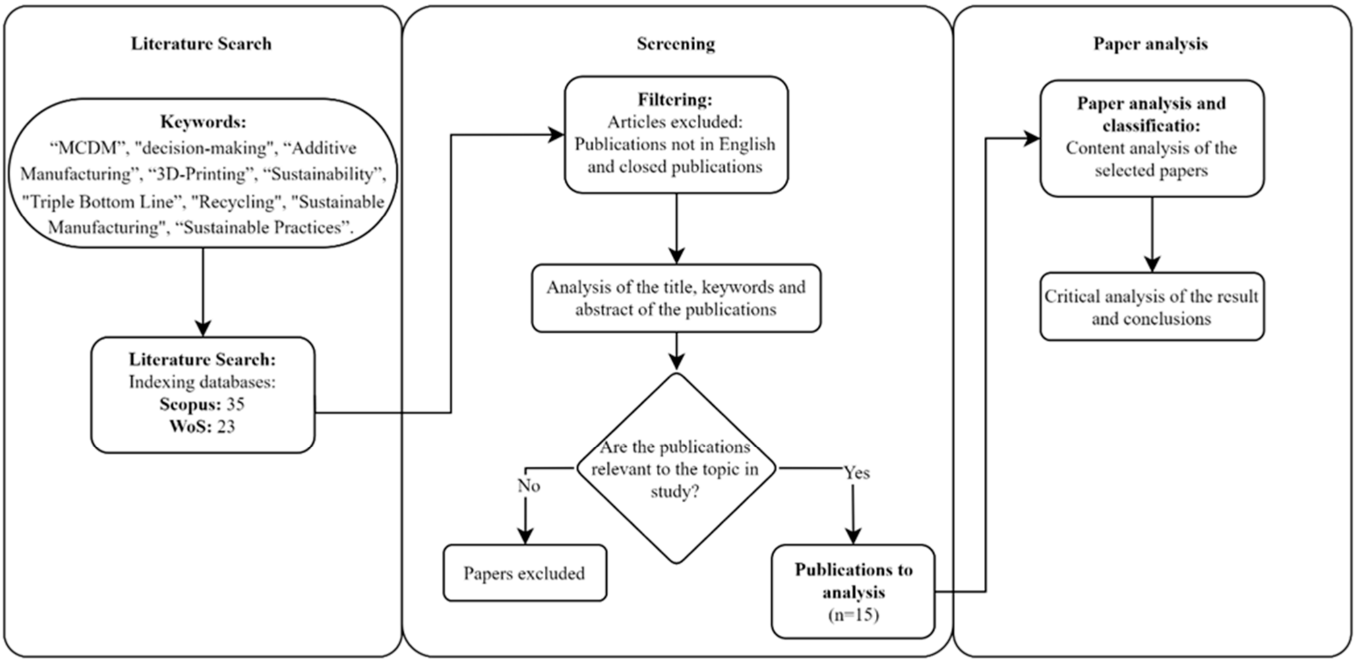

Figure 2. Paper selection process.

With the combination of the several keywords presented, thirty-five publications were found in the indexing database Scopus and twenty-three in WoS. After briefly analyzing the found publications, especially their titles and abstracts, only fifteen matched the topic of this research. Through most of the combination of keywords, the same publications were obtained. The combination of keywords that presented more publications was "Additive manufacturing" AND "Sustainable manufacturing" AND "decision-making". This is related to the fact that these keywords were the most general ones and were used to make sure that no publications were lost with the other combinations. Even though this combination of keywords was the one with the most results, it was also the one where more articles were rejected since their scope was out of this review's aim.

Even though the number of publications existing within this scope is very limited, it is clear that this is an emerging topic. All the analyzed papers were published after 2019, with the highest number of six in 2021, followed by 2023, which accounts for four papers, and one article has already been published in the present year (refer to Figure 3).

