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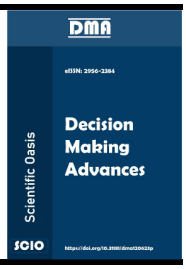

Supplier Selection in the Age of Industry 4.0: A Review on MCDM Applications and Trends

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ABSTRACT

The advent of Industry 4.0 has triggered a profound transformation in manufacturing and supply chain management, necessitating the adaptation of supplier selection processes to this evolving technological landscape. This comprehensive review paper places a significant focus on the role of multi-criteria decision-making (MCDM) methodologies and emerging trends in the context of supplier selection within Industry 4.0. It underscores the critical importance of effective supplier selection in achieving operational excellence and bolstering supply chain resilience in this new era, exploring the challenges and opportunities presented by technological advances such as the Internet of Things, big data analytics, artificial intelligence, and advanced manufacturing techniques. The paper looks into the theoretical underpinnings of MCDM techniques, highlighting their suitability for addressing the complex, multi-dimensional criteria associated with supplier selection. As a valuable resource, this study caters to researchers, practitioners, and decision-makers navigating the intricate landscape of supplier selection within the dynamic area of Industry 4.0, emphasizing the pivotal role of MCDM methodologies and the ever-evolving dynamics shaping supplier selection processes in the digital age.

1. Introduction

Industry 4.0, often referred to as the fourth industrial revolution, has had a profound and far-reaching impact on supply chains. This transformation has fundamentally reshaped how businesses design, manage, and optimize their supply chain operations. At its core, Industry 4.0 represents a paradigm shift in the way companies leverage digital technologies to enhance efficiency, visibility, and responsiveness within their supply chains. One of the most significant impacts of Industry 4.0 on supply chains is the integration of cutting-edge technologies. These include the Internet of Things (IoT), artificial intelligence (AI), machine learning, big data analytics, and automation. These

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technologies enable real-time monitoring of supply chain processes, facilitating data-driven decision-making. IoT sensors placed on assets such as products, vehicles, and equipment collect vast amounts of data, providing valuable insights into the status and location of goods at any point in the supply chain [1]. AI and machine learning algorithms can process this data to predict demand, optimize routes, and even perform predictive maintenance on equipment, reducing downtime and costs.

Another key aspect of Industry 4.0's impact on supply chains is the concept of a "smart" and interconnected supply chain ecosystem. Through digital twins, companies can create virtual replicas of their supply chains, allowing for in-depth modeling and simulation. This enables businesses to test various scenarios, identify bottlenecks, and develop more efficient strategies. Furthermore, these digital twins can also be used to monitor and control processes in real time, enabling agile adjustments to mitigate disruptions or seize opportunities. Automation and robotics play a pivotal role in Industry 4.0-enabled supply chains. With the use of autonomous robots, drones, and automated material handling systems, the physical movement of goods is more efficient and precise. Warehouses and distribution centers are increasingly adopting automated systems to speed up order fulfillment and reduce errors. Additionally, the use of 3D printing in manufacturing can bring about a significant shift in the supply chain by enabling localized and on-demand production, reducing the need for vast inventories and long-distance transportation [2].

Industry 4.0 fosters collaboration and transparency throughout the supply chain. Blockchain technology is leveraged to create immutable and secure ledgers of transactions and product movements. This enhances trust and traceability, particularly in industries with complex and multi-tiered supply chains, like food and pharmaceuticals. Stakeholders can access a shared source of truth, ensuring product authenticity and safety. Furthermore, Industry 4.0 enables a shift from a linear supply chain model to a more circular and sustainable approach. By utilizing data-driven insights, companies can reduce waste, optimize resource utilization, and improve the environmental footprint of their operations. Sustainability and corporate social responsibility are increasingly becoming critical components of supply chain strategies, and Industry 4.0 tools help in achieving these objectives.

1.1 Role of Supplier Selection in Supply Chain Management

The decision to choose a supplier has significant effects on the operations, effectiveness, and success of an organization, hence it is vital in the field of supply chain management (SCM). The process of choosing suppliers is integral to ensuring the smooth flow of materials, products, and services through the supply chain. A well-thought-out supplier selection strategy involves a comprehensive assessment of various factors, each of which can significantly impact the supply chain. One of the primary considerations in supplier selection is the assessment of the supplier's capabilities and reliability. Organizations must evaluate a potential supplier's capacity to meet their production and delivery requirements. This involves examining the supplier's production capabilities, capacity utilization, and lead times. A reliable supplier should be able to consistently deliver the required quantities of high-quality goods or services on time. Failure in this regard can result in disruptions to the supply chain, increased lead times, and potential damage to customer relationships.

