# STUDY OF INDUSTRY 4.0 TECHNOLOGIES FOR SUSTAINABLE CONSTRUCTION IN INDIA

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*By*


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New Delhi, June 2024 **Ankur Tayal**

***I dedicate this Ph.D. thesis to my Late Grand Father for his blessings and my parents, wife and son for their unwavering support and unconditional love.***

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# CANDIDATE'S DECLARATION

I, **Ankur Tayal**, hereby certify that the thesis entitled **STUDY OF INDUSTRY 4.0 TECHNOLOGIES FOR SUSTAINABLE CONSTRUCTION IN INDIA**, in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the **Department of Delhi School of Management, Delhi Technological University**, is an authentic record of my own work carried out during the period from **2021 to 2025** under the supervision of **Dr. Saurabh Agrawal** and **Prof. (Dr.) Rajan Yadav**.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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**Candidate's Signature**

This is to certify that the student has incorporated all the corrections suggested by the examiner in the thesis and the statement made by the candidate is correct to the best of our knowledge.

**Signature of Supervisors** **Signature of External Examiner**

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## CERTIFICATE BY THE SUPERVISOR

Certified that **ANKUR TAYAL (2K21/PhD/DSM/12)** has carried out his research work presented in this thesis entitled **STUDY OF INDUSTRY 4.0 TECHNOLOGIES FOR SUSTAINABLE CONSTRUCTION IN INDIA,** for the award of Doctor of Philosophy from **Delhi School of Management, Delhi Technological University, Delhi**, under our supervision. The thesis embodies results of original work, and studies are carried out by the student himself. The contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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Abstract

### Objective

The study aims to explore and evaluate the adoption of Industry 4.0 technologies in the Indian construction industry, emphasizing their role in achieving sustainability. Key objectives include identifying enablers and barriers, analyzing sustainability dimensions (economic, social, and environmental), assessing perceived risks, and formulating strategies for effective technology integration.

### Rationale

The construction industry, traditionally resistant to innovation, faces significant challenges in adopting advanced digital technologies. With growing demands for sustainable practices, Industry 4.0 offers transformative potential, particularly in developing nations like India. However, barriers such as high costs, skill shortages, and regulatory uncertainties necessitate a comprehensive study to bridge research gaps and provide actionable insights.

### Methodology

A mixed-method approach was employed, including:

- **Systematic Literature Review**: Identifying gaps and establishing a knowledge foundation.
- **Empirical Analysis**: Utilizing methods like Fuzzy SWARA, Fuzzy COPRAS, and Fuzzy AHP to rank enablers, barriers, and sustainability factors.
- **Case Studies**: Examining real-world implementations of Industry 4.0 technologies in Indian construction firms.
- **Surveys and Expert Interviews**: Collecting data from industry stakeholders to understand perceptions and challenges.

**Key Findings**

1. **Enablers**: Strategic planning, government regulations, and technological innovations like AI, IoT, and BIM were critical.
2. **Barriers**: High initial costs, lack of skilled workforce, and cybersecurity threats emerged as significant challenges.
3. **Sustainability Impact**: Industry 4.0 technologies enhanced efficiency, reduced waste, and improved safety, addressing the triple bottom line dimensions.
4. **Risk Perceptions**: Cybersecurity risks and data privacy were the most critical concerns for stakeholders.

**Implications**

The findings underscore the need for a robust framework to facilitate Industry 4.0 adoption. By addressing barriers and leveraging enablers, the construction industry can achieve significant advancements in sustainability, productivity, and competitiveness.

**Recommendations and Future Research**

- **Policy Recommendations**: Develop standardized regulations and offer financial incentives to reduce adoption barriers.
- **Training Programs**: Enhance workforce readiness through industry-academia collaboration.
- **Technology Customization**: Tailor Industry 4.0 solutions to local contexts.
- Future research should explore long-term impacts of Industry 4.0 adoption on job markets and urban infrastructure planning.

**Conclusions and Limitations**

The research highlights Industry 4.0 as a pivotal driver for sustainable transformation in construction. However, its adoption is constrained by financial, technological, and organizational challenges. Limitations include the focus on Indian contexts and the reliance on self-reported data, which may introduce biases.

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## List of Abbreviations

- **AI** - Artificial Intelligence
- **AR** - Augmented Reality
- **BIM** - Building Information Modeling
- **CPS** - Cyber-Physical Systems
- **IoT** - Internet of Things
- **ML** - Machine Learning
- **3D Printing** - Three-Dimensional Printing
- **ROI** - Return on Investment
- **VR** - Virtual Reality
- **SWARA** - Step-wise Weight Assessment Ratio Analysis
- **AHP** - Analytic Hierarchy Process
- **DEMATEL** - Decision Making Trial and Evaluation Laboratory
- **SMEs** - Small and Medium-Sized Enterprises
- **FAHP** - Fuzzy Analytic Hierarchy Process
- **FDEMATEL** - Fuzzy DEMATEL
- **Fuzzy SWARA** - Fuzzy Step-wise Weight Assessment Ratio Analysis
- **DT** - Digital Twin
- **SML** - Supervised Machine Learning
- **ERP** - Enterprise Resource Planning
- **LCA** - Life Cycle Assessment
- **DSS** - Decision Support System
- **RFID** - Radio-Frequency Identification
- **UAV** - Unmanned Aerial Vehicle
- **PPE** - Personal Protective Equipment
- **GDPR** - General Data Protection Regulation
- **CT** - Construction Technology

# 1 Introduction

This chapter serves as a foundational section that outlines the primary goals of this thesis, which are to identify and analyze the key factors influencing the adoption of Industry 4.0 technologies in the Indian construction industry, with a focus on sustainability and practical implementation. It provides an overview of the impact of Industry 4.0 on the construction industry, emphasizing the significance of these technologies in enhancing economic, environmental, and social performance. The chapter also highlights the current practices in the Indian construction industry, comparing them with global standards, and identifies critical enablers and barriers to effective technology adoption. The chapter concludes with a detailed explanation of the thesis structure, outlining how each subsequent chapter will contribute to addressing the identified research gaps and objectives.