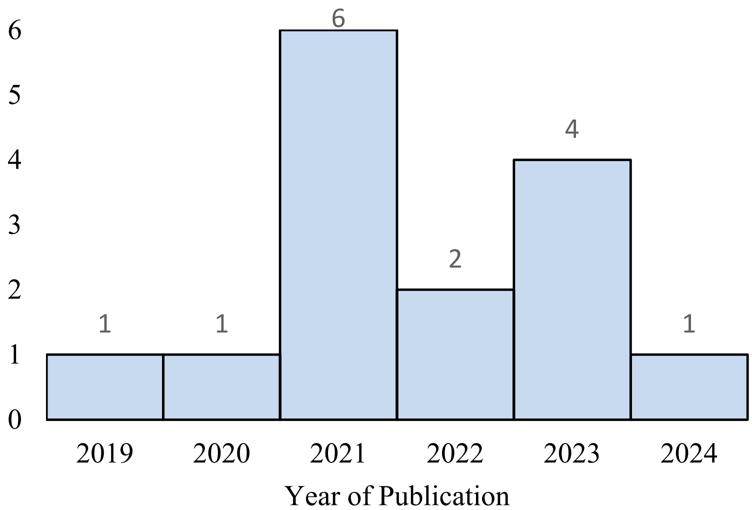

Figure 3. Number of publications per year.

3. Results

From the literature study, it was possible to conclude that there are not many studies that integrate MCDM or decision making concepts and sustainability into AM. The main domains into which the analyzed articles can be classified are driver/challenge prioritization, material selection, process selection/evaluation, quality, supply chain (SC) implication, and supplier selection. Table 2 lists all the analyzed documents and important information on their content.

In the domain of driver/challenge prioritization, Alsaadi identified and analyzed the potential challenges associated with the implementation of SAM practices. In this research article, at first, through a literature review, fifteen challenges to the adoption of SAM were identified [17]. Some of the identified challenges are low cost-effectiveness and energy efficiency at low production quantities, limited possibility for material recycling, and limited reliability of AM technologies. With these challenges identified, the G-TOPSIS (gray technique for order of preference by similarity to ideal solution) method was used to prioritize them and understand their impact on ensuring sustainability in AM. For the prioritization, four criteria were considered: resource efficiency, time compression, product functionality, and environmental impact. To make the evaluation, data from professionals with over ten years of experience in AM were used. TOPSIS is a widely used MCDM method for criteria-based prioritization. In this method, there are two ideal solutions: the positive ideal solution (PIS) and the negative ideal solution (NIS). The mechanism of TOPSIS is used to compare the alternatives with both the PIS and the NIS. The best option will be the one with the least distance from the PIS and the greatest distance from the NIS. In this study, the three topmost identified challenges to the adoption of SAM were the "training of designers and engineers concerning the potential utilization and benefits of SAM", "limited materials recycling potential", and "low-cost effectiveness and energy efficiency at low production volumes". With the performed analysis, the authors state that to ensure sustainability in AM, the organizations must improve the designers' and engineers' skills regarding sustainability, and to increase resource efficiency, actions must be taken to optimize the product and process design, the material input processing, and fabricating the product or component as made-to-order. Jamwal et al. presented a study where the goal was to provide a framework for Industry 4.0 sustainable practices for MSMEs (micro, small, and medium enterprises) [7]. Initially, the literature was used to identify Industry 4.0's social, economic, and environmental enablers. Then, to develop the framework, a hybrid MCDM approach based on F-AHP (fuzzy analytical hierarchy process) and DEMATEL (decision-making trial and evaluation laboratory) was used. The F-AHP was used to pairwise compare the enablers, and DEMATEL was used to find their interrelationship. Expert opinions were required in this process. Results showed that the primary source of Industry 4.0 sustainability hurdles is environment- and supply-chain-related enablers. Also, in this domain, Wankhede and Vinodh evaluated sustainable barriers for 4D printing [18]. The foundation of 3D printing is maintained by 4D printing technology, but its constituent parts can be altered to take on the desired shape at any time. These parts are manufactured in a controlled, dynamic way according to the shapes, and they can change in size and properties over time [1,19]. In the study, eighteen barriers to 4D printing were identified and analyzed against six criteria also using the G-TOPSIS approach. To perform the evaluation, inputs from experts were considered. As findings of this research, significant barriers are found to be "Improper disposal strategy", "Lack of interaction between smart materials and 3D printing technology", and "Lack of Smart materials compatible with AM technologies". On the other hand of this domain, Agrawal and Vinodh analyzed the potential drivers of sustainable AM [20]. The purpose of this study was to prioritize drivers of SAM using the best–worst method (BWM). For this, forty drivers were identified from the literature and were analyzed from eight perspectives: customer/supplier/competitor, management and stakeholders, design and process, collaboration and trends, materials, technology, and standards and regulations. For the analysis, data were collected from experts in the field with over ten years of experience. Based on the analysis, the most significant category is

"Technology", followed by "Design", and the least significant category is "Management and Stakeholders". In this study, the authors also performed a sensitivity analysis to check the bias of the results. Energy conservation, eco-design, and green innovation are the key drivers identified for SAM in this study.