Quality is another critical aspect of supplier selection. Ensuring the quality of incoming materials or products is fundamental to producing consistent and reliable end products [3]. Organizations must assess a supplier's quality control processes, certifications, and track record. Quality-related issues can lead to defective products, increased rework or scrap, and customer dissatisfaction, all of which have a direct impact on the efficiency and effectiveness of the supply chain. Cost considerations are

essential in supplier selection as well. While it is crucial to select a supplier that can provide quality products on time, organizations must also be mindful of the cost implications. The cost of goods and services from suppliers directly affects a company's profitability [4]. Supplier selection involves analyzing various cost factors, including the purchase price, transportation costs, inventory carrying costs, and any hidden costs such as customs duties or taxes. A well-balanced approach is necessary, as selecting the lowest-cost supplier may not always be the most cost-effective choice when considering the total cost of ownership.

Geographical considerations also come into play during the supplier selection process. The location of suppliers can impact transportation costs, lead times, and overall supply chain efficiency. Proximity to suppliers can be advantageous in terms of reducing shipping costs and shortening lead times, especially for perishable or time-sensitive goods [5]. On the other hand, global supply chains often rely on suppliers from different regions, which can introduce complexity but may be necessary to access specific materials or take advantage of cost advantages in different markets.

Supplier relationships and compatibility are often underestimated but are crucial in supplier selection. Effective communication, shared values, and a mutually beneficial relationship can lead to collaboration, innovation, and responsiveness. It's not just about selecting a supplier; it's also about building a partnership that fosters trust and reliability. A strong supplier relationship can lead to shared risk management, joint problem-solving, and the development of new products or processes that benefit both parties.

1.2 Importance of Supplier Selection in the Age of Industry 4.0

In the age of Industry 4.0, where digital technologies and automation are transforming the manufacturing and supply chain landscape, the importance of supplier selection becomes even more pronounced. Industry 4.0 represents a new era of smart manufacturing and SCM, driven by technologies such as IoT, big data analytics, AI, and automation. In this context, the process of selecting and managing suppliers takes on a strategic role in ensuring the smooth and efficient operation of supply chains. One of the key aspects of Industry 4.0 is the emphasis on data-driven decision-making. Suppliers play a pivotal role in this data ecosystem, as they provide critical components, materials, or services that feed into the digital supply chain. Supplier selection must account for a supplier's ability to integrate and share data seamlessly. This means evaluating a supplier's digital capabilities, their use of IoT sensors and devices, and their compatibility with your data systems. Suppliers that can provide real-time data on the status of shipments, production, and inventory levels enable supply chain managers to make more informed and agile decisions, ultimately improving overall supply chain performance.

Quality and reliability are still paramount in Industry 4.0, but the tools and methods for ensuring them have evolved. Data analytics and AI-driven quality control can help identify quality issues early in the production process, reducing defects and rework. SS, therefore, should consider a supplier's commitment to quality management and its ability to integrate with digital quality control systems. In line with the values of Industry 4.0, a high-quality supplier may assist in maintaining product uniformity and minimizing disruptions brought on by flaws. Another crucial component of supplier selection in the context of Industry 4.0 is cost optimization. While the initial cost is significant, a more thorough investigation is needed. The total cost of ownership, which includes expenditures for transportation, inventory carrying, and the effectiveness of the supplier's manufacturing processes, must be taken into account by organizations [6]. The integration of digital technologies can help suppliers streamline their operations and reduce costs, and organizations should look for suppliers who embrace Industry 4.0 practices to achieve cost efficiencies and competitiveness. Globalization

and digital connectivity have expanded the reach of supply chains, often involving suppliers from various regions. Supplier selection in Industry 4.0 should consider the geographical location of suppliers about the organization's facilities and markets. Proximity to suppliers can help reduce lead times and transportation costs, which are essential in today's fast-paced, customer-driven markets [7]. Here is how Industry 4.0 views supplier selection:

i. *Data-driven decision-making* – Industry 4.0 relies heavily on data analytics and real-time information. When selecting suppliers, companies can use data-driven insights to evaluate supplier performance, quality, delivery times, and other key metrics. This enables more informed decision-making and helps in choosing suppliers that align with the organization's strategic goals.
ii. *Enhanced transparency* – Industry 4.0 technologies, such as IoT, provide transparency throughout the supply chain. Suppliers' performance and product quality can be monitored in real-time, ensuring that the selected suppliers meet the agreed-upon standards and requirements.
iii. *Digital collaboration* – Industry 4.0 facilitates digital collaboration with suppliers through platforms and tools that enable communication, document sharing, and data exchange securely and efficiently. This fosters closer relationships with selected suppliers and streamlines the procurement process.
iv. *Supply chain integration* – Industry 4.0 emphasizes supply chain integration and visibility. Supplier selection involves choosing partners who can seamlessly integrate their systems with yours, making it easier to exchange data and coordinate processes.
v. *Predictive maintenance* – Suppliers of machinery and equipment can play a crucial role in predictive maintenance, a key component of Industry 4.0. Companies should select suppliers that offer IoT-enabled machinery and equipment with built-in predictive maintenance capabilities to minimize downtime and optimize production.
vi. *Agile and responsive supply chain* – Industry 4.0 enables agile and responsive supply chains. Supplier selection is critical to ensure that suppliers can adapt to changing market conditions and quickly adjust production schedules, product configurations, or delivery timelines as required.
vii. *Quality and compliance assurance* – Supplier selection should prioritize suppliers who adhere to quality standards and regulatory requirements. Industry 4.0 tools can assist in monitoring and ensuring compliance with these standards.
viii. *Risk mitigation* – Industry 4.0 allows for a more comprehensive assessment of supplier risk, including factors like geopolitical, environmental, and economic risks. Supplier selection should consider these aspects to mitigate potential disruptions in the supply chain.
ix. *Sustainability and environmental impact* – Industry 4.0 encourages sustainable practices, and supplier selection should reflect this by choosing suppliers committed to eco-friendly manufacturing processes and ethical sourcing of materials.
x. *Cost optimization* – Industry 4.0 technologies can help in cost analysis and optimization. Supplier selection should consider total cost of ownership rather than just initial purchase costs, taking into account factors like maintenance, energy consumption, and logistics.

Supplier selection in Industry 4.0 is about choosing partners that align with the organization's digital transformation and supply chain goals. It involves leveraging data-driven insights, fostering collaboration, ensuring transparency, and prioritizing sustainability and agility to create a resilient

and efficient supply chain. The right suppliers can be key contributors to a company's success in the Industry 4.0 era.

1.3 Scope of the Proposed Study

The scope of the research article includes the following:

i. Provide an overview of Industry 4.0 and its impact on supply chains.
ii. Emphasize the importance of supplier selection in this evolving digital landscape.
iii. Review existing research on supplier selection, focusing on both traditional and digital supply chain contexts.
iv. Examine the methodologies and criteria used in prior studies.
v. Explore the core technologies associated with Industry 4.0, such as IoT, AI, big data analytics, and automation.
vi. Provide a detailed analysis of criteria relevant to Industry 4.0, including cost, quality, sustainability, and digital readiness.
vii. Include case studies and examples illustrating the implementation of multi-criteria decision-making (MCDM) methodologies in real-world Industry 4.0 scenarios.

1.4 Objective of the Proposed Study

The objectives of the proposed study are:

i. To provide a comprehensive review of supplier selection methods and models in the context of Industry 4.0.
ii. To examine the evolving criteria for supplier selection in the context of Industry 4.0, considering factors such as digitalization readiness, cybersecurity, etc.
iii. To analyze the techniques and methodologies employed for choosing suppliers in the age of Industry 4.0, with a focus on MCDM approaches.
iv. To assess the integration of IoT, big data analytics, and AI in the supplier selection process and explore their impact on decision-making and SCM.

The primary objective of this study is to facilitate a comprehensive examination and juxtaposition of the traditional methods and models found in the literature in light of the influence of Industry 4.0. Section 2 will introduce the historical context and significance of the Industry 4.0 era, specifically as it pertains to the process of supplier selection. The previous investigations, together with their areas of practical application and the various factors considered in supplier selection, will be elaborated on in Section 3. The models that have been carefully chosen for examination in this study will be expounded upon in Section 4. Lastly, in Section 5, the study will conclude by presenting the key insights and findings derived from the research.

