Economic Sciences
https://economic-sciences.com
ES (2026) 22(1), 82-104 | ISSN:1505-4683

Prioritizing Barriers to Industry 4.0 Adoption in Manufacturing MSMEs of Uttarakhand: A Fuzzy AHP and Sensitivity Analysis Approach

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Abstract

Industry 4.0 technologies offer significant opportunities for improving the competitiveness of manufacturing MSMEs, yet their adoption remains limited due to several persistent challenges. This study identifies and prioritizes the key barriers to Industry 4.0 adoption in manufacturing MSMEs using a fuzzy Analytic Hierarchy Process (Fuzzy AHP) approach. Drawing on an extensive literature review, four main barriers and sixteen sub-barriers were identified and evaluated through expert judgments. Fuzzy AHP was applied to rank these barriers under conditions of uncertainty, and sensitivity analysis was conducted to test the stability of the ranking results. The findings show that a small number of critical barriers play a dominant role in hindering adoption, and their rankings remain largely stable across different scenarios. The study provides practical insights for MSME managers and policymakers by highlighting priority areas for intervention and supports the use of fuzzy AHP as a reliable decision-making tool for analysing complex adoption challenges.

***Keywords**: Industry 4.0, adoption, Manufacturing, MSMEs, Fuzzy AHP,*

1. Introduction

In the modern industrial landscape, Industry 4.0 represents the fourth stage of the Industrial Revolution, characterized by the integration of digital technologies into core industrial operations. This paradigm shift leverages innovations such as cyber-physical systems, the Internet of Things (IoT), artificial intelligence, and big data to enhance operational efficiencies, productivity, and sustainability (Mehra, 2023). The global Industry 4.0 market has seen exponential growth, valued at USD 114.55 billion in 2021 and projected to reach USD 377.30 billion by 2029, with a compound annual growth rate of 16.3% (Mehra, 2023). Moreover, the United Nations forecasts a staggering market value of $9.5 trillion by 2030, reflecting the immense economic potential of these transformative technologies (United Nations, 2023).

Industry 4.0 technologies have already demonstrated remarkable benefits across various sectors. For instance, a leading multinational in the plastics sector utilized energy sensors to reduce power expenses by approximately 40%, achieving annual savings of over $200,000 (World Economic Forum, 2022). Similarly, in the aerospace sector, advanced manufacturing techniques have enabled the production of lighter aircraft parts, significantly lowering fuel consumption. However, while countries like the United States and China dominate the knowledge landscape of Industry 4.0, accounting for 30% of global publications and nearly 70% of patents, the adoption of these technologies remains limited in many developing economies, including India (United Nations, 2023).

1.1 Industry 4.0 in India

India's manufacturing sector stands at a critical juncture, with Industry 4.0 offering opportunities for unprecedented growth and competitiveness. The sector, which contributes 16-17% to India's GDP, is gradually transitioning towards automation and digital transformation, supported by government initiatives such as the National Manufacturing Policy and the Production Linked Incentive (PLI) scheme (IBEF, 2023). These policies aim to increase the manufacturing share in GDP to 25% by 2025, fostering India's emergence as a global manufacturing hub.

The adoption of Industry 4.0 technologies in India has already yielded significant successes. A Mumbai-based switchgear manufacturer, for example, employed Digital Twin IoT systems and video analytics to increase its product variants from 77 to over 200 within 18 months, reducing production cycle time by over 50% (Deloitte, 2023). Further, widespread adoption of these technologies could potentially boost India's GDP by $957 billion by 2035 (B. J. Singh & Sodhi, 2023).

Despite these promising developments, the adoption rate among Indian manufacturing firms remains low. According to the World Economic Forum, only 17% of Indian businesses have undertaken significant digital transformations (Pune International Center, 2022). Challenges such as financial constraints, limited technical expertise, and inadequate infrastructure hinder the integration of Industry 4.0 technologies. Moreover, smaller firms, particularly Micro, Small, and Medium Enterprises (MSMEs), face unique barriers, including resource limitations and a lack of digital literacy.

1.2 The Role of MSMEs in India

MSMEs are the backbone of the Indian economy, accounting for 30% of the national GDP and nearly 36% of manufacturing Gross Value Added (Press Information Bureau, 2024). Employing over 110 million people across 63 million enterprises, this sector plays a vital role in driving economic growth, fostering innovation, and ensuring equitable regional development (IBEF, 2024). However, the potential of MSMEs remains underutilized due to their slow adoption of Industry 4.0 technologies. Financial constraints, limited access to technology, and a lack of skilled workforce are among the primary barriers hindering digital transformation (B. Kumar & Gajakosh, 2021).

1.3 The Context of Uttarakhand's Manufacturing Sector

In Uttarakhand, the manufacturing sector is a cornerstone of the state's economy, contributing 46.21% to the state's GDP (Uttarakhand Survey Report). Within this sector, MSMEs play a pivotal role, with over 58,000 registered units providing employment to approximately 4 lakh workers as of 2021 (B. Kumar & Gajakosh, 2021). Haridwar, Dehradun, and Udham Singh Nagar are among the districts with the highest concentration of MSMEs, highlighting their significance in regional economic development.

However, MSMEs in Uttarakhand face distinct challenges in adopting Industry 4.0. These include inadequate technical skills, limited access to modern technologies, and a lack of awareness about the benefits of digital transformation (Panwar et al., 2024). Additionally, infrastructural deficiencies and a lack of supportive ecosystems exacerbate these challenges, impeding the sector's ability to compete in the global market (Rawat & Karmakar, 2021).

1.4 Research Significance

The slow pace of Industry 4.0 adoption among Uttarakhand's MSMEs represents not only a missed opportunity for economic growth but also a risk of marginalization in the rapidly evolving global industrial landscape. As the United Nations has noted, the gap between developed and developing nations in technological adoption is widening, with serious implications for industrial competitiveness and sustainability (United Nations, 2023). Addressing these barriers is crucial for harnessing the full potential of Industry 4.0 and ensuring the long-term viability of MSMEs in Uttarakhand.

This study aims to identify the barriers to Industry 4.0 adoption in Uttarakhand's manufacturing MSMEs and propose actionable strategies to overcome them. By addressing these challenges, the research seeks to contribute to a sustainable roadmap for digital transformation, fostering competitiveness, resilience, and sustainable growth within the region.