AM is one of the technologies of Industry 4.0, and two of the studies found are not directly related to AM itself but to Industry 4.0 and its impact on SC. Singh et al. explored the features of Industry 4.0 developed by the integration of AM technologies into the production system that enable SC optimization [21]. In this study, ten attributes of Industry 4.0 facilitated by the adoption of AM that contribute to supply chain optimization were prioritized. The evaluation was performed using the gray influence analysis (GINA) technique. This technique is applicable to survey-based studies with numerous responses, and that is the primary reason for the authors to use it. The goal of this technique is to use input-output models and the foundations of gray theory to analyze the relationships of influence between a set of features or factors. Using a questionnaire, specialists with knowledge of Industry 4.0, additive manufacturing, and supply chain optimization from academia, research, and industry were interviewed to obtain their input on the subject. The ten examined characteristics that assist supply chain optimization are flexibility, agility, customization, risk management, sustainable manufacturing, on-demand manufacturing, integration, cloud manufacturing, distributed manufacturing, and collaboration. The results of this study reveal that Cloud manufacturing is ranked first as the feature that enables supply chain optimization through AM. AM-enabled cloud manufacturing reduces the requirement for physical inventories by enabling the construction of a cloud-based repository for digital designs that can be accessed at any time. The feature that ranked second when it comes to optimizing the supply chain through AM is sustainable manufacturing. By decreasing waste, energy use, and the requirement for transportation, AM makes sustainable manufacturing methods possible, contributing to supply chain optimization. Also, in [22], the impacts of Industry 4.0 technologies on supply chain sustainability are evaluated, considering the triple bottom line. The analysis is made through a combination of the analytical hierarchy process (AHP) and VIKOR. Of the three pillars of sustainability, the economic pillar was considered the most important to the evaluation, followed by the environmental and social. In this study, the results show that 3D printing is the technology that contributes the least to enabling sustainability in the supply chains.

In the field of manufacturing, material selection is crucial when considering sustainability aspects [15], and this topic should also be considered in AM. A systematic approach for material selection was presented in a study by Mittal et al. to assess commercially available powders for the selective laser sintering (SLS) technique [13]. To develop the framework, the aggregation multiplicative rule (AMR) approach was used. Eight criteria regarding the mechanical qualities of the powders were considered when ranking sixteen commercially available powders for the SLS process using the established framework. The results of the study revealed that the best-ranked commercially available SLS powder is Duraform GF. In this study, a sensitivity analysis was performed, and the nearly constant ranking results attest to the reliability of the findings. A hybrid framework was also developed in [23] for material selection, with sustainability concerns, for AM industries in India. The evaluation of alternatives was made using the Fuzzy-TOPSIS methodology and with inputs from experts, both from industry and academia. To evaluate the alternatives, the three pillars of sustainability were considered. This study revealed that the use of conventional materials leads to significant CO_2 emissions and other environmental issues that can be resolved with the use of eco-friendly, sustainable materials.

Process selection is also important in manufacturing settings, and AM is not an exception, especially when considering SAM. Moiduddin et al. proposed a decision advisor for the selection of AM machines based on uncertainty theories F-AHP and gray relational analysis (GRA) [24]. For the selection, a database was developed with thirty-nine different AM machines. These machines are used in six AM technologies and three AM systems. The proposed decision advisor can be used as a guideline in selecting the most appropriate AM machines but can also be modified to help in other applications, such as supplier identification and project selection. A study by Zhang et al. offered a model to assist in the selection of forming principles when processing a metallic part [11]. The proposed model considered the entire manufacturing life cycle, including material production, transportation, manufacturing procedures, and recycling, and assessed the forming principles in terms of energy savings. In this study, through the developed model that can be used as a decision-making framework, the energy consumption between subtractive manufacturing and additive manufacturing was compared. In the applied case study, AM turned out to be more energy-efficient than subtractive manufacturing. Even though these results benefit AM, it is important to consider that the sustainability of this process depends on many aspects, including the parts to be produced, so some sensitivity is needed when evaluating these results. In [25], an evaluation of the sustainable performance of the production of face shield brackets was performed. This evaluation compared the production of the face shield bracket through AM, injection molding, and laser cutting. The sustainability analysis was made through the MCDM AHP. For the evaluation, thirty-eight indicators from the three dimensions of sustainability were considered. The results of this study show that 3D printing has a better performance in terms of environment, while the injection model shows better social and economic performance.