2. Literature Review

There has been a conspicuous lack of research on supplier selection in the context of the Industry 4.0 era in the past few years. The purpose of this section is to give a thorough summary of the hybrid MCDM methods that have been used for supplier selection. Within this context, we aim to underscore the extensive utility of fuzzy approaches, such as the fuzzy analytic hierarchy process

(FAHP), fuzzy technique for order of preference by similarity to ideal solution (FTOPSIS), decision making trial and evaluation laboratory (DEMATEL), and complex proportional assessment of alternatives (COPRAS) analysis in supplier selection processes within the Industry 4.0 framework.

2.1 Criteria Used in Supplier Selection

In this part, we look into the digital criteria utilized for supplier selection, offering a thorough introduction and elucidation of these criteria, which are pivotal in enhancing supplier selection strategies in the Industry 4.0 landscape.

The significance of supplier selection using MCDM approaches in the context of Industry 4.0 cannot be emphasized [8]. Industry 4.0 represents a paradigm shift characterized by smart manufacturing, data-driven decision-making, and the integration of cutting-edge technologies. As a result, supplier selection criteria play a pivotal role in ensuring the efficiency and competitiveness of businesses operating in this era. These criteria serve as the guiding principles for evaluating and prioritizing potential suppliers, taking into account various factors such as cost, quality, flexibility, responsiveness, sustainability, and digital readiness. The digital aspect, in particular, has gained prominence, with criteria related to data exchange, compatibility with Industry 4.0 technologies, and cybersecurity becoming increasingly critical. By utilizing MCDM methods, businesses can weigh these criteria effectively, making informed supplier choices that align with the demands and opportunities of Industry 4.0, ultimately fostering resilience, innovation, and enhanced performance in the rapidly evolving industrial landscape.

Supplier selection criteria have joined forces with traditional research criteria in the age of Industry 4.0. Table 1 highlights a few industry 4.0-related requirements.

Table 1
Description of the parameters utilized in Industry 4.0

Sl. no.	Criteria	Description	References
1	Cybersecurity	Supplier's measures for data and network security	[9]
2	Digital collaboration	Ability to collaborate digitally and share data effectively	[10]
3	Robotics	Integration of robotics and automation in production	[11]
4	Smart logistics	Implementation of smart supply chain systems	[12]
5	Cost	Total cost of provided products or services	[13-15,17,20,23]
6	IoT	Utilization of IoT devices and data in their processes.	[16]
7	Quality	Service quality, including standards and defects	[13,18,20,23,24]
8	Lead time	Supplier's delivery time and reliability	[17,19]
9	Flexibility	Ability to adapt to changing demand and requirements	[15,17,18,20,23]
10	Responsiveness	How quickly the supplier responds to requests and issues	[19]
11	Sustainability	Environmental and ethical considerations	[20]
12	Innovation	Commitment to innovation and technology adoption	[15,21,22]
13	Capacity	Supplier's production capacity and scalability	[17,23-25]
14	Location	Proximity to the buyer's facilities and transportation costs	[17,26-28]
15	Risk management	Strategies for mitigating risks and disruptions	[17,25]
16	Reputation	Supplier's market reputation and past performance	[29, 32]
17	Compliance	Adherence to regulatory and compliance requirements	[23,30]
18	Product variety	Range of products or services offered by the supplier	[30,32]
19	Payment terms	Negotiated terms and financial stability of the supplier	[23, 36]

Numerous research employing MCDM methods for supplier selection in traditional and digital SCM have been carried out. The previous investigations in traditional and digital supply chains are displayed in Tables 2 and 3, with a focus on their objectives and the selection of criteria.

Table 2
Previous investigations on traditional supplier selection

Sl. no.	Year	Objective	MCDM method	List of criteria	References
1	2020	Improve supplier risk mitigation	AHP, DEMATEL	Cost, strategic impact, safety, dependence, occurrence, detection	[35]
2	2020	Enhance supplier selection for healthcare	ANN, fuzzy-VIKOR	Price, quality, timely delivery, payment terms, the supplier's background, packaging, transporting quality	[36]
3	2023	Optimize supplier network in Industry 4.0	IVIF TOPSIS	Equipment depreciation, cutting risk, chemical radiation, noise hazard, radiation hazard	[34]
4	2023	Enhance supplier selection efficiency	SWARA, WASPAS	Logistics, service, environmental, finance	[33]
5	2023	Optimize supplier selection for companies	Pythagorean fuzzy AHP, COPRAS	Cost, quality, lead time, technology, service, flexibility, distance, variety, technical capability, economic, social	[37]
6	2023	Enhance supplier collaboration in Industry 4.0	Fuzzy EDAS	Digital collaboration, innovation, cost, quality, lead time, responsiveness, compliance, risk management, capacity, location	[38]

When taking into account the requirements and prospects of Industry 4.0, these studies offer insightful information on supplier selection within digital SCM.