## 1.1 **Industry 4.0**

Industry 4.0, also known as the Fourth Industrial Revolution, represents a significant transformation in the manufacturing and production sectors, driven by the integration of digital technologies. It involves the convergence of cyber-physical systems, the Internet of Things (IoT), cloud computing, and artificial intelligence (AI) to create smart factories where machines communicate and cooperate with each other and humans in real-time (Kagermann, 2015). This transformation is not just about implementing new technologies but also about creating new ways of organizing production processes.

### Key Components of Industry 4.0

a) **Cyber-Physical Systems (CPS):** These are integrations of computation, networking, and physical processes, where embedded computers and networks monitor and control physical processes with feedback loops (Lee et al., 2015). CPS plays a crucial role in the development of smart factories by enabling real-time data collection and analysis.

b) **Internet of Things (IoT):** IoT allows devices to connect and communicate with each other over the internet. In Industry 4.0, IoT enables machines to share information, initiate actions, and control each other independently (Atzori, Iera, & Morabito, 2010). This connectivity is fundamental to the development of automated and interconnected production systems.

c) **Big Data and Analytics:** The vast amount of data generated by CPS and IoT devices requires advanced analytics to extract valuable insights. Big Data analytics enables companies to optimize their operations, predict failures, and improve decision-making processes (Wang et al., 2016).

d) **Artificial Intelligence (AI) and Machine Learning (ML):** AI and ML are pivotal in enabling machines to learn from data, adapt to new inputs, and perform tasks that traditionally required human intelligence. In the context of Industry 4.0, AI and ML facilitate predictive maintenance, quality control, and process optimization (Russell & Norvig, 2016).

e) **Cloud Computing:** Cloud computing provides the infrastructure necessary to store and process the massive amounts of data generated by Industry 4.0 technologies. It offers scalable resources that enable companies to access and analyze data from anywhere at any time (Marston et al., 2011).

“The construction industry, traditionally slow to adopt new technologies, is beginning to embrace Industry 4.0 principles. The integration of digital tools and processes in construction is leading to improved project management, reduced costs, and enhanced safety. For example, Building Information Modeling (BIM) combined with IoT devices allows for real-time monitoring of construction projects, leading to better decision-making and resource management (Oesterreich & Teuteberg, 2016). While the potential benefits of Industry 4.0 are significant, challenges such as cybersecurity risks, the need for a skilled workforce, and the high cost of implementation remain. Addressing these challenges requires collaboration between industry, academia, and government to develop standards, training programs, and policies that support the widespread adoption of Industry 4.0 (Schwab, 2016). Industry 4.0 represents a paradigm shift in the manufacturing and construction industry, driven by the integration of advanced digital technologies. While the benefits are clear, the challenges must be addressed to fully realize the potential of this revolution.

### 1.2 Construction 4.0

Construction 4.0 is the adaptation of Industry 4.0 principles specifically tailored to the construction industry. It embodies the integration of advanced technologies and digital tools to transform construction practices, aiming to enhance efficiency, productivity, and safety in the industry (Bimschas et al., 2020). This new era leverages innovations such as Building Information Modeling (BIM), Internet of Things (IoT), robotics, and artificial intelligence (AI) to revolutionize construction processes.

a) **Building Information Modeling (BIM):** BIM is a digital representation of the physical and functional characteristics of a facility. It allows for the creation of 3D models that integrate various aspects of a construction project, such as design, materials, and timelines (Eastman et al., 2011). BIM facilitates better project coordination, reduces errors, and improves decision-making by providing a comprehensive view of the project.

b) **Internet of Things (IoT):** IoT involves the deployment of sensors and devices that collect and transmit data over the internet. In construction, IoT applications include smart wearables for worker safety, sensors for equipment monitoring, and real-time tracking of materials and progress (Díaz et al., 2018). These technologies provide valuable insights that enhance project management and operational efficiency.
c) **Robotics and Automation:** Robotics and automation are increasingly used in construction to perform repetitive or hazardous tasks. Examples include robotic arms for bricklaying, drones for site surveys, and automated machinery for material handling (Gosling et al., 2015). These innovations improve productivity and safety by reducing manual labor and minimizing human error.
d) **Artificial Intelligence (AI) and Machine Learning (ML):** AI and ML are used to analyze data, predict outcomes, and optimize processes. In construction, AI can be applied to tasks such as predictive maintenance, risk assessment, and project scheduling (Chong et al., 2017). Machine learning algorithms can analyze historical data to improve project estimates and decision-making.
e) **Augmented Reality (AR) and Virtual Reality (VR):** AR and VR technologies provide immersive experiences that enhance design visualization and training. For example, VR can be used to create virtual walkthroughs of buildings before construction begins, while AR can overlay digital information onto physical environments to assist in on-site tasks (Pereira et al., 2017).

Construction 4.0 is transforming the industry by addressing long-standing challenges such as inefficiency, safety concerns, and project delays. By integrating advanced technologies, Construction 4.0 improves project outcomes through better planning, real-time monitoring, and enhanced collaboration (Goulding et al., 2017). Despite its potential, Construction 4.0 faces several challenges, including high initial costs, the need for skilled workforce, and data security concerns. Addressing these challenges requires collaboration among industry stakeholders, continuous research and development, and the establishment of standards and best practices (Bock et al., 2016).

Construction 4.0 represents a significant advancement in the construction industry, driven by the integration of digital technologies and data-driven approaches. By leveraging tools such as BIM, IoT, robotics, and AI, the construction industry can achieve greater efficiency, safety, and productivity.