Given the various issues that AM-based technologies face in this area—such as adhesion, warping, porosity, gaps between layers, clogged nozzles, distortion from shrinking, and poor dimensional accuracy—the quality of the products made using AM techniques is a feature that needs to be addressed. Three-dimensional printing can take several hours to print, and sometimes, some unacceptable surface distortions are not immediately detected. In terms of SAM, the evaluation of the quality of the products can have an impact on waste prevention and resource efficiency [26]. In this sense, Lishchenko et al. proposed a quantitative method to evaluate the quality of the first layer printed through AM [27]. The method relies on computer vision, an area of artificial intelligence (AI) that allows systems to extract data from visual inputs such as digital photos, movies, or other formats. Computer vision can be used to quantify the difference between the printed object's dimensions and the CAD model and to assess the surface quality by determining whether surface defects are present. With the proposed method, it is possible to evaluate the distance between filament lines, detecting defects on the first layer of the products. An experiment confirmed that this method is useful for quickly evaluating the produced surface quality for future studies on online quality monitoring for 3D printing. The experiment verified the usability of this method for quick quality assessment of the printed surface.

In a research work by Ambilkar et al., an integrated fuzzy Delphi and neutrosophic best–worst framework for selecting a sustailient (sustainable and resilient) supplier for an AM-enabled industry was developed [28]. Supplier selection plays an important role in an organization's productivity, profitability, and stakeholder relations [23]. To address this issue, the framework considers four groups of criteria: traditional, resilient, sustainable, and AM-specific. For the evaluation of criteria, inputs from eighteen industry experts were considered. The framework's applicability was tested in an industry setting. The proposed framework can help in reducing the risk of purchasing by evaluating the suppliers beforehand in a structured and clear way.

Another paper that discussed the importance of AM in achieving sustainable manufacturing by reducing costs, material waste, energy consumption, and CO_2 emissions was by Wu [29]. This paper proposed a business model that focuses on the evaluation of AM and conventional manufacturing processes, as well as collaborative patterns. The model consisted of three parts: a strategy control model, a business model that incorporates the evaluation results from the CRM model into a benchmarking cost model, and a collection–recycling–manufacturing (CRM) model. The paper addressed issues such as scaling, speed, and size of products in AM and emphasized the need for industrial collaboration and standardization to overcome these challenges. This research suggests the establishment of a common platform and forum for academia, enterprises, government, manufacturers, consumers, and AM designers to share information transparently. According to the authors, a software package that supports decision making might be created using the suggested business model.

Table 2. Characteristics of the selected papers.

Ano	Publication Type	Domain	Goal	Results	AM Technology	MCMD Method	Use Area	Ref.
2021	Research Article	Driver/Challenge prioritization	Identification and evaluation of the challenges related to the adoption of SAM.	To guarantee sustainability in additive manufacturing, manufacturing companies should enhance the sustainability-related competencies of their designers and engineers. Additionally, optimizing resource efficiency should also be a priority.	N\A	G-TOPSIS	-	[17]
2019	Research Article	Process selection/evaluation	Proposal of a decision advisor for the selection of AM machines based on uncertainty theories.	The decision advisor was used to evaluate AM machines from a database with the help of experts in the field. The consistency of the results was assessed through a sensitivity analysis that showed robustness. According to the authors, the decision advisor can be customized to be useful in many applications and can be used as a reference when choosing the best AM equipment.	Several	F-AHP, GRA	-	[24]
2023	Conference Paper	SC implication	This study investigates the aspects of Industry 4.0 that support supply chain optimization and that integrate AM into the production system.	Distributed manufacturing, Cloud manufacturing, on-demand manufacturing, and sustainable manufacturing are the predominant features of Industry 4.0 enabled by AM.	N\A	GINA	-	[21]
2021	Conference Paper	Driver/Challenge prioritization	The goal of the study was to create a framework for Industry 4.0 sustainable practices for MSMEs. Industry 4.0's sustainability enablers were identified.	The key enablers of sustainability for Industry 4.0 for MSMEs were identified. The findings showed that the supply chain and environmental enablers are the primary sources of sustainability hurdles in Industry 4.0.	N\A	F-AHP, DEMATEL	-	[7]