Table 3
Previous investigations on digital supplier selection

Sl. no.	Year	Objective	MCDM method	List of criteria	References
1	2015	Developing a green supplier selection	DANP, VIKOR	Environmental management systems, quality, price/cost, service, technology, green design, green image, environmental performance, environmental competencies, green collaboration with suppliers	[47]
2	2019	Sustainable supplier selection in a construction company	FUCUM, COPRAS	Economic, social, environmental	[43]
3	2019	Solving the supplier selection problem	Fuzzy-TOPSIS, fuzzy-WASPAS, fuzzy-ARAS	Product price, transportation cost, delivery time, company rating, established cooperation	[45]
4	2020	Digital supplier selection for a garment business	Interval type-2 fuzzy TOPSIS	Digital production systems, information and communication technologies, intelligent logistics and inventory, maintenance and repair, management	[41]
5	2020	Sustainable supplier selection in healthcare industries	MARCOS	Economic, social, environmental	[46]
6	2021	Supplier selection in digital supply chains	MULTIMOORA, COPRAS	Real-time visibility, advanced analytics, technical capability, continuous collaboration, alignment, as well as lack of tools and technologies, planning, information sharing, knowledge, digital collaboration, and technology integration	[42]

Table 3 (*continued*)

Sl. no.	Year	Objective	MCDM method	List of criteria	References
7	2022	Enhancing supplier selection in the circular economy and Industry 4.0	SWARA and COPRAS	Economic, environmental, social	[39]
8	2022	Applicability of Industry 4.0 technologies in reverse logistics	BWM and COBRA	Technological, socio-political, economic-operational	[40]
9	2022	Automotive supplier industry	AHP-QFD	Benefits, tools, challenges	[44]

These investigations provide information on the crucial supplier selection elements of Industry 4.0-related digital SCM.

2.2 Novelty

This review paper introduces several novel dimensions to the field of SCM and supplier selection. Notably, it places a central emphasis on the integration of Industry 4.0 technologies, such as the IoT, AI, and big data analytics, into the supplier selection process. A distinctive feature of this paper is its specific focus on MCDM methodologies within the supplier selection context. While supplier selection has been a subject of research, this paper uniquely underscores the critical role that MCDM techniques play in addressing the complex, multi-dimensional criteria involved in supplier selection in the Industry 4.0 era. This provides a fresh perspective on the suitability and effectiveness of MCDM methodologies in the rapidly evolving digital supply chain landscape.

Additionally, the paper explores the emerging realm of digital criteria in supplier selection. In the age of Industry 4.0, digital criteria like cybersecurity, digital collaboration, and IoT integration have gained paramount importance. The paper reviews and accentuates these digital criteria, underlining their significance in ensuring the reliability and adaptability of suppliers in the digital age.

2.3 Research Gap

Despite the growing body of literature on supplier selection and Industry 4.0, there is a noticeable research gap in comprehensive reviews that holistically consolidate the multifaceted dimensions of this intricate topic. This research paper aims to bridge this gap by offering a holistic review of MCDM applications and trends in supplier selection within the context of Industry 4.0, thereby providing a more interconnected understanding of this complex field.

Another research gap pertains to the evolving role of digital criteria in supplier selection. While their significance is increasingly recognized, the literature lacks in-depth examinations of criteria such as cybersecurity, digital collaboration, and IoT integration in the supplier selection process within the context of Industry 4.0. This paper aims to address this gap by providing a comprehensive review of these digital criteria and their implications for effective supplier selection.

Moreover, while many research papers in this domain often focus on theoretical aspects, there is a discernible need for practical insights into how Industry 4.0 and MCDM methodologies are being applied in real-world supplier selection scenarios. This paper endeavors to fill this void by incorporating practical case studies and examples, thereby offering valuable lessons for practitioners and decision-makers.

3. Techniques for Choosing Suppliers in the Era of Industry 4.0

The success of enterprises in the era of Industry 4.0 depends on choosing the appropriate suppliers. To enable more intelligent data-driven supplier selection processes, traditional approaches are changing to embrace cutting-edge technology like data analytics, AI, and blockchain [48].