2. Literature review

The scope, magnitude, and complexity of Industry 4.0 differ significantly from those of the previous three industrial revolutions. Industry 4.0 evolved to execute cognitive activities as well, whereas the previous three industrial revolutions arose to perform muscular work for humanity (Sayem et al., 2022).With the potential to produce unimaginable increases in productivity and security, I4.0 and related technologies have fundamentally altered how businesses operate by increasing connectivity between their partners and staff (Rossini et al., 2019; Vijayakumar & Chandrasekar, 2019). Keeping an eye on this new revolution has grown more difficult due to the numerous changes. The industrial scenario's rapid transitions ultimately hampered the change management process, necessitating a more dynamic posture of the company's leaders and culture(J. Lee et al., 2014) Most experts concur that more research is necessary to fully examine the obstacles associated with Industry 4.0

implementation, as they are mainly unexplored in the current body of literature(Horváth & Szabó, 2019a; S. Kamble et al., 2018; Oesterreich & Teuteberg, 2016). Some disjointed examination of these barriers has been done(Horváth & Szabó, 2019a). For example, some authors contend that a shortage of skilled labor and disputes among employees as a result of shifting work conditions (Kiel, Arnold, et al., 2017a). lack of financial resources(Kiel et al., 2017).data security (Cugno et al., 2021a; Horváth & Szabó, 2019b; Matt et al., 2020; Raj et al., 2020a). low levels of standardization, inadequate comprehension of systems architecture and integration(V. Kumar et al., 2021). are the main challenges facing Industry 4.0's adoption. But up until now, each of these obstacles has only been examined separately, usually from a technological standpoint. The process of implementing Industry 4.0 is intricate, with multiple factors influencing one another.(Horváth & Szabó, 2019c). consequently, a thorough investigation of all these aspects is required. Based on the literature review four categories of barriers are identified. These are organisational barrier, financial and economic barrier, technological barrier and Legal and regulatory barrier

2.1 Organizational Barrier

These Barriers associated with the problem of Resistance to change, lack of Knowledge about the industry 4.0 concept, lack of management commitment, lack of digital skills, inadequate organizational strategies and lack of Training(Dixit & Kumar, 2024a; Hossain et al., 2023a; Muller et al., 2024a; Nimawat & Gidwani, 2021; Zulfiqar et al., 2023a). Manufacturing MSMEs stand to gain a great deal from Industry 4.0, which is defined by the combination of cyber-physical systems, IoT, big data, and AI. However these barriers hinder its adoption. The social climate within the organization may be disrupted by middle managers whose roles shift from managing people to performing expert work requiring higher qualifications, as well as by employees who fear losing their jobs or who lack the skills needed for new technologies(Horváth & Szabó, 2019a).

Human resources' cultural and technical acceptance is still a major barrier because many workers are afraid of being watched more closely and having their workflows altered(Birkel et al., 2019; Haddud et al., 2017; Horváth & Szabó, 2019c; Moeuf et al., 2019; Raj et al., 2019a; Theorin et al., 2016). Experts and scholars alike have a remarkably poor grasp of the implications of Industry 4.0. It is obvious that writing needs to be thoroughly organized, and the main work has particular Industry 4.0 relevance. Supervisors of industry and research undoubtedly understand how critical it is to integrate Industry 4.0 in production. However, they are still unclear on their exact configurability goals and outcomes(Almada-Lobo, 2016; Hofmann & Rüsch, 2017).

The application of technologies like AI, CPS, big data analytics, IoT, cloud computing, AR, and VR in a business is still not well understood(Dixit & Kumar, 2024a; S. S. Kamble et al., 2018; Nimawat & Gidwani, 2021).Furthermore, research shows that organizational policy and accepted behaviors originate at the highest levels, making top management's lack of support a major obstacle(Hossain et al., 2023b; Nimawat & Gidwani, 2021; Zulfiqar et al., 2023b). In addition to making decisions, top management is essential in showing dedication, which inspires staff to support Industry 4.0 initiatives(S. Kumar et al., 2016). The problem is made worse by the workforce's lack of digital skills, which keeps businesses from employing Industry 4.0 solutions to their full potential(Cugno et al., 2021b; Dixit & Kumar, 2024a; Erol et al., 2016a; Horváth & Szabó, 2019c; Hossain et al., 2023b; Nimawat & Gidwani, 2021; Shamim et al., 2016).

Since user interaction with machines is essential to the successful deployment of Industry 4.0, proper training is essential. Inadequate training prevents organizations from achieving their goals and results in needless costs(Nimawat & Gidwani, 2021). A workforce with the necessary skills, including communication, information and data literacy, digital content creation, safety, security, and problem-solving, is essential(Flores et al., 2020). The adoption of innovative technology practices is encouraged by the cheaper cost of hiring trained and skilled labor(S. Kumar et al., 2020a; S. Singh et al., 2019). However, SMEs struggle to adapt and successfully implement Industry 4.0 due to a lack of skilled personnel, a problem that has been noted in multiple studies(Rauch et al., 2019a).

2.2 Technological Barrier

Technological barriers are those that restrict access to relevant and helpful hardware with the right software, especially when physical labor is insufficient to finish a task(A. Kumar & Krishna, 2025). Technological Barrier includes technology compatability, technology maturity, data security concern and Lack of infrastructure(Cugno et al., 2021b; Horváth & Szabó, 2019c; Hossain et al., 2023b; I. Lee & Lee, 2015; Nimawat & Gidwani, 2021). The compatibility of new digital innovations with old technologies has a major impact on the adoption of Industry 4.0. Economic issues are an important consideration because the change necessitates a significant expenditure in altering machinery, equipment, and artifacts. Investors, managers, and business owners are frequently hesitant to replace all of the current equipment without first performing a comprehensive cost-benefit analysis(Nimawat & Gidwani, 2021).

However, the switch to Industry 4.0 becomes more alluring if existing equipment can be upgraded or retrofitted with affordable add-ons(I. Lee & Lee, 2015). In order to create such low-cost modification techniques that can promote a more seamless transformation process, engineers and technocrats are essential. Another major barrier is the low maturity of Industry 4.0 technologies.(Cugno et al., 2021b; S. Kumar et al., 2020a; I. Lee & Lee, 2015; Raj et al., 2020b)draw attention to the dangers of implementing unproven, early-stage technology that might not be stable in terms of data security, privacy, and standards. Operational problems may result from the growing number of partially tested gadgets in a networked technology ecosystem. Such unpredictability could provide serious dangers for businesses using Industry 4.0 solutions in a linked world. Concerns about data security further impede adoption of Industry 4.0.