### 1.3 Industry 4.0 in Construction: Focus on Developing Nations (India)

Industry 4.0, characterized by the integration of digital technologies into manufacturing and production, is beginning to make significant inroads into the construction industry. While much of the focus has been on advanced economies, developing nations, particularly India, are also adopting these technologies. The integration of Industry 4.0 technologies in construction holds the promise of addressing inefficiencies and modernizing the sector in these regions (Kumar et al., 2021). BIM is becoming increasingly relevant in the Indian construction industry. It provides a digital representation of physical and functional characteristics, facilitating improved project coordination and management. In India, BIM adoption is being driven by both government initiatives and private sector projects aimed at improving infrastructure quality and efficiency (Saini et al., 2020). IoT applications in construction, such as smart sensors and connected machinery, are being explored in India to enhance real-time monitoring and management of construction sites. IoT enables better tracking of project progress, resource utilization, and safety conditions, which is critical for improving productivity and reducing delays in a country with rapid urbanization and infrastructure needs (Singh & Kumar, 2019). The use of robotics in construction is still in its nascent stages in India. However, there is growing interest in automated machinery for tasks such as bricklaying and concrete pouring. The deployment of drones for site surveys and progress monitoring is also gaining traction, offering potential improvements in efficiency and accuracy (Rao & Kumar, 2021). **Artificial Intelligence (AI) and Machine Learning (ML)** are being applied in the Indian construction industry to enhance project planning and management. AI algorithms are used for predictive maintenance, risk assessment, and optimizing construction schedules. These technologies are particularly valuable in a developing country where resource management and cost control are crucial (Sharma et al., 2020). **Augmented Reality (AR) and Virtual Reality (VR)** technologies are beginning to be utilized in India for design visualization and training. AR applications help workers by overlaying digital information onto physical environments, while VR provides immersive experiences for design reviews and client presentations (Kumar et al., 2021).

**Challenges in Adopting Industry 4.0 in India**

a) **Infrastructure and Investment:** The adoption of Industry 4.0 technologies in India faces challenges related to inadequate infrastructure and high initial costs. Developing the necessary digital infrastructure and making substantial investments in technology are significant hurdles (Saini et al., 2020).
b) **Skilled Workforce:** There is a shortage of skilled professionals who are proficient in Industry 4.0 technologies. Training and upskilling the workforce are essential for successful implementation (Singh & Kumar, 2019).
c) **Regulatory and Standardization Issues:** The lack of standardized regulations and guidelines for Industry 4.0 technologies can hinder their adoption. Establishing clear standards and policies is crucial for ensuring consistency and quality in construction practices (Rao & Kumar, 2021).
d) **Data Security and Privacy:** With the increased use of digital technologies, data security and privacy concerns are becoming more prominent. Ensuring robust cybersecurity measures is essential to protect sensitive information (Sharma et al., 2020).

For India to fully realize the benefits of Industry 4.0 in construction, there must be a concerted effort to address these challenges. Government support, investment in infrastructure, and initiatives to develop a skilled workforce are critical. Additionally, fostering innovation and collaboration between industry stakeholders and educational institutions can drive the adoption of these technologies (Kumar et al., 2021).

Industry 4.0 technologies offer significant opportunities for the construction industry in developing nations like India. While there are challenges to overcome, the potential benefits in terms of efficiency, productivity, and quality make it a promising avenue for development. With continued focus and investment, India can harness the power of Industry 4.0 to transform its construction industry.

## 1.4 **Industry 4.0 in Construction for Achieving Sustainability in Developing Nations: A Focus on India**

Industry 4.0, characterized by the integration of digital technologies and cyber-physical systems, has the potential to transform the construction industry by enhancing sustainability. In developing nations, including India, this transformation is crucial for addressing the pressing social, economic, and environmental challenges associated with rapid urbanization and infrastructure development (Kumar et al., 2021). By leveraging Industry 4.0 technologies, the construction industry can make significant strides towards sustainability in these areas.

### Environmental Sustainability

1. **Resource Efficiency and Waste Reduction:** Industry 4.0 technologies such as Building Information Modeling (BIM) and Internet of Things (IoT) can significantly improve resource efficiency and reduce waste. BIM enables precise planning and simulation, which helps in optimizing material use and minimizing construction waste (Saini et al., 2020). IoT sensors track material usage in real-time, allowing for better inventory management and reducing excess consumption (Singh & Kumar, 2019).
2. **Energy Efficiency and Emission Reduction:** Smart building systems, powered by IoT and AI, can optimize energy consumption by adjusting lighting, heating, and cooling based on real-time occupancy and weather conditions. This results in significant reductions in energy use and greenhouse gas emissions (Sharma et al., 2020). In India, where energy demand is rapidly increasing, these technologies can help mitigate environmental impact and support sustainable development goals.
3. **Sustainable Construction Practices:** Robotics and automation can streamline construction processes, reducing the environmental footprint of construction activities. For instance, automated machinery can perform tasks with greater precision, reducing the need for heavy equipment that contributes to soil erosion and pollution (Rao & Kumar, 2021). Additionally, the use of drones for site inspections can minimize the environmental impact associated with traditional survey methods.

**Economic Sustainability**

a) **Cost Efficiency and Resource Optimization:** Industry 4.0 technologies contribute to cost savings by improving project planning, execution, and management. BIM facilitates accurate cost estimation and budget management, reducing the likelihood of cost overruns (Kumar et al., 2021). AI-driven analytics help optimize construction schedules and resource allocation, enhancing overall efficiency and reducing operational costs.

b) **Improved Productivity and Competitiveness:** Automation and robotics increase construction productivity by performing repetitive and labor-intensive tasks more efficiently. This leads to faster project completion times and reduced labor costs, enhancing the competitiveness of construction firms (Gosling et al., 2015). For developing nations like India, where labor costs and productivity are critical issues, these improvements can drive economic growth and development.

c) **Job Creation and Skill Development:** While automation may lead to the displacement of certain jobs, it also creates new opportunities for skilled workers in areas such as technology management and maintenance. By investing in training and skill development, the construction industry can foster job creation and support economic stability (Sharma et al., 2020).

**Social Sustainability**

a) **Safety and Health:** Industry 4.0 technologies improve construction site safety and worker health. IoT devices and wearable sensors can monitor workers' vital signs and detect hazardous conditions, reducing the risk of accidents and health issues (Díaz et al., 2018). Robotics and automation reduce the need for manual labor in dangerous tasks, further enhancing worker safety.

b) **Quality of Life:** Smart building technologies contribute to better living conditions by creating more comfortable and energy-efficient environments. In rapidly urbanizing areas of India, these technologies can improve the quality of housing and infrastructure, benefiting residents and enhancing overall well-being (Pereira et al., 2017).

c) **Community Engagement and Transparency:** Digital technologies facilitate better communication and transparency between construction firms and local communities. Platforms for stakeholder engagement and feedback enable communities to participate in decision-making processes, ensuring that construction projects align with local needs and preferences (Kumar et al., 2021).