3.1 Using Multi-Agent Theory for Intelligent Supplier Selection

The ideas of Industry 4.0 are supported by the creative and sophisticated method of choosing intelligent suppliers utilizing multi-agent theory. In this method, each potential supplier is conceptualized as an autonomous agent within a multi-agent system. These agents are endowed with the capacity to autonomously gather, process, and exchange information, creating a collaborative environment for supplier selection. The crux of this approach lies in its ability to harness the power of intelligent agents that work collectively to assess and evaluate supplier attributes based on predetermined criteria [49].

The ability of multi-agent theory to gather and share information is one of its main advantages in supplier selection. These agents can gather a wide range of pertinent information, such as specifics regarding price, quality, lead time, digital readiness, and other factors. Additionally, they can speak with one another and exchange this knowledge, enabling a more thorough and educated decision-making process. The collaborative nature of multi-agent systems is instrumental in this context [50]. The agents work in concert to appraise each supplier's attributes, leveraging sophisticated decision-making algorithms, often including MCDM techniques. They meticulously evaluate the suppliers, weighing their strengths and weaknesses, to determine the most suitable and intelligent choices.

Multi-agent systems also shine in their adaptability and resilience. In the dynamic landscape of Industry 4.0, where changes in the supplier landscape or criteria are common, these systems can adjust seamlessly. They continually update their assessments and rankings, ensuring that the supplier selection process remains relevant and aligned with the latest data and requirements. Additionally, multi-agent systems are equipped to handle conflicts or discrepancies that may arise during the supplier evaluation process. They have built-in mechanisms for conflict resolution, ensuring that consensus is reached and disputes are addressed effectively.

The result of employing multi-agent theory in supplier selection is a well-informed ranking of suppliers. This ranking showcases the most intelligent and suitable suppliers based on the predefined criteria, empowering organizations to make sound decisions that align with the demands and opportunities of Industry 4.0. This approach thrives in its adaptability, collaboration, and efficiency in processing vast volumes of data, which are pivotal elements in modern SCM.

3.2 Choice of Suppliers using Adaptive Neuro-Fuzzy Methods

Fuzzy logic and neural networks work together to create adaptive neuro-fuzzy approaches, which are a cutting-edge methodology for choosing suppliers. This strategy is especially suitable for the dynamic and data-rich environment of Industry 4.0. Neural networks, which are capable of learning and adapting from data, are paired with fuzzy logic, a mathematical foundation for coping with uncertainty and imprecision, to develop a reliable system for supplier selection. In this approach, each supplier's attributes and criteria are expressed as linguistic variables within the framework of fuzzy logic. This enables the system to handle the inherent ambiguity in supplier evaluation, especially when dealing with criteria that are not easily quantified.

The procedure gains an adaptable and learning character thanks to the neural network component. To find patterns and trends, it can examine enormous volumes of historical and real-time data while taking supplier performance from the past into account. This capacity allows the system to continuously improve its supplier selection decisions as it accumulates more data. Furthermore, the adaptive fuzzy-Neuro approach is particularly well-suited for handling non-linear and complex relationships between supplier attributes [51]. In Industry 4.0, where digital transformation and technological advancements have introduced a multitude of factors to consider, this method excels in providing a holistic and adaptable framework for supplier selection.

A highly intelligent and adaptable system that can make supplier selection judgments in line with the dynamic needs of contemporary SCM is the result of this methodology. It helps organizations maintain their competitiveness in the rapidly changing environment of Industry 4.0 by reducing their reliance on manual and static decision-making processes. In conclusion, the adaptive neuro-fuzzy approach provides a strong remedy for supplier selection by combining the advantages of fuzzy logic and neural networks to handle the difficulties and complexities of the digital age.

3.3 Choosing Suppliers Using Mixed MCDM Strategies

Hybrid MCDM approaches to supplier selection offer a sophisticated and thorough methodology to handle the complex problems of supplier selection in Industry 4.0. They integrate various MCDM techniques, combining their strengths to arrive at a more well-rounded and accurate decision-making process.