Numerous studies highlight data ownership concerns, cybersecurity threats, and businesses' anxieties about losing sensitive information to outside service providers(Cimini et al., 2017a; Hossain et al., 2023b; Kiel, Arnold, et al., 2017a, 2017b). Concerns over data security are heightened by value chain partners' increased connectedness, as businesses are wary of the dangers of exchanging information across digital networks (Gadekar et al., 2022; Muller et al., 2024b; Rauch et al., 2019b).Breunig et al. (2016) stress that in Industry 4.0 settings, companies are worried about data leaks to outside service providers in addition to cyberthreats.I. Lee & Lee (2015) further stress that IoT implementation exposes firms to cyberattacks, making data security a critical challenge. Advanced cybersecurity measures are required to safeguard the massive volumes of real-time data created by Industry 4.0 against cyber threats(Park & Huh, 2018).S. S. Kamble et al. (2018) also draw attention to security issues as a crucial component in implementing Industry 4.0 sustainably, emphasizing that businesses need dependable and secure servers for adoption to be successful. Important issues like data integrity, system usability, and illegal access must be addressed by security measures (Kagermann, 2013). In this regard, maintaining cybersecurity is still essential as neglecting to do so drastically lowers top management's readiness to embrace Industry 4.0(S. S. Kamble et al., 2018; Rauch et al., 2019b).

Adoption of Industry 4.0 is made more difficult by the absence of technological infrastructure(Dixit & Kumar, 2024b; Goel et al., 2022; Zulfiqar et al., 2023a). Birkel et al. (2019) contend that businesses' competitiveness is lowered by insufficient economic infrastructure. Industry 4.0 requires dependable broadband infrastructure, yet even industrialized nations like Germany have trouble giving SMEs access to high-speed internet(Schröder, 2016) lack of technichal infrastructure is particularly obvious in developing nations such as india, where IT infrastructure differs greatly between urban and rural areas, preventing the general adoption of industry 4.0 technologies(Leitão et al., 2016; Pfohl et al., 2017; Yadav et al., 2018).

S. Kamble et al. (2019) further stress that a significant barrier to the adoption of IoT in the retail supply chain—a crucial element of Industry 4.0—is the absence of internet connectivity Additionally Müller, Kiel, et al. (2018) contend that the costs of IT infrastructure, such as those associated with hiring IT staff and purchasing cutting-edge networking equipment, put businesses in a difficult financial position. Lack of high-speed internet access hinders IoT operations and data analytics, two essential steps in the digital transformation process(Dixit & Kumar, 2024b). Erol et al. (2016b) Keep in mind that since Industry 4.0 demands smooth connectivity between suppliers, customers, and manufacturing facilities, IT infrastructure is a requirement for real-time data transfer and system integration. Businesses find it difficult to connect cutting-edge technologies like fog/edge computing, which are crucial for the digitalization process, with traditional industrial processes in the absence of a strong infrastructure(Dixit & Kumar, 2024b). IT components like networks, security, storage, servers, business apps, operating systems, and databases are all included in Industry 4.0. It serves as a link between IT software programs and manufacturing equipment via cyber-physical systems (CPS). Therefore, the successful implementation of Industry 4.0 depends on dependable and effective IT infrastructure management(Kiraz et al., 2020; Kusiak, 2018).

The ongoing difficulties brought on by insufficient infrastructure emphasize the necessity for businesses to have strong IT frameworks. Additionally(S. S. Kamble et al., 2018). emphasize that a global strategy is needed to achieve cybersecurity in Industry 4.0, guaranteeing data protection against alteration, deletion, and illegal access. The main goals of cybersecurity initiatives should be usability (assessing system performance within predetermined time restrictions), integrity (ensuring data accuracy and proper system functioning), and confidentiality (limiting access to data and operations to authorized individuals)('Kagermann, 2013). Because of the ongoing security issues that organizations confront with regard to permission, privacy, authentication, and system access, cybersecurity is a crucial factor in determining the adoption of Industry 4.0(Dixit & Kumar, 2024b). Businesses will be more inclined to adopt Industry 4.0 techniques if there is affordable, compatible, and safe technology infrastructure available(S. Kumar et al., 2020b).

2.3 Financial Barrier

Although the shift to Industry 4.0 signifies a "Manufacturing Renaissance" driven by technology, the financial burden is still a significant obstacle, especially for businesses in developing nations. One of the main deterrents to implementing Industry 4.0 technologies, such as automation, digitalization, and cyber-physical systems (CPS), is frequently the high initial investment needed. This is particularly true for small and medium-sized businesses (SMEs), which face challenges like unclear return on investment and scarce financial resources(Enyoghasi & Badurdeen, 2021; Hossain et al., 2023a). Customers' pressure to provide highly tailored products at reduced prices adds to the financial strain and makes it much harder for businesses to defend the large upfront expenditures required for digital transformation(Dermott et al., 2021).

Financial limitations are a significant obstacle to Industry 4.0 adoption, according to numerous research. Businesses are frequently unable to allocate enough finances for infrastructure modernization and sustainable process innovations due to the requirement for large capital expenditure at the early stages of implementation(Erol et al., 2016a; Kiel, Arnold, et al., 2017a; Kiel, Müller, et al., 2017). In addition to internal financial constraints, businesses usually have trouble obtaining outside funding since banks and private investors are hesitant to support unconventional, high-risk projects like Industry 4.0(Birkel et al., 2019; Cugno et al., 2021b; 'Kagermann, 2013; Müller et al., 2018). Because of this, companies are still reluctant to undertake extensive digital transformation projects out of concern for protracted and unpredictable payback periods(Birkel et al., 2019; Cugno et al., 2021b).

Another significant obstacle is the large investment requirement. Businesses must spend a lot of money on IT infrastructure, data storage facilities, and employee training in addition to investing in cutting-edge technologies(Goel et al., 2022b; Hossain et al., 2023b; Müller, Kiel, et al., 2018; Raj et al., 2020b; Zulfiqar et al., 2023b). For SMEs, whose managers frequently choose more conventional, low-risk investments over high-tech transformation initiatives, this cycle of continuous investment is especially troubling(Calabrese et al., 2020; Cugno et al., 2021b; Sayem et al., 2022). Furthermore, studies on Brazilian enterprises. Dalenogare et al. (2018). show that when investing in digitalization, businesses in emerging markets expect even more financial hurdles. Beyond the company level, supply chain management and research and development (R&D) are further complicated by financial constraints. Because of the high expenses of acquiring and integrating new technologies, many businesses are still hesitant to invest in R&D related to Industry 4.0.(Breunig et al., 2016; Dalenogare et al., 2018). According to research, most businesses do not set aside specific funds for technological advancements, which makes it challenging to build the skills required for digital transformation(Theorin et al., 2017).