Table 2. *Cont.*

Ano	Publication Type	Domain	Goal	Results	AM Technology	MCMD Method	Use Area	Ref.
2021	Research Article	Driver/Challenge prioritization	Propose a business model to enhance cost modeling and collaboration in sustainable manufacturing that can be used as a rigorous evaluation method to position AM effectively in the industry.	The proposed business model addresses challenges faced by AM in scaling, speed, and size of products. The model shows that collaboration patterns and industry collaboration connect different manufacturers into an AM society for full exploitation of AM advantages and SAM.	N\A	-	-	[29]
2022	Conference Paper	Material Selection	Development of a systematic material selection framework to evaluate the commercially available powders for the SLS technique.	The ranking of the available SLS powder was obtained. The commercially available powder ranked first was Duraform GF, while Windform GT occupied the last place in the ranking.	SLS	AMR	-	[13]
2022	Conference Paper	Quality	Proposal of a quantitative method for evaluating the quality of products' first layer printed through 3D printing. The method is based on computer vision.	The proposed method was tested in real 3D printing situations. The method shows some flaws, such as the fact that it can only detect defects in the first layer of the printed product and the fact that it is necessary to stop the printing process to capture images to be analyzed.	FDM	-	-	[27]
2021	Research Article	Driver/Challenge prioritization	This study aims to prioritize drivers of SAM.	Eight perspectives are used to analyze the forty SAM drivers. Energy conservation, green innovation, and eco-design are recognized as important drivers.	N\A	BWM		[20]

Table 2. *Cont.*

Ano	Publication Type	Domain	Goal	Results	AM Technology	MCMD Method	Use Area	Ref.
2020	Conference Paper	Process selection/evaluation	To assist in determining which forming principle could result in greater energy savings during the production of a metallic part, this paper offers a decision-support model. This model primarily compares the energy consumption of additive manufacturing and subtractive manufacturing based on material efficiency.	The relationship between material efficiency and energy consumption for manufacturing is the primary focus of the suggested decision-making tool, while many other considerations are considered when choosing the forming principle for producing a single item. It is important to consider other variables like quantity, geometry, and material property to create more realistic and precise calculation models.	N\A	-	-	[11]
2021	Conference Paper	Material Selection	The goal of this research project is to develop a hybrid multi-criteria model that takes the TBL into account while assessing the most sustainable materials for use in Indian industrial sectors.	The use of sustainable, environmentally friendly materials has the potential to address the significant CO_2 emissions and other environmental issues caused by conventional materials. The research indicates that political concerns rank highly for the Indian additive manufacturing sector, with health and safety coming in second.	N\A	BWM, Fuzzy-TOPSIS	-	[23]
2023	Research Article	Supplier selection	This research work has built an integrated methodology for selecting the sustailient (resilient and sustainable) supplier for an AM-enabled sector.	A 3D-printed trinket manufacturer is used as an industrial case to illustrate the applicability of this methodology. Resiliency, sustainability, and AM-related traits are better understood by AM decision makers with the support of the proposed research.	N\A	Fuzzy, Delphi, and neutrosophic BWM	Additively manufactured trinkets (jewelry)	[28]

Table 2. *Cont.*

Ano	Publication Type	Domain	Goal	Results	AM Technology	MCMD Method	Use Area	Ref.
2023	Research Article	Driver/Challenge prioritization	This article aims to identify and evaluate barriers to sustainable 4D printing through expert consultation and literature review.	Eighteen sustainable 4D printing were identified and analyzed against six criteria. The significant barriers identified are found to be "Improper disposal strategy", "Lack of interaction between smart materials and 3D printing technology", and "Lack of Smart materials compatible with AM technologies".	N\A	Gray TOPSIS	Automotive Industry	[18]
2023	Research Article	SC implication	The purpose of this article is to analyze how the supply chain's sustainability is affected by the adoption of disruptive technologies. Big data, blockchain, robotics, IoT, and cloud computing are among the technologies under study.	3D printing was considered the least important technology in the sustainability of the supply chain in this study.	N\A	AHP, VIKOR	-	[22]
2021	Research Article	Process selection/evaluation	This study's primary goal is to assess the viability of three different technologies for creating a face shield bracket. Injection molding, 3D printing, and laser cutting are employed to produce three different face shield brackets.	The findings showed that injection molding performed better economically and socially performance, whereas 3D printing performed better environmentally.	N\A	AHP	Faceshield Bracket Manufacturing	[25]
2024	Research Article	Process selection/evaluation	Proposal of a decision model for solving 3D printer selection problem for industries.	The proposed framework was tested in two related case studies in the car manufacturing industry. The proposed model incorporated some criteria, and the study showed that the most effective criteria are "Accuracy" and "Quality". The model was tested through a sensitivity analysis and showed robustness and consistency.	Several	FF–SWARA, FF–RAFSI	Automotive Industry	[30]

4. Critical Analysis

This study has provided a small literature review on the integration of sustainability and MCDM or decision-making tools into the AM industry. Even though not many studies have been performed on the mentioned topic, the publications show a wide range of applications. It was possible to classify the analyzed articles into seven domains: driver/challenge prioritization, material selection, process selection/evaluation, quality, SC implication, and supplier selection.