Despite the potential benefits, several challenges must be addressed to fully leverage Industry 4.0 for sustainability in India:

a) **Infrastructure and Investment:** Developing the necessary digital infrastructure and securing investment for Industry 4.0 technologies are major hurdles. Public-private partnerships and government support are essential for overcoming these barriers (Saini et al., 2020).
b) **Skill Development:** There is a need for comprehensive training programs to develop a workforce skilled in Industry 4.0 technologies. Collaboration between educational institutions and industry stakeholders is crucial for this purpose (Singh & Kumar, 2019).
c) **Regulatory Framework:** Establishing clear regulations and standards for Industry 4.0 technologies is necessary to ensure their effective and safe implementation (Rao & Kumar, 2021).

Industry 4.0 technologies offer significant opportunities for achieving sustainability in the construction industry of developing nations, particularly India. By enhancing environmental stewardship, economic efficiency, and social well-being, these technologies can drive progress towards sustainable development goals. Addressing the associated challenges through strategic investment, skill development, and regulatory frameworks will be key to realizing these benefits.

## 1.5 Research Objectives

The research objectives were formulated following a thorough review of the literature and consultations with both academic and industry experts.

**Objective 1:** To study and analyze various factors in construction from Industry 4.0 perspectives.

**Objective 2:** To identify and rank significant Industry 4.0 Enablers in Indian construction industry.

**Objective 3:** To identify and prioritize significant Industry 4.0 Barriers in Indian construction industry.

**Objective 4:** To identify and prioritize sustainability criterias for Industry 4.0 adoption in Indian construction industry.

**Objective 5:** To analyze and rank perceived risks of Industry 4.0 adoption from Indian Customer Perspectives.

## 1.6 Scope of the research study

This study investigates the impact of Industry 4.0 technologies on the construction industry, with a focus on the triple bottom line dimensions—economic, environmental, and social performance. It encompasses identifying and ranking the key enablers and barriers for Industry 4.0 adoption in Indian construction projects, analyzing the challenges and opportunities for sustainable implementation, and examining customer perceptions of technology adoption. The scope includes a comprehensive review of current practices, empirical analysis, and the formulation of strategies to enhance the effective integration of these technologies. The findings of this study will provide valuable insights into how Industry 4.0 technologies can be leveraged to improve sustainability in construction. By identifying and ranking enablers and barriers, the research will help in developing practical frameworks for technology adoption and overcoming obstacles. The study will also contribute to a better understanding of customer perspectives in developing nations, facilitating the customization of technology solutions to meet local needs. Overall, this research aims to enhance the theoretical and practical understanding of Industry 4.0 technologies in construction, promoting their effective and sustainable integration.

### 1.7 Overview of research design and method

The research will investigate Industry 4.0 in the Indian construction industry through a mixed-method approach. Initially, a **Systematic Literature Review** will provide a foundational understanding of current knowledge and identify gaps. To identify and rank significant factors, the study will use **In-depth Interviews** with industry experts and **Case Studies** of firms adopting Industry 4.0 technologies, applying **Fuzzy SWARA** and **Fuzzy COPRAS** for enablers, and **Fuzzy AHP** for barriers, sustainability dimensions and perceived risks. Challenges and opportunities in sustainable implementation will be analyzed using a combination of literature review. This integrated approach aims to provide a comprehensive analysis of Industry 4.0's impact and adoption challenges in the Indian construction industry.

### 1.8 Research Contributions

This research makes several significant contributions to the existing body of knowledge on Industry 4.0 technologies in the construction industry, with a particular focus on sustainability and practical implementation.

a) **Expanding Understanding of Industry 4.0's Impact on Sustainability**: The study provides a comprehensive analysis of how Industry 4.0 technologies influence the sustainable dimensions—economic, environmental, and social performance—within the construction industry. By addressing the gap in understanding the full spectrum of impacts, the research offers insights into how these technologies can be integrated more effectively to promote sustainability in construction practices.
b) **Identification and Prioritization of Industry 4.0 Enablers and Barriers**: The research identifies and systematically ranks the key enablers , barriers, sustainability criterias and risks for the effective application of Industry 4.0 technologies in Indian construction projects. Through the use of advanced decision-making methods like Fuzzy SWARA, Fuzzy COPRAS, and Fuzzy AHP,

the study provides practical insights into which factors are most critical for successful technology adoption. This contribution is essential for developing robust project management frameworks that leverage Industry 4.0 technologies.

c) **Analysis of Challenges and Opportunities in Sustainable Implementation**: The research delves into the challenges and opportunities associated with the sustainable implementation of Industry 4.0 technologies in construction. By applying tools like Fuzzy AHP, the study analysis factors that are crucial for developing strategies and address the complexities of integrating advanced technologies in a sustainable manner.

d) **Insight into Customer Perspectives in Developing Nations**: One of the unique contributions of this research is its focus on customer perspectives in developing nations, particularly in the context of Industry 4.0 adoption in construction. By examining perceived risks and their impact on technology adoption, the study provides valuable guidance for customizing technology solutions to meet local needs and overcome resistance. This contribution is significant for ensuring the successful adoption of Industry 4.0 technologies in diverse socio-economic contexts.

Overall, this research advances both the theoretical and practical understanding of Industry 4.0 technologies in the construction industry, offering valuable insights for academics, practitioners, and policymakers involved in promoting sustainable and innovative construction practices.