Businesses' capacity to fully adopt Industry 4.0 is ultimately constrained by their inability to upgrade production facilities, construct the required infrastructure, and upskill their personnel without consistent financial assistance(Dixit & Kumar, 2024b; Raj et al., 2020a). Research has also indicated that industry-academia cooperation can lower the total cost of digital investments, albeit these kinds of alliances are still difficult to form(Dixit & Kumar, 2024a; Preuveneers & Ilie-Zudor, 2017).

In the end, one of the biggest obstacles keeping companies from implementing Industry 4.0 is a lack of funding. Building the required digital infrastructure is tough since businesses are still having trouble obtaining both internal and external funding(Birkel et al., 2019; Calabrese et al., 2020; Cugno et al., 2021b; 'Kagermann, 2013; Müller, Kiel, et al., 2018). These limitations are consistent with more general results in the literature that highlight businesses' reluctance to invest in Industry 4.0 because of the high implementation costs and unpredictable returns(Cordeiro et al., 2024; S. S. Kamble et al., 2018; Satyro et al., 2022).

2.4 Legal and regulatory Barrier

Adoption of Industry 4.0 is a complex transformation that calls for a well-organized legal and regulatory environment; it is not just a technology change. However, a significant obstacle that limits both intra- and inter-firm collaboration is the absence of clear norms and laws(Kovaitė et al., 2020; Raj et al., 2020b). Companies find it difficult to integrate digital technologies, ensure safe data transmission, and maintain robust machine-to-machine communication—all essential to the adoption of Industry 4.0—in the absence of defined norms(Cimini et al., 2017b; Kiel, Arnold, et al., 2017c; Sung, 2018; Varghese & Tandur, 2014). The fragmented nature of the digital economy, where companies use different data standards, makes these issues even worse and makes it challenging for supply chains to link seamlessly(Birkel & Müller, 2020). (Schröder, 2016) discusses small and medium-sized businesses' (SMEs') reluctance to embrace Industry 4.0 because of the absence of uniform norms and laws. The author goes on to say that SMEs face difficulties when they join value-creation networks and activities because of this absence of standards. Furthermore, lawmakers and regulators are always faced with new challenges due to the rapid advancement of technology. When they are not accustomed to the constantly evolving technology and its wide-ranging effects, they struggle to protect.

Therefore, in order for regulators to understand what they are regulating, they must quickly adjust to evolving technical advancement(Raj et al., 2020b). Implementing industry 4.0 requires that different firms adhere to global norms of practice(Weyer et al., 2015). The right standards should be developed since Industry 4.0 aims to enable organizations' systems management and integration through value networks. Efforts to standardize should focus on defining the data that will be exchanged and the cooperation systems. The reference architecture refers to the complete, specialized representation and implementation of certain configurations. In this sense, the reference architecture serves as a general model that can be used to all of the partner firms' products and services. It provides a framework for the planning, development, integration, and operation of the technological frameworks relevant to the Industry 4.0 idea. Although several specialist fields, competent organizations, and working clusters now use a few developed standards, there is currently a lack of an ordered outline of these standards.

Thus, it is crucial that current standards be included into new global standards or reference architectures, such as those in the sphere of computerization (industrial correspondence, designing, demonstrating, IT security, gadget coordination, advanced processing plants, etc.)(Kagermann, 2013; Nimawat & Gidwani, 2021). A pre-made execution strategy with clear standards draws in managers, business owners, and investors. An industry or profit-making model that has been successfully adopted serves as a catalyst for other industries, especially those in the same sector, to follow suit. A small number of industries, including e-commerce, automotive, consumer electronics, and others, will soon be available as successfully implemented role models. Some industries have already begun effectively integrating I4.0 methods. Others will follow their models, standards, and implementation strategies(S. Kumar et al., 2020a).

Sixteen barriers have been identified which have been categorized into for main categories, vij., organizational, financial, technological and legal. Each of them is shown in Table 1 and discussed above in detail.

Table 1 List of Main Barrier and Sub-Barrier to industry 4.0 adoption in MSMEs

Main Barrier	**Sub-Barrier Code**	**Sub-Barrier Description**	**Supporting Literature**
Organizational Barriers (OB)	OB1	Resistance to change	(Luthra & Mangla, 2018; Tortorella et al., 2022)
	OB2	Lack of top management commitment	(Mittal et al., 2018; Yadav et al., 2020)
	OB3	Inadequate digital culture	(Birkel & Müller, 2020; Frank et al., 2019)
	OB4	Poor interdepartmental coordination	(Horváth & Szabó, 2019c)
	OB5	Inadequate organizational strategies	(Alcácer & Cruz-Machado, 2019; S. S. Kamble et al., 2018)
	OB6	Limited change management capability	(Sony & Naik, 2020)
Financial Barriers (FB)	FB1	High initial investment cost	(Luthra & Mangla, 2018; Raj et al., 2020b)
	FB2	Uncertainty in return on investment	(Mittal et al., 2018; Müller, Kiel, et al., 2018)
	FB3	Limited access to financial resources	(R. Kumar, 2020; The World Bank, 2019)
Technological Barriers (TB)	TB1	Lack of digital infrastructure	(Frank et al., 2019; S. Kamble et al., 2018)
	TB2	Data security and privacy concerns	(Ghobakhloo, 2018)
	TB3	Lack of interoperability and standards	(Sony & Naik, 2020)
	TB4	Complexity of Industry 4.0 technologies	(Rossini et al., 2019)
Legal Barriers (LB)	LB1	Inadequate government support and policies	(Ghobakhloo, 2018)
	LB2	Regulatory and compliance challenges	(S. Kamble et al., 2019; Müller, Kiel, et al., 2018)
	LB3	Lack of Government support and policies(LB3)	(S. Kamble et al., 2018; Luthra & Mangla, 2018; Raj et al., 2019b)

2.5 SMEs and Industry 4.0

Nowadays, the majority of businesses are aware of the potential effects of Industry 4.0. SMEs, on the other hand, are typically less equipped to handle the new technologies and demands(Horváth & Szabó, 2019c). Numerous authors have noted that SMEs' development projects might be severely hampered by a lack of funding(Horváth & Szabó, 2019c; Mcmahon, 2001; Mittal et al., 2018). Several technologies have yet to be implemented by many small and medium-sized businesses (SMEs), despite the introduction of Industry 4.0 ten years ago. Consequently, it is still difficult to integrate SMEs along the end-to-end, vertical, and horizontal engineering dimensions. Understanding SMEs' obstacles and corresponding facilitators for Industry 4.0 integration is essential given the significance of SMEs for industrial value chains(Muller et al., 2024a) Even though SMEs are crucial to the generation of industrial value, they have difficulty integrating into Industry 4.0.(Moeuf et al., 2018, 2020; Müller, Kiel, et al., 2018). There is little empirical evidence of Industry 4.0 acceptance among manufacturing SMEs outside of one or two countries, despite the research on the topic growing quickly(Müller, Buliga, et al., 2018) SMEs suffer from low levels of automation, niche-oriented business models, scarce resources, and non-standardized operational procedures in comparison to large corporation(Horváth & Szabó, 2019c; Mittal et al., 2018). Adoption of Industry 4.0 involves some complexity for SMEs because each technology can be used in various value chain activities with distinct goals and with limited resources(Estensoro et al., 2022).