A multitude of criteria are taken into account, including cost, quality, responsiveness, digital readiness, sustainability, and more, making it highly adaptable to the complex demands of modern SCM. What sets the hybrid MCDM approach apart is its ability to consider and weigh these criteria effectively, often leveraging various decision-making algorithms such as AHP, TOPSIS, and others. By using a combination of these methods, organizations can minimize the limitations of any single approach and arrive at more robust and reliable supplier selection decisions. Furthermore, the hybrid MCDM approach embraces the data-rich environment of Industry 4.0. It can process and analyze vast volumes of data, incorporating both historical and real-time information to make informed choices about suppliers [52]. Integrating multiple decision-making methods and embracing the digital transformation of Industry 4.0 helps ensure that supplier selection aligns with the demands of a dynamic and technology-driven supply chain landscape. This approach, driven by both quantitative and qualitative data, enhances an organization's ability to make strategic supplier decisions in a rapidly evolving business environment.

3.4. Utilising Hybrid Fuzzy MCDM Techniques for Supplier Selection

In order to meet the complicated requirements of supplier selection in the context of Industry 4.0, a sophisticated and adaptable system was developed for supplier selection using a hybrid fuzzy MCDM methodology. This method offers a more thorough and complex decision-making process by fusing the flexibility of fuzzy logic with the resilience of MCDM procedures. In this method, a wide array of criteria is taken into account, reflecting the diverse factors involved in supplier selection, such as cost, quality, responsiveness, digital readiness, sustainability, and more. What distinguishes the hybrid fuzzy MCDM approach is its ability to manage the inherent uncertainty and vagueness often associated with these criteria. Fuzzy logic allows for the representation of imprecise or ambiguous information, which is quite common in the real-world supplier selection process.

The hybrid nature of this approach often involves the integration of various MCDM methods, such as AHP, TOPSIS, and others. This amalgamation of methods aims to overcome the limitations of any single technique and provide a more well-rounded assessment of suppliers. Moreover, the hybrid fuzzy MCDM approach is well-suited to leverage the abundance of data available in the Industry 4.0 era. It can process and analyze large datasets, incorporating historical and real-time information to make informed decisions about suppliers. This data-driven aspect ensures that supplier selection remains adaptable and responsive to changes in supplier performance and evolving market dynamics. Combining the strengths of MCDM methods and fuzzy logic allows organizations to make well-informed choices about suppliers that align with the complexities of a rapidly evolving, technology-driven supply chain environment. This method, enriched by its ability to handle imprecise and uncertain information, enhances an organization's capacity to make strategic supplier decisions with a more comprehensive understanding of supplier attributes.

3.5 Hybrid Fuzzy Multi-Criteria Decision-Making Techniques for Choosing a Green Supplier

A hybrid fuzzy MCDM approach to green supplier selection strives to find and work with suppliers who are not only effective and efficient from a cost and efficiency standpoint, but also environmentally conscientious. Sustainability and environmental concerns have grown in importance in SCM in the age of Industry 4.0, making the hybrid fuzzy MCDM approach particularly pertinent. This approach encompasses a multifaceted evaluation of potential suppliers. Criteria related to environmental sustainability, such as carbon footprint, waste reduction, eco-friendly practices, and adherence to environmental regulations, are integrated alongside traditional criteria like cost, quality, and responsiveness. What distinguishes the hybrid fuzzy MCDM approach is its ability to handle the imprecise and uncertain nature of green criteria. Fuzzy logic allows for the representation of vague or uncertain information, which is often encountered in sustainability assessments. Moreover, this approach takes full advantage of the data-rich environment of Industry 4.0. It can process and analyze extensive data, including information about suppliers' environmental performance and practices. This data-driven aspect ensures that the supplier selection process remains adaptable and responsive to changes in environmental regulations, supplier sustainability initiatives, and evolving market dynamics.

4. Leveraging Internet of Things, Big Data, Artificial Intelligence, and Advance Manufacturing in Supplier Selection

Due to the incorporation of cutting-edge technology like the IoT, big data analytics, AI, and new manufacturing techniques, effective supplier selection has experienced a radical metamorphosis. These technologies have altered the SCM environment in the age of Industry 4.0, improving decision-making procedures. By supplying real-time data and connection across the supply chain, IoT has played a crucial role. IoT-enabled sensors and devices capture data on supplier performance, product quality, and logistics, creating a continuous stream of information for evaluation. This data allows for more accurate and timely assessments of suppliers, reducing the reliance on historical data alone.

Big data analytics complements IoT by processing and extracting insights from the vast volumes of data generated. It enables organizations to identify patterns, trends, and anomalies that might be missed by traditional analysis. Supplier selection benefits from data-driven decision-making, which results in more informed and strategic choices. Artificial intelligence, particularly machine learning, further refines the supplier selection process. AI algorithms can assess and predict supplier performance based on historical data, current conditions, and future projections. Machine learning

models adapt and self-improve over time, increasing the accuracy of supplier evaluations and recommendations.