# 2 Literature Review

This chapter provides a comprehensive literature review on Industry 4.0 in the construction industry, focusing on its enablers, barriers, challenges, opportunities, impacts on sustainability, and perceived risks. It highlights key enablers such as employee training, strategic planning, stakeholder investment, and advanced technologies like AI, IoT, robotics, and BIM, which drive the adoption of Industry 4.0. The chapter also addresses significant barriers, including high implementation costs, skill gaps, regulatory challenges, and market resistance. It discusses opportunities and challenges associated with cutting-edge technologies, emphasizing their potential to improve efficiency, safety, and project outcomes. The chapter further explores the role of Industry 4.0 in achieving sustainability by contributing to social, economic, and environmental goals through waste reduction, resource optimization, and energy efficiency. Additionally, it identifies perceived risks such as cybersecurity threats, data privacy concerns, and resistance to change, which hinder widespread adoption. Finally, the chapter reviews existing research studies, providing insights into the benefits, barriers, and strategies for implementing Industry 4.0 technologies in construction

## 2.1 Industry 4.0 Enablers

The integration of Industry 4.0 technologies into the construction industry, particularly in developing countries like India, necessitates the identification and implementation of critical enablers that can promote wider adoption and effective application. These enablers serve as key areas of activity that influence companies to achieve their objectives and mitigate the risk of project failures. The successful implementation of Industry 4.0 in construction is heavily reliant on these enablers, which act as powerful management tools (Dallasega et al., 2018). These enablers include a mix of human, technological, and regulatory factors. Employer training combined with corporate ethics is a crucial starting point, ensuring that workers receive continuous education on Industry 4.0 technologies such as robotics, automation, and artificial intelligence, while maintaining adherence to corporate ethics and safety standards (Santos et al., 2020). Through such programs, employees stay up-to-date with the latest technological advancements, which is vital for maintaining competitiveness in a rapidly changing industry.

Organizational strategic planning plays an equally critical role in adopting Industry 4.0. This enabler ensures that long-term corporate goals are aligned with the integration of smart technologies such as automation, digital twins, and building information modeling (BIM). Effective strategic planning enables firms to stay ahead of the curve in digital transformation (Mardani et al., 2018). Moreover, fostering a risk-taking behavior within the organization encourages innovation by supporting experimentation with new technologies, even when the outcomes may not be guaranteed (Luthra et al., 2021). This willingness to take calculated risks is essential for adapting to the fast-paced changes in Industry 4.0.

Government regulations also have a significant influence on the adoption of Industry 4.0 technologies. Regulatory bodies shape the framework within which construction companies operate, encouraging or sometimes inhibiting the use of technologies like BIM, robotics, and other digital solutions (Mahmud et al., 2022). Regulatory support can lead to faster technological adoption, as companies feel more confident about compliance and standardization.

Rewards and incentives are another key enabler, motivating employees and stakeholders to embrace new technologies. Offering both financial and non-financial rewards helps to boost morale and engagement, ensuring that everyone in the organization is committed to adopting and utilizing Industry 4.0 tools effectively (Khan & Farooq, 2021). Alongside this, profitability becomes a driver, as the adoption of advanced technologies like artificial intelligence (AI), 3D printing, and automation improves productivity, reduces project delays, and cuts costs by minimizing waste and material usage (Ustundag & Cevikcan, 2018).

Stakeholder investment is essential in driving the shift towards smart technologies. Involving stakeholders ensures that there is adequate funding and support for integrating innovative solutions, which in turn leads to more sustainable and efficient project outcomes (Dallasega et al., 2020). This drive is fueled by market demand, as consumers increasingly expect high-quality, sustainable, and faster construction solutions. Industry 4.0 technologies allow construction firms to meet these demands more effectively (Holbert & Garcia, 2020).

Several technological advancements are central to Industry 4.0. Artificial intelligence (AI) is instrumental in automating decision-making processes, performing predictive analytics, and improving project management by providing data-driven insights that enhance accuracy and reduce errors (Bock & Linner, 2021). 3D printing has revolutionized the construction industry by enabling modular and custom-built components to be created efficiently, reducing both material waste and project timelines (Wu et al., 2018). Building Information Modeling (BIM) and digital twins play a key role in the planning and execution stages of construction projects by providing real-time synchronization of data and virtual representations of structures, ensuring better project management (Eastman et al., 2018).

The Internet of Things (IoT) enables the connection of construction machinery and equipment to the internet, allowing for real-time data collection and analysis. This facilitates smarter construction processes and helps in monitoring and managing resources more effectively (Rose et al., 2020). Robotics and automation are being increasingly applied in tasks such as bricklaying, welding, and excavation, improving safety, reducing human error, and speeding up project timelines (Bogue, 2021).

Cloud computing and big data analytics support centralized data management, making real-time collaboration possible across remote construction sites. This enables efficient project tracking and predictive maintenance by processing large datasets collected from different sources (Zaheer et al., 2019; Bilal et al., 2016). Cyber-Physical Systems (CPS) integrate physical construction processes with digital systems, enabling real-time monitoring, autonomous decision-making, and remote project management (Trentesaux et al., 2019).

Additionally, augmented reality (AR) and virtual reality (VR) technologies provide enhanced visualization of construction designs, enabling stakeholders to validate designs before implementation, offer safety training, and facilitate better collaboration among project teams (Wang et al., 2020). Blockchain technology ensures transparency and security across the supply chain, fostering trust by enabling secure transactions and contract management (Li et al., 2021).

In terms of physical advancements, smart sensors are employed to monitor environmental conditions, material performance, and the structural health of buildings in real-time, ensuring more responsive and adaptive construction processes (Anil et al., 2018). Drones or unmanned aerial vehicles (UAVs) assist with surveying, site monitoring, and inspections, providing highly accurate data with minimal human intervention (Irizarry et al., 2019). Wearable technology, such as smart helmets and vests, improves worker safety by monitoring health and environmental conditions and providing real-time communication on-site (Teizer et al., 2017).

Another significant innovation is the use of self-healing materials, which autonomously repair damage, extending the lifespan of structures and reducing maintenance costs (De Belie et al., 2020). Collaborative robots (cobots) work alongside human laborers to perform precision tasks, further enhancing productivity and safety on construction sites (Bogue, 2016).

The use of digital supply chain management ensures smoother project execution by integrating Industry 4.0 technologies to automate processes, reduce delays, and lower costs (Hofmann & Rüsch, 2017). Similarly, 5G networks provide the high-speed connectivity needed for real-time data transmission and collaboration on construction projects (Liu et al., 2020). Mobile and cloud computing allow for project management and collaboration, even in remote areas, providing teams with access to real-time data and updates (Turk & Klinc, 2017).