This review highlights the use of various decision-making methodologies such as TOPSIS, BWM, Fuzzy-AHP, and others, demonstrating the diverse approaches researchers employ to address complex problems in AM. The most used MCDM method was AHP [7,22,24,25]. This method was used by itself and combined with others. In many of the analyzed studies, the gray environment has been used [18,20,21,24]. The gray environment is usually used to deal with decision-making inconsistencies [31] and when dealing with incomplete, inadequate, and discrete information with uncertainties [18] and is particularly useful when considering qualitative or semi-quantitative data, as they allow for the incorporation of imprecise information and subjective judgments and when gathering inputs from experts [32].

Most of the studies incorporate inputs from experts into the research. The involvement of experts in the studies enhances the credibility of the research findings and gives real applicability to the research into the industry, fomenting the communication and involvement between academia and industry. Even though this involvement is essential and beneficial, it is important to guarantee that conflicts of interest and subjectivity are avoided.

An aspect that was, in many of the studies, stated by the authors is the replicability of the proposed methods. While the studies provide valuable insights into specific aspects of sustainable AM, their applicability and generalizability to broader contexts and industries is a concern that the authors have considered. This replicability enables the industry's development and enhances collaboration practices.

This review shows that the concept of SAM has been gaining attention from researchers and industry-related stakeholders. This concept that aims to add sustainability concepts into the AM industry has been gaining relevance in the performed studies as the evaluation of the processes, material, and overall performance is essential to enhancing sustainable practices in the sector. Even though big efforts have been made in this sense, there is still a long road ahead in this topic. Several avenues for future research can be identified. In the mentioned domains, there is still room for more research to be performed, and complementary studies to the analyzed ones can be performed. Even though this research focuses on sustainability in AM, most of the studies focus only on the dimension of the environment, leaving the economic and social dimensions aside. More studies could be performed on assessing the environmental and social aspects of AM. Future studies could integrate MCDM methods to conduct a cost-benefit analysis of implementing SAM practices to show the economic benefits of sustainability initiatives, such as energy efficiency, process optimization, and waste reduction. The same could be accomplished for the social dimension. When considering sustainability, it is essential to evaluate the entire supply chain in any industry. The analyzed studies focused more on singular aspects of AM rather than on the whole SC. A way to evaluate the sustainability of the entire process is to integrate lifecycle assessment in AM. Some efforts have been made in this optic, but there is still space for more research. This analysis would enable the evaluation of the impacts of AM technologies across the entire product lifecycle in terms of energy, waste, emissions, manufacturing, use, disposal, and others. The construction of a decision-support tool that integrates lifecycle assessment into AM could help to fill this gap. The development of tools that help in sustainable design in terms of process and materials is also a topic where more work can be developed.

5. Conclusions

This study aimed to develop a short literature review on the integration of sustainability and decision making, especially MCDM, into AM. Despite the limited number of studies found on this topic, this review revealed various domains where sustainability and decision making have been integrated into AM processes, including material selection, process evaluation, quality assessment, supply chain implications, and supplier selection.

This review showcased the diverse decision-making methodologies utilized in these studies, such as TOPSIS, BWM, and Fuzzy-AHP, among others. This demonstrates researchers' dedication to addressing complex challenges within AM. In most studies, experts were invited to participate, enhancing the credibility and applicability of the findings to real-world scenarios.

This review identified several promising avenues for future research. These include expanding assessments to encompass economic and social dimensions of sustainability, integrating lifecycle assessment into AM processes, developing decision-support tools for sustainable design, and evaluating the entire supply chain sustainability within the context of AM.

While some progress has been made in integrating sustainability and decision making into AM processes, there is ample room for further development and exploration in this area. By addressing the identified gaps and pursuing future research avenues, the AM industry can continue advancing towards more sustainable and efficient practices, contributing to environmental efficiency and economic and social development.

In the context of AM industries, it is essential to consider sustainability when making decisions. This consideration will strengthen the development of AM and its market growth, enhance competitiveness, foster innovation, and contribute to a more sustainable future, which is now a critical point in manufacturing industries.

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