It is impossible to overlook the role that SMEs play in a country's economic development. One of the biggest challenges to the next generation of industry change is ignorance and lack of preparation. Economies of scale are a minor concern in SMEs. Therefore, I 4.0 is less beneficial to them(Chonsawat & Sopadang, 2020). Nevertheless, economies have entered a new era of transparency and knowledge, which makes it challenging for startups and small businesses to compete. Therefore, these SMEs can enhance their product quality, time and cost savings, on-time operations, long-term client relationships, etc. if they accurately assess the success rate of this revolution(NGUYEN & LUU, 2020). Businesses in general and SMEs in particular continue to face unique challenges as a result of Industry 4.0. Because they lack the organizational capacity to adopt Industry 4.0, SMEs are not prepared. SMEs typically have less qualified personnel and fewer financial resources for research and development than larger corporations(Matt et al., 2018). Because I4.0 demands large technological investments, it can be difficult for small and medium-sized businesses (SMEs) to fully realize its potential.

This is insufficient, though, as IT capabilities, a top management strategic vision, and an organizational environment prepared to support the transformation process and reap the advantages of these technologies must also be taken into account(Agostini & Nosella, 2019). Regarding the SME context, the economic crisis and the banks credit crunch have resulted in a reduction in the resources available to them since 2011. However, the I4.0 revolution's increased pervasiveness, which makes it possible to produce smart products and optimize manufacturing processes, has increased the dynamism and complexity of the SME market and technology environment(Neirotti & Raguseo, 2017). increasing their competitive pressures, altering market equilibria, and changing industry structure.

Due to the high cost of sustainable practices, a lack of training and expertise, a lack of defined criteria, and a slow acceptance of emerging technology, SMEs in developing nations like India are unable to guarantee sustainable manufacturing operations(R. Kumar, 2020, 2021). The performance of SMEs may be impacted by the partial adoption of innovative and sustainable technical procedures(Shashi et al., 2019). Radziwon et al. (2014) have ascertained that Industry 4.0 technologies can help in improving the sustain ability and efficiency of operations. SMEs can improve their environmental performance, flexibility, responsiveness, and productivity by implementing emerging technologies(Pedersen et al., 2016).

Technologies of industry 4.0 can be used for resolving sustainability problems(R. Kumar, 2020). R. Kumar et al. (2014)have discovered that the absence of efficient techniques causes SMEs to struggle with supply chain management. The use of smart technology has significantly altered the manufacturing sector's focus in recent years(Jain et al., 2017) Implementing Industry 4.0 principles in SMEs presents a number of challenges, including supply chain integration, networking, and security. Therefore, it is necessary to examine various obstacles in the implementation of developing technologies in order to address these kinds of issues in SMEs(Marques et al., 2017) It has been noted that relatively few studies have looked at the obstacles SMEs in developing nations like India face when implementing new technologies(R. Kr. Singh et al., 2019).

2.6 MSME and Uttarakhand

The MSME industry in Uttarakhand makes a significant economic contribution to the state and is crucial to job creation and manufacturing investment. According to the MSME annual report for 2020–21, there are 4.17 lakh MSME enterprises in Uttarakhand, with roughly 6.60 lakh employees. As of July 2021, 58,040 MSME units with more over 4 lakh employees were registered, according to the Uttarakhand Directorate of Industry. The districts of Haridwar, Dehradun, Udham Singh Nagar, and Pauri Garhwal have the most registered MSME units(B. Kumar & Gajakosh, 2021). According to the India Brand Equity Foundation, Uttarakhand's MSME sector employs about 1.5 million people directly, making it the state's second-largest employment after agriculture(IBEF, 2023). Using technical methods, like machines and equipment, increases output levels and quality while saving money, time, and effort. Innovation and technology are essential to MSMEs' expansion and development.

Companies that employ technology and innovation are more competitive. However, MSMEs in Uttarakhand face challenges such inadequate technical expertise, limited access to technology, and a lack of knowledge and information. Additionally, there is a lack of research and development in the business(B. Kumar & Gajakosh, 2021) MSMEs in Uttarakhand struggle with accessing technology(virk & negi, 2019). Their capacity to develop and upgrade is hampered by a lack of awareness, information, and technical expertise.

There is less innovation and modernization in the sector as a result of inadequate research and development efforts. The issue of economic marginalization among MSMEs in the area is made worse by this technical stagnation(B. Kumar & Gajakosh, 2021) Growth and development may be hampered by the sector's antiquated technology, lack of current infrastructure, and numerous laws and regulations. A cycle of technological stagnation and economic marginalization is sustained when there are insufficient support systems for talent development, technology adoption, and innovation(Ali Anis & husain firoz, 2014; Panwar et al., 2024; Rawat & Karmakar, 2021). Growth and development may be hampered by the sector's antiquated technology, lack of current infrastructure, and numerous laws and regulations. A cycle of technological stagnation and economic marginalization is sustained when there are insufficient support systems for talent development, technology adoption, and innovation. (Ali Anis & husain firoz, 2014; Rawat & Karmakar, 2021)

3. Research Methodology

Introduced by Saaty in 1980, the Analytic Hierarchy Process (AHP) is a popular Multi-Criteria Decision-Making (MCDM) tool that allows decision-makers to use pairwise comparisons to assess and rank options according to a defined hierarchy of criteria and alternatives. However, in complicated, real-world decision-making settings that are marked by ambiguity and vagueness, standard AHP frequently expects accurate and consistent numerical judgments, which is unrealistic(Mahtani & Garg, 2018).Chang (1996) developed the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) to overcome these constraints by combining the extent analysis method with fuzzy set theory to handle imprecise judgments.

By converting linguistic phrases absolute, very strong, strong, weak, and just equal. into triangular fuzzy numbers, this method enables experts to express preferences. Fuzzy arithmetic is then used to determine weights(Kabra & Ramesh, 2015; Zadeh, 1965). When faced with ambiguity, fuzzy AHP offers a more adaptable and reliable tool for decision-making(D. Kumar & Garg, 2017; Prakash & Barua, 2015). This study uses fuzzy AHP to systematically identify and prioritize hurdles affecting Indian MSMEs, allowing for a more realistic and trustworthy evaluation procedure given the subjectivity and uncertainty inherent in expert judgments linked to Industry 4.0 adoption.