For a successful transition to Industry 4.0, employee training is critical. Providing workers with the necessary skills to operate advanced technologies like AI, robotics, and big data analytics ensures that companies can fully realize the benefits of these innovations (Nascimento et al., 2019). The importance of budget allocation for the adoption and maintenance of Industry 4.0 technologies cannot be overstated, as this ensures the procurement and smooth implementation of necessary tools (Latan et al., 2021). Additionally, secure industrial practices are vital to protecting the vast amount of data and digital systems associated with Industry 4.0 technologies, ensuring cybersecurity and system integrity (Seuring et al., 2019).

Finally, additive manufacturing, also known as 3D printing, has a profound impact on construction processes by enabling the precise creation of complex structures while minimizing waste (Menegon & Isatto, 2023). The use of big data analytics helps in processing large amounts of data generated by these technologies, aiding decision-making and process optimization (Jha, 2022). Blockchain technology further secures transaction and contract management, ensuring data integrity and trust among all stakeholders involved (Yap et al., 2021).

Standardization and planning are essential to ensure efficient resource usage and reduce environmental impacts, while the capability and experience of contractors are crucial for effectively managing the integration of complex construction technologies (Norouzi et al., 2021; Wuni & Shen, 2020). Engaging high management early in the adoption process ensures that organizations secure the commitment and resources needed for successful implementation, while maintaining a well-trained and adaptable workforce through continuous training is indispensable for keeping up with technological advancements

(Leesakul et al., 2022). Additionally, effective site management and supply chain management optimize construction activities and ensure that materials are available when needed, minimizing project delays (Wuni & Shen, 2020).

The study has identified 35 enablers through systematic literature review that encourage implementation of Industry 4.0 as shown in **Table 1**. The successful integration of Industry 4.0 technologies in the construction industry requires a comprehensive approach that incorporates both organizational and technological enablers. By focusing on these critical enablers, companies in developing countries can overcome barriers to adoption and achieve significant improvements in project management, sustainability, and overall performance. Addressing these enablers will also help in reducing the low adoption rates of Industry 4.0 technologies in residential construction projects in developing nations, thereby enhancing the global competitiveness of the construction industry.

Table 1. Industry 4.0 Enablers in construction Industry

| S.No | Enabler Name | Description | References |
|---|---|---|---|
| 1 | Employer Training with Corporate Ethics | Continuous skill development programs to ensure proficiency in Industry 4.0 technologies while adhering to corporate ethics and safety. | Leesakul et al., 2022; Santos et al., 2020; Nascimento et al., 2019 |
| 2 | Organization Strategic Planning | Aligning organizational goals with Industry 4.0 technologies, such as automation and digital transformation, to enhance competitiveness and project delivery. | Mardani et al., 2018 |
| 3 | Risk-Taking Behavior | Encourages innovative approaches and the adoption of emerging technologies, accepting the associated risks to remain competitive in the evolving | Luthra et al., 2021 |

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| | | market. | |
| 4 | Governmental Regulations | Legal frameworks and regulations that support or hinder the adoption of Industry 4.0 technologies in construction, such as BIM and robotics. | Mahmud et al., 2022 |
| 5 | Rewards and Incentives | Offering incentives (financial or non-financial) to employees and stakeholders to encourage the adoption of advanced technologies. | Khan & Farooq, 2021 |
| 6 | Profitability | Enhancing cost efficiency, productivity, and long-term profitability by adopting Industry 4.0 technologies to reduce construction time and material waste. | Ustundag & Cevikcan, 2018 |
| 7 | Stakeholder Investment | Encouraging stakeholders to invest in smart technologies and digital innovations for sustainable and efficient project outcomes. | Dallasega et al., 2020 |
| 8 | Market Demand | Rising consumer demand for sustainable, high-quality, and faster construction projects drives the need for Industry 4.0 adoption. | Holbert & Garcia, 2020 |
| 9 | Artificial Intelligence (AI) | AI helps automate decision-making, predictive analytics, and project management in construction, improving efficiency and accuracy in project delivery. | Bock & Linner, 2021 |

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| 10 | 3D Printing | Using 3D printing technology to create modular building components, reducing waste and enabling faster project completion in construction. | Wu et al., 2018 |
| 11 | Building Information Modeling (BIM) & Digital Twin | BIM facilitates virtual modeling of buildings, while Digital Twin enables real-time data synchronization for better project monitoring and management. | Eastman et al., 2018 |
| 12 | Internet of Things (IoT) | IoT connects construction equipment and machinery to the internet, allowing real-time data collection and analysis for smart construction projects. | Rose et al., 2020 |
| 13 | Robotics and Automation | Robotics and automation technologies are applied to tasks such as bricklaying, welding, and excavation, improving safety and efficiency. | Bogue, 2021 |
| 14 | Cloud Computing | Cloud-based platforms enable centralized management of construction data, facilitating remote collaboration and real-time updates on project progress. | Zaheer et al., 2019 |
| 15 | Big Data Analytics | Big data enables the processing of vast datasets collected from various sources in construction, aiding in predictive maintenance and decision-making. | Bilal et al., 2016; Jha, 2022 |
| 16 | Cyber-Physical Systems (CPS) | CPS integrates physical construction processes with digital | Trentesaux et al., 2019 |

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| | | systems, allowing for real-time monitoring, autonomous decision-making, and remote operations. | |
| 17 | Augmented Reality (AR) and Virtual Reality (VR) | AR and VR provide enhanced visualization for construction projects, facilitating design validation, safety training, and collaboration among stakeholders. | Wang et al., 2020 |
| 18 | Blockchain Technology | Blockchain ensures transparency and security in the construction supply chain by enabling secure data sharing, contract management, and transaction tracking. | Li et al., 2021; Yap et al., 2021 |
| 19 | Simulation Models | Simulation tools are used to test construction processes and project designs in a virtual environment to optimize performance before implementation. | Jupp et al., 2020 |
| 20 | Smart Sensors | Smart sensors monitor environmental conditions, material performance, and structural health in real-time, leading to more responsive and adaptive construction. | Anil et al., 2018 |
| 21 | Drones (Unmanned Aerial Vehicles) | Drones are used for surveying, site monitoring, and inspection, offering enhanced accuracy and safety in construction operations. | Irizarry et al., 2019 |
| 22 | Wearable Technology | Wearables such as smart helmets and vests monitor workers' health, enhance safety, and provide real- | Teizer et al., 2017 |