Advanced manufacturing techniques, including automation, robotics, and 3D printing, have also influenced supplier selection. Suppliers that embrace these technologies can offer benefits such as reduced lead times, improved quality, and cost efficiency. Organizations look to align with suppliers that are technologically advanced and can enhance their competitiveness.

In conclusion, the integration of IoT, big data analytics, AI, and advanced manufacturing techniques has ushered in a new era of supplier selection in Industry 4.0. These technologies empower organizations to make more informed, data-driven, and strategic choices when evaluating and partnering with suppliers, ensuring a more efficient and effective supply chain.

5. Conclusion

A thorough overview of supplier selection in the era of Industry 4.0 is provided by the study presented in this paper, with an emphasis on the use of MCDM techniques and new trends. The classic supplier selection process has experienced a significant development in this dynamic age of digital transformation, prompting a re-evaluation of methodology and approaches. Adopting MCDM approaches has been extremely helpful in tackling the variety of issues brought on by Industry 4.0. These techniques provide a planned and methodical examination of potential suppliers taking into account a wide range of traditional and digital factors. MCDM applications have been adapted to incorporate criteria such as digital readiness, cybersecurity, sustainability, and innovation, reflecting the demands of the modern industrial landscape.

The research also emphasized the growing significance of using cutting-edge technologies, such as IoT, big data analytics, artificial intelligence, and innovative manufacturing techniques, in the supplier selection process. By giving businesses real-time data, predictive insights, and enhanced automation, these developments have revolutionized data-driven decision-making. The new trends highlight how flexible supplier selection is in Industry 4.0. Fuzzy logic and neural network integration, green supplier selection, and sustainability concerns have all gained popularity, highlighting the importance of comprehensive and flexible decision-making processes.

5.1 Managerial Implication

The results of this study on SCM in the era of Industry 4.0 have several significant managerial ramifications for businesses looking to boost the effectiveness and competitiveness of their supply chains. The usage of MCDM methodologies in supplier selection processes must be embraced by managers in the first place. These methods enable a thorough assessment that takes into account both conventional criteria and digital features. To properly use MCDM and realize the full potential of these approaches, managers should invest in training and knowledge.

Additionally, there is a management necessity to integrate cutting-edge technology like the IoT, big data analytics, and artificial intelligence. The monitoring of supplier performance and data-driven decision-making can both be considerably enhanced by these tools. Managers should consider investing in these technologies and fostering a culture of digital readiness within their organizations. In addition, recognizing the growing emphasis on sustainability and green supplier selection is crucial. Managers should actively seek suppliers that align with sustainability goals and environmental regulations, promoting corporate social responsibility. Lastly, staying abreast of emerging trends like the integration of fuzzy logic and neural networks is essential. Managers should explore these innovative approaches to enhance the adaptability and accuracy of supplier selection. Incorporating

these implications into managerial decision-making can result in more strategic, effective, and long-lasting supplier selections, thereby boosting an organization's ability to compete and adapt in the ever-changing world of Industry 4.0.

5.2 Practical Limitation

The focus of this study is on how difficult and resource-intensive it is to integrate cutting-edge technological advancements like AI and IoT into the supplier selection process. These technologies may be difficult for small and medium-sized businesses to embrace due to their limited infrastructure and financial resources. Additionally, not all providers may be equally ready or motivated to embrace the digital transformation, leading to differences in the availability and quality of data. A major investment in data management infrastructure may also be necessary to handle and secure the massive volume of created data. This limitation emphasizes the necessity for a balanced strategy that takes both consumers' and suppliers' capabilities and constraints into account while using Industry 4.0 technologies.

5.3 Future Scope

Future research in this field should examine the creation of useful frameworks and tools that span the gap between theoretical understanding and Industry 4.0-driven supplier selection implementation in the real world. This includes creating decision support systems that are customizable and available to companies of all sizes by integrating MCDM approaches and cutting-edge technologies. In the framework of Industry 4.0, additional research can also focus on the creation of sector-specific best practices for sustainable and green supplier selection. A fascinating area for future research is examining how Blockchain technology and smart contracts might improve the openness and reliability of supplier relationships.

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Conflict of Interest

The authors declare no conflicts of interest related to the research, ensuring objectivity and transparency in reporting findings.

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