The Barriers are identified and ranked using a two-phase hybrid technique in this study. The first stage entails determining the barriers to the adoption of industry 4.0 in Manufacturing MSMEs by reviewing the literature and consulting experts. The second stage is assessing and prioritizing the barriers and sub barriers by applying the fuzzy AHP method.

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Review of Literature

↓

Identify criteria and alternatives

↓

Collected Expert Opinions(from industry and academia)

↓

Apply fuzzy set theory to handle uncertainity and human subjectivity

↓

Use Triangular Fuzzy Numbers (TFNs) to represent linguistic terms

↓

Construct a fuzzy positive reciprocal matrix

↓

Used Chang's extent analysis to compute fuzzy synthetic extent values

↓

Calculate preference weights and prioritize the critical barriers

↓

Enable continuous improvements based on expert feedbacks and results

Fuzzy Analytic Hierarchy process (fuzzy AHP)

Step:1 Identifying the barriers through literature literature review

To identify the key barriers affecting the adoption of Industry 4.0 technologies in MSMEs, an extensive review of scholarly literature was first undertaken. This helped establish a theoretical foundation and reveal the commonly cited challenges in digital transformation. To further validate and refine these themes, unstructured interviews were conducted with MSME owners and domain experts, providing practical insights into the on-ground difficulties faced during implementation. Based on the combined evidence from literature and expert inputs, the barriers were consolidated into four major categories, which served as the evaluation criteria for the study. A pairwise comparison questionnaire was then developed to apply the Fuzzy AHP methodology for systematically prioritizing these barriers.

Step:2 Developing the Questionnaire and Collecting data

Following the identification of the major barrier categories, a pairwise comparison questionnaire was developed to operationalize the Fuzzy AHP methodology. Each barrier category was positioned on both axes of the comparison matrix, enabling respondents to evaluate their relative importance. A five-point linguistic scale—ranging from "just equal" to "absolute importance"—was used to capture expert judgments, which were later converted into triangular fuzzy numbers to address the inherent subjectivity in qualitative assessments. After clearly explaining the purpose of the study and the procedure for completing the matrix, data were collected from **25 domain experts** with experience in Industry 4.0 technologies and MSME operations. This judgmental sampling approach ensured that the respondents possessed adequate technical and operational understanding to provide reliable and meaningful evaluations for the subsequent fuzzy analysis.

Step:3 Data Analysis using fuzzy Analytic Hierarchy process

The Fuzzy Analytic Hierarchy Process (Fuzzy AHP) was used to analyze the data after the pertinent barriers were identified through a thorough literature research (Step 1) and expert opinions were gathered using a structured questionnaire (Step 2). In order to accurately reflect the ambiguity and uncertainty included in human judgments, especially when experts assess intricate and qualitative criteria like Industry 4.0 adoption hurdles, the fuzzy technique was used. Chang's extent analysis method, which is one of the most popular approaches for applying Fuzzy AHP because of its ease of use, resilience, and appropriateness for multi-criteria decision-making issues, was used in this work(Nguyen et al., 2020). After the response were collected each criterion was assigned a triangular fuzzy number using the scale as described by Saaty (1990) and shown in Table 2.

Table 2 Triangular Fuzzy conversion scale

Value	Fuzzy pairwise comparison value
Equally	(1.0,1.0,1.0)
Weak	(1.0,2.0,3.0)
Fairly strong	(2.0,3.0,4.0)
Very strong	(3.0,4.0,5.0)
Absolute	(4.0,5.0,6.0)

Step 3.1: Estimation of the fuzzy synthetic Extent Value

In the first stage of fuzzy AHP analysis, the fuzzy synthetic extent value was calculated for each barrier with respect to the ath Object. Expert responses collected through pairwise comparisons were first converted into triangular fuzzy numbers(TFNs). These fuzzy judgements were then aggregated to obtain the collective fuzzy comparison matrix

Let *Aij* denote the fuzzy judgement corresponding to the importance of criterion i relative to criterion j. the fuzzy synthetic extent Ei for the i^{th} criterion was computed as:

$$S_i = \left(\sum_{j=1}^{P} Xij\right) \otimes \left(\sum_{\{i=1\}}^{q} \sum_{\{i=1\}}^{P} Xij\right)^{-1}$$

where:

- ⊛ denotes fuzzy multiplication,
- −1 represents the inverse of a triangular fuzzy number,
- q is the total number of criteria under consideration, and
- p denotes the number of pairwise comparisons.

This computation was performed separately for:

- the **main barrier level**, and
- the **sub-barrier level** under each corresponding main barrier.

The resulting fuzzy synthetic extents reflect the aggregated fuzzy importance of each barrier and sub-barrier.

Step 3.2: Computation of the degree of the possibility

After obtaining the fuzzy synthetic extent values, the degree of possibility was calculated to compare the relative dominance of one fuzzy extent over another. This steps enables pairwise comparison between criteria under fuzzy conditions

Si=(li, mi, ui) and

Sj=(lj, mj, uj)

The degree of possibility that *Si* is greater than or equal to *SJ was determined as:*

$$P(Si \geq Sj) = \begin{cases} 1, & \\ 0, & if\ mi \geq mj \\ \dfrac{ui - ij}{(ui - mi) + mj - lj)'} & if lj \geq ui \\ & Otherwise \end{cases}$$

This comparison was carried out for all pairs of fuzzy extents, enabling a comprehensive evaluation of relative dominance among the barriers

Step 3.3 Calculation of weight vector

Based on the calculated dominance values, the unnormalized fuzzy weight for each criterion was obtained by identifying the minimum degree of dominance of that criterion over all others. This reflects the most conservative estimate of its relative importance.

$$w^f_{i=} \min[P(\tilde{S}i \geq \tilde{S}j)], \forall j \neq i$$

The resulting vector:

$$W^f = (w^f_1, w^f_2, \ldots\ldots w^f_n)$$

Represents the preliminary priority weights of the criteria prior to normalization

The pairwise comparison matrix in Table 3. Represents the triangular fuzzy numbers obtained through data collected for the main barriers of this study

Table 3 Pairwise comparison matrix of main barriers categories

	Organizational Barrier			Financial Barrier			Technological Barriers			Legal and Regulatory Barrier		
Organizational Barrier	1	1	1	0.33	0.5	1	2	3	4	2	3	4
Financial Barrier	1	2	3	1	1	1	1	1	1	1	1	1
Technological Barriers	0.25	0.33	0.5	1	1	1	1	1	1	1	1	1
Legal and Regulatory Barrier	0.25	0.33	0.5	1	1	1	1	1	1	1	1	1