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| | | time communication on construction sites. | |
| 23 | Self-Healing Materials | Advanced materials capable of autonomously repairing damage, extending the lifespan of structures and reducing maintenance costs in construction. | De Belie et al., 2020 |
| 24 | Digital Supply Chain Management | Integrating Industry 4.0 technologies to streamline the supply chain, improving efficiency, reducing delays, and lowering costs through automation and data integration. | Hofmann & Rüsch, 2017 |
| 25 | Collaborative Robots (Cobots) | Cobots work alongside human workers to improve precision, productivity, and safety in construction tasks such as material handling and assembly. | Bogue, 2016 |
| 26 | Mobile and Cloud Computing | Cloud and mobile computing facilitate real-time collaboration, data access, and project management in construction, even in remote areas. | Turk & Klinc, 2017 |
| 27 | 5G Networks | The implementation of 5G networks enables faster communication, real-time data transmission, and connectivity on construction sites, boosting productivity. | Liu et al., 2020 |
| 28 | Integrated Industrial Systems | The seamless integration of industrial systems is essential for the efficient functioning of | Devi et al., 2021 |

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| | | Industry 4.0 technologies in construction. | |
| 29 | Budget Allocation for Industry 4.0 | Allocating a dedicated budget to support the adoption of Industry 4.0 technologies is critical for procurement, implementation, and maintenance. | Latan et al., 2021 |
| 30 | Secure Industrial Practices | Ensuring the security of industrial practices is essential to protect data and systems associated with Industry 4.0 technologies. | Seuring et al., 2019 |
| 31 | Additive Manufacturing | Additive manufacturing, or 3D printing, enables the creation of complex structures with high precision, reducing material waste and accelerating construction processes. | Menegon & Isatto, 2023 |
| 32 | Standardization and Planning | Developing standardized processes and effective planning systems is crucial for the efficient use of resources and the reduction of environmental impacts in construction. | Norouzi et al., 2021 |
| 33 | Contractor Capability and Experience | The capability and experience of contractors are key to the successful implementation of Industry 4.0 technologies, managing complex construction technologies effectively. | Wuni & Shen, 2020 |
| 34 | Early Engagement of High Management | Involving senior management early in Industry 4.0 adoption is essential for securing commitment | Wuni & Shen, 2020 |

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| | | and resources needed for successful implementation. | |
| 35 | Site Management and Supply Chain Management | Effective site and supply chain management optimizes construction activities, minimizes delays, and ensures material availability for smooth execution. | Wuni & Shen, 2020 |

**2.2 Industry 4.0 Barriers**

The adoption of Industry 4.0 technologies in the construction industry faces several significant barriers. These barriers can be categorized into financial, technological, regulatory, organizational, and market-related challenges, each of which poses unique obstacles to the successful integration and implementation of advanced technologies. **Table 2** illustrates summary of 36 Industry 4.0 barriers in construction industry identified through systematic literature review."

One of the prominent barriers highlighted is the **high initial investment** required, which can particularly deter smaller firms with limited financial resources (Kamarudin et al., 2019). This investment often comes with **uncertain returns**, leading to reluctance among firms to commit to long-term technological advancements (Olsson et al., 2021). Compounding this issue is the **lack of funding** available for many construction companies, further limiting their ability to implement these new technologies (Hartmann & Fischer, 2018).

**Cost-benefit analysis challenges** also affect decision-making as construction firms struggle to assess the long-term value of these technologies (Spaan & Abraham, 2023). Moreover, the **complexity of Industry 4.0 technologies** creates a significant barrier, as firms may find it difficult to understand and effectively implement these innovations (Kumar et al., 2021). Additionally, the absence of **universal standards and protocols** within the construction industry further complicates integration (Nagy et al., 2021).

**Data management and security** issues arise due to the large volumes of data generated by Industry 4.0 technologies, raising concerns over securing this data (Jayaraman et al., 2018). Meanwhile, the **skill gaps and training needs** for managing and implementing these technologies pose a significant challenge for firms lacking in-house expertise (Kamarudin et al., 2019). In terms of legal considerations, **privacy regulations** and **safety and liability concerns** can delay technological adoption due to stringent regulatory requirements (Hartmann & Fischer, 2018; Spaan & Abraham, 2023).

Furthermore, **ethical and social implications**, such as job displacement due to automation, also create hesitancy in adopting these advanced technologies (Olsson et al., 2021). Meanwhile, **poor tax rebates** and a **lack of leadership and vision** within firms hinder the drive for innovation (Kumar et al., 2021; Nagy et al., 2021). Resistance to change is a recurring theme in many conservative industries like construction, making the adoption of Industry 4.0 even more difficult (Jayaraman et al., 2018).

**Market fragmentation**, particularly with small and medium-sized enterprises (SMEs), and **limited customer awareness** further contribute to the slow pace of technological diffusion (Spaan & Abraham, 2023; Olsson et al., 2021). Challenges such as **vendor lock-in** and **market volatility** also limit flexibility and investment potential (Hartmann & Fischer, 2018; Nagy et al., 2021). Integrating new technologies with **legacy systems** remains a significant technical challenge, as many firms continue to rely on outdated systems (Amiri et al., 2022). Additionally, the risk of **cybersecurity threats** remains high, particularly as digital infrastructures expand (Jayaraman et al., 2018).

**Regulatory compliance** and **interoperability issues** also serve as substantial barriers, with firms struggling to navigate complex regulations and integrate diverse systems (Kamarudin et al., 2019; Olsson et al., 2021). **Cultural resistance** and **lack of collaboration** in the supply chain exacerbate the challenge of industry-wide technological integration (Hartmann & Fischer, 2018; Spaan & Abraham, 2023).