Step 3.4: Determination of Normalised Priority weights

The fuzzy synthetic extent values obtained for each of the main barriers were further processed to derive their respective weights. Let $\tilde{S}i$ denote the fuzzy synthetic extent to the i^{th} barrier category. Using the aggregated fuzzy comparison matrix, the fuzzy synthetic extents for the main barriers were obtained as follows

$$\tilde{S}OB = (lOB, mOB, uOB) \otimes \left(\sum_{i=1}^{n} \tilde{S}\, i\right)^{-1}$$

$$\tilde{S}FB = (lFB, mFB, uFB) \otimes \left(\sum_{i=1}^{n} \tilde{S}\, i\right)^{-1}$$

$$\tilde{S}TB = (lTB, mTB, uTB) \otimes \left(\sum_{i=1}^{n} \tilde{S}\, i\right)^{-1}$$

$$\tilde{S}LB = (lLB, mLB, uLB) \otimes \left(\sum_{i=1}^{n} \tilde{S}\, i\right)^{-1}$$

Where OB, FB,TB, and LB represent organisational, financial, technological, and legal–regulatory barriers, respectively Following this, the **degree of dominance** of each fuzzy synthetic extent over the others was calculated. The minimum degree of dominance for each barrier category was then determined using:

$$\mu(Bi) = \min\,[\mathrm{P}(\tilde{S}i \geq \widetilde{Sj}], \forall j \neq i$$

Based on this computation, the minimum values of the possibility vector for each main barrier were obtained as

$\mu(OB) = 0.18$

$\mu(FB) = 0.12$

$\mu(TB) = 0.35$

$\mu(LB) = 0.35$

These values represent the unnormalized priority scores of the main barriers. The resulting weight vector is expressed as:

W=(0.18,0.12,0.35,0.35)

Since the sum of these values equals unity, the vector directly represents the final normalised weights of the main barrier

The result indicate the technological barrier and legal and regulatory barrier are the most influential barrier affecting Industry 4.0 adoption in manufacturing MSMEs each contributing as equal and dominant share to the overall decision hierarchy. Organisational barriers occupy a moderate position, while financial barriers, though relevant exhibit comparatively lower influence

An identical computational procedure was applied at the sub barrier level within each main barrier category. The fuzzy synthetic extents of sub-barriers were evaluated, minimum dominant values were determined. These local weights were then multiplied with their respective main barrier weights to calculate the global weight of sub-barriers, which formed the basis for final ranking and subsequent sensitivity analysis

4. Results and Discussions

4.1 Result of Fuzzy AHP Analysis

The fuzzy AHP analysis produced priority weights and corresponding ranks for both the main barriers and their associated sub-barriers affecting the adoption of industry 4.0 technologies in manufacturing MSMEs. Technological barriers received the largest relative relevance of all barrier types at the main-barrier level, ranking first. Organizational barriers were given the second place after this. Third place went to financial barriers, and fourth place went to legal and regulatory barriers. The ranking order makes it abundantly evident that internal organizational and technological difficulties outweigh external and budgetary limitations when it comes to affecting Industry 4.0 adoption.

4.2 Ranking and Analysis of Sub-barriers

A detailed ranking of sub barriers further clarifies the specific constraints within each main barrier category

Sub-barriers pertaining to system compatibility and technological infrastructure readiness were ranked highly within the Technological Barrier category, underscoring their crucial impact on adoption choices. Technologically less important aspects, on the other hand, were placed lower, suggesting a relatively less impact.Resistance to change (OB1) was the most highly scored sub-barrier in the Organizational Barrier category, closely followed by insufficient organizational strategies (OB5). These sub-barriers were ranked higher than other organizational characteristics, highlighting the importance of strategic orientation and managerial attitude in determining Industry 4.0 preparedness. Secondary influence was suggested by the lower ranking of other organizational sub-barriers. High initial investment costs and restricted access to financial resources received moderate rankings for financial barriers, suggesting that although they are important, they are not the most significant barriers. Sub-barriers relating to operational costs were scored lower in this category. Sub-barriers related to policy support and compliance concerns ranked lowest overall among Regulatory and Legal Barriers, indicating that regulatory conditions are viewed as less restrictive than internal firm-level challenges.

The weights of all the sub-barriers are determined. These weights are given in Table 4. Sub-barriers local weights are multiplied with the parent relative preference weights (main barrier categories) to compute the global weight of each sub barrier. The global ranks are determined using the global weights to prioritize the sub-barriers. Finally, the main barriers and sub-barriers are subjected to sensitivity analysis which is detailed in section 4.3 sensitivity analysis. Along with that the top 5 barriers are shown in Table 5.

Table 4. ***Barrier weights and ranks***

Barriers	Relative Preference Weight	Relative Rank	Local Weights	Relative Ranks	Global Weights	Global Ranks
Organizational Barrier	0.18	3				
Resistance to change (OB1)			0.0400	6	0.0072	15
Lack of knowledge of industry 4.0 concept (OB2)			0.0800	4	0.0144	12
lack of management commitment (OB3)			0.0500	5	0.0090	14
Lack of digital skills (OB4)			0.2900	2	0.0522	7
inadequate organizational strategies (OB5)			0.1000	3	0.0180	11
Lack of Training (OB6)			0.4300	1	0.0774	5

Financial Barrier (FB)	0.12	4				
Lack of Resources (FB1)			0.4200	2	0.0504	8
High Investment Requirement (FB2)			0.0800	3	0.0096	13
Lack of funding (FB3)			0.5000	1	0.0600	6
Technological Barrier	0.35	1				
Technology compatability (TB1)			0.1400	3	0.0490	9
Low technology maturity (TB2)			0.1300	4	0.0455	10
data security concerns (TB3)			0.3600	2	0.1260	4
lack of infrastructure (TB4)			0.3700	1	0.1295	3
Legal Barrier	0.35	2				
Lack of Regulatory Framework (LB1)			0.0000	3	0.0000	16
Legal Uncertainity (LB2)			0.4800	2	0.1680	2
Lack of Government support and policies (LB3)			0.5200	1	0.1820	1

Table 5 ***Top 5 Barriers of adoption of industry 4.0***

Sub barrier	Barrier code	Global Rank
Lack of Government support and policies	LB3	1
Legal Uncertainty	LB2	2
Lack of Infrastructure	TB4	3
Data Security Concerns	TB3	4
Lack of training	OB6	5

4.3 Sensitivity Analysis

Sensitivity is a type of reliability evaluation that confirms the effectiveness of the employed methodology. Sensitivity analysis has been employed in an number of research that employ MCDM approaches like fuzzy AHP to support their conclusions(Dhingra et al., 2023; Garg, 2016) The analysis shows that the top-ranked sub-barriers' relative positions are essentially constant under a variety of weight fluctuation scenarios. Only slight changes were seen among lower-ranked sub-barriers, even when significant changes were made to the importance weights of the primary barriers. This shows a high level of ranking stability, indicating that the fuzzy AHP model's priority is not unduly sensitive to slight changes in expert opinions. This stability increases the decision framework's dependability and validates that the identified significant barriers are fundamentally dominant obstacles to the adoption of Industry 4.0 in manufacturing MSMEs. Furthermore, the methodological power of combining fuzzy logic with AHP in managing the subjectivity and uncertainty present in expert-based evaluations is demonstrated by the rankings' consistency across sensitivity scenarios. The fact that important obstacles remain at the top positions in both SA-1 and SA-2 scenarios suggests that these barriers continue to have an impact despite shifts in decision-maker preferences or weighting assumptions. As a result, the sensitivity analysis not only confirms the model's robustness but also strengthens trust in the results' applicability for managerial and policy-level decision-making.

The Values of Technological Barriers category were ranged from 0.1 to 0.9 as shown in table 6 and their impact on other main barriers and sub barriers are studied. The different ranks thus obtained are shown in Table 7.

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ES (2026) 22(1), 82-104 | ISSN:1505-4683

Table 6. ***Impact of Technological barriers on other barriers***

Main Barriers	Weights of Barriers									
	Original Value	Input 1	Input 2	Input 3	Input 4	Input 5	Input 6	Input 7	Input 8	Input 9
OB	0.18	0.2492	**0.2215**	**0.1938**	**0.1662**	**0.1385**	**0.1108**	**0.0831**	**0.0554**	**0.0277**
FB	0.12	0.1662	0.1477	0.1292	0.1108	0.0923	0.0738	0.0554	0.0369	0.0185
TB	**0.35**	**0.1000**	**0.2000**	**0.3000**	**0.4000**	**0.5000**	**0.6000**	**0.7000**	**0.8000**	**0.9000**
LRB	0.35	0.4846	0.4308	0.3770	0.3230	0.2692	0.2154	0.1615	0.1077	0.0538
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 7 Different barriers ranks using sensitivity analysis on varying the customer related barriers

Sub-Barrier	**0.1**	**0.2**	**0.3**	**0.35 *(Original)***	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
OB1	10	12	12	**15**	12	12	12	12	12	12
OB2	12	14	14	**12**	14	14	14	14	14	14
OB3	12	14	14	**14**	14	14	14	14	14	14
OB4	4	7	7	**7**	9	9	9	9	9	9
OB5	10	12	12	**11**	12	12	12	12	12	12
OB6	5	6	5	**5**	5	5	5	5	5	5
FB1	5	8	8	**8**	10	10	10	10	10	10
FB2	9	11	11	**13**	11	11	11	11	11	11
FB3	3	6	6	**6**	7	8	8	8	8	8
TB1	14	9	9	**9**	6	6	6	4	4	4
TB2	15	10	10	**10**	7	7	7	5	5	5
TB3	8	5	5	**4**	4	3	3	3	3	3
TB4	7	4	4	**3**	2	2	2	2	2	2
LB1	16	16	16	**16**	16	16	16	16	16	16
LB2	2	2	2	**2**	5	5	5	7	7	7
LB3	1	1	1	**1**	3	4	4	6	6	6

5. Conclusion and Managerial implication

This study used a fuzzy AHP framework backed by sensitivity analysis to identify the main obstacles preventing manufacturing MSMEs from implementing Industry 4.0 technology. The study was able to systematically rank both the primary obstacles and the related sub-barriers by taking expert judgment uncertainty into consideration. The findings unequivocally demonstrate that rather than a large variety of equally significant factors, Industry 4.0 adoption in MSMEs is influenced by a small number of major barriers. Crucially, the sensitivity analysis improves confidence in the findings' robustness by confirming that these priorities stay mostly constant even when the relative importance of the primary obstacles varies.

The findings provide useful advice for MSME owners and managers at a time when resources are few and decisions about digital transformation carry a high degree of risk. Managers can determine where their focus and efforts are most likely to have an impact by rating the barriers. Managers may strengthen the foundation for Industry 4.0 implementation by concentrating initially on the most important obstacles rather than trying to solve every issue at once. This methodical and well-informed strategy can enhance preparedness, lower implementation failures, and promote better long-lasting adoption results.

Additionally, governments and support organizations that assist MSMEs will clearly be impacted by the findings. Broad, one-size-fits-all digitization strategies may not fully address the actual difficulties faced by MSMEs, as indicated by the constancy of barrier rankings across various sensitivity scenarios. When targeted solutions are in line with the most significant obstacles found in this study, they are more likely to be successful. Examples of these interventions include targeted skill development programs, customized financial help, and easily available technological consulting services. Such alignment can speed up the adoption of Industry 4.0 technology among MSMEs and increase the effectiveness of public programs. All things considered, this study adds to the body of knowledge on Industry 4.0 adoption both practically and methodologically. Sensitivity analysis and fuzzy AHP together offer a dependable framework for decision-support in the examination of complicated, uncertain problems. More significantly, the study provides managers and policymakers with practical insights that can guide them away from theoretical debates about digital transformation and toward specific, goal-oriented tactics that promote the long-term viability and competitiveness of manufacturing MSMEs.

6. Limitation and Scope of Future Research

Despite the contributions of this study, certain limitations should be acknowledged, which also open avenues for future research. The analysis is primarily based on expert judgments, and although the use of fuzzy logic helps to capture uncertainty and reduce subjectivity, the findings may still reflect perceptual biases inherent in expert-based evaluations. Additionally, the study focuses on manufacturing MSMEs within a specific contextual setting, which may limit the generalizability of the results to other sectors or regions where institutional, technological, and market conditions differ. The study adopts a cross-sectional approach, capturing expert opinions at a single point in time; future research could employ longitudinal designs to examine how the importance of Industry 4.0 barriers evolves as firms progress through different stages of digital transformation. Moreover, the current framework prioritizes barriers but does not empirically link their mitigation to measurable firm-level performance outcomes. Future studies could extend this work by integrating hybrid multi-criteria decision-making methods or combining barrier analysis with quantitative performance indicators to better understand the impact of overcoming specific barriers on eco nomic, social, and environmental sustainability outcomes.

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