Other barriers include **insufficient government support** in terms of policies and incentives (Kumar et al., 2021), as well as **infrastructure limitations** in underdeveloped areas (Rao et al., 2020). The **aging workforce** and the **limited R&D** in the construction industry slow down technological adoption (Zhang et al., 2022; Olsson & Spaan, 2021). Finally, issues such as **lack of pilot projects**, **environmental and sustainability**

**concerns**, and **digital twins expertise** further complicate the implementation of Industry 4.0 (Hartmann & Fischer, 2018; Kamarudin et al., 2019; Amiri et al., 2022).

Table 2. Industry 4.0 Barriers in construction industry

| S.No. | Barrier Name | Description | References |
|---|---|---|---|
| 1 | High Initial Investment | Significant capital is required for the implementation of Industry 4.0 technologies, which can be a deterrent for smaller firms with limited budgets. | Kamarudin et al., 2019 |
| 2 | Uncertain Return on Investment | There is uncertainty about the return on investment (ROI) for Industry 4.0, making firms reluctant to commit to long-term investments. | Olsson et al., 2021 |
| 3 | Lack of Funding | Many construction companies lack the necessary financial resources to invest in new technologies required for Industry 4.0. | Hartmann & Fischer, 2018 |
| 4 | Cost-Benefit Analysis Challenges | Difficulty in accurately assessing the cost-benefit ratio of Industry 4.0 technologies, which affects decision-making processes. | Spaan & Abraham, 2023 |
| 5 | Complexity of Technologies | The high complexity of Industry 4.0 technologies poses a significant challenge for construction firms in terms of understanding and implementation. | Kumar et al., 2021 |

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| 6 | Poor Standards and Protocols | The absence of universal standards and protocols in the construction sector makes it difficult to integrate Industry 4.0 technologies. | Nagy et al., 2021 |
| 7 | Data Management and Security | Managing and securing the large volumes of data generated by Industry 4.0 technologies is a concern for construction firms. | Jayaraman et al., 2018 |
| 8 | Skill Gaps and Training Needs | There is a lack of skilled personnel to effectively implement and manage Industry 4.0 technologies in the construction sector. | Kamarudin et al., 2019 |
| 9 | Privacy Regulations | Compliance with stringent privacy regulations can complicate the adoption of digital technologies. | Hartmann & Fischer, 2018 |
| 10 | Safety and Liability Regulations | Complex safety and liability regulations in the construction industry can delay the implementation of advanced technologies. | Spaan & Abraham, 2023 |
| 11 | Ethical and Social Implications | The potential ethical and social consequences of automation and job displacement create hesitancy in adopting Industry 4.0. | Olsson et al., 2021 |
| 12 | Poor Tax Rebates | Inadequate tax incentives or rebates from the government for firms adopting new technologies further hinder investment. | Kumar et al., 2021 |
| 13 | Lack of Leadership and Vision | The absence of strong leadership and a clear vision for the future of | Nagy et al., 2021 |

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| | | technology in construction firms limits the adoption of Industry 4.0. | |
| 14 | Resistant to Change | Resistance to change, especially in traditionally conservative industries like construction, poses a barrier to technological adoption. | Jayaraman et al., 2018 |
| 15 | Short-Term Focus and Risk Aversion | The industry's focus on short-term gains and aversion to risk discourages investment in long-term technological advancements. | Hartmann & Fischer, 2018 |
| 16 | Lack of Performance Measures | Construction firms face difficulty in defining and measuring the performance indicators for Industry 4.0 technologies, complicating decision-making. | Kamarudin et al., 2019 |
| 17 | Market Fragmentation | The fragmentation of the construction market, with many small and medium-sized enterprises (SMEs), makes it difficult to achieve uniform technological adoption. | Spaan & Abraham, 2023 |
| 18 | Limited Customer Awareness | A lack of awareness among customers about the potential benefits of Industry 4.0 technologies reduces demand and pressure for adoption by construction firms. | Olsson et al., 2021 |
| 19 | Vendor Lock-In | Dependency on a specific vendor for technological solutions can limit the flexibility and scalability of Industry 4.0 implementations. | Hartmann & Fischer, 2018 |

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| 20 | Market Volatility | The construction industry is highly sensitive to market fluctuations, which makes firms reluctant to invest in new technologies during uncertain economic times. | Nagy et al., 2021 |
| 21 | Integration with Legacy Systems | Many construction companies rely on outdated legacy systems, making it challenging to integrate new Industry 4.0 technologies without disrupting current operations. | Amiri et al., 2022 |
| 22 | Cybersecurity Threats | Industry 4.0 technologies increase the exposure to cyberattacks, and the lack of cybersecurity measures in the construction sector poses a significant barrier. | Jayaraman et al., 2018 |
| 23 | Regulatory Compliance | Compliance with various governmental and industry-specific regulations can make the adoption of new technologies in the construction sector cumbersome. | Kamarudin et al., 2019 |
| 24 | Interoperability Issues | A lack of interoperability between different systems and devices in construction makes it difficult to seamlessly adopt Industry 4.0 technologies. | Olsson et al., 2021 |
| 25 | Cultural Resistance | Organizational culture, especially in traditional construction firms, often resists the adoption of | Hartmann & Fischer, 2018 |

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| | | innovative technologies due to fear of change. | |
| 26 | Lack of Collaboration in Supply Chain | The fragmented nature of the construction industry supply chain leads to difficulties in collaborative adoption of Industry 4.0 technologies across partners. | Spaan & Abraham, 2023 |
| 27 | Insufficient Government Support | Limited government incentives, policies, or funding for the construction sector in adopting Industry 4.0 technologies further slows down the transformation. | Kumar et al., 2021 |
| 28 | Infrastructure Limitations | The need for a robust technological infrastructure is a key challenge in adopting Industry 4.0 technologies, especially in remote or underdeveloped areas. | Rao et al., 2020 |
| 29 | Workforce Aging | The aging workforce in the construction industry presents a challenge, as older workers may be less inclined to adopt new digital tools and technologies. | Zhang et al., 2022 |
| 30 | Limited R&D in Construction Sector | The construction sector has traditionally lagged behind other industries in terms of research and development (R&D), affecting the pace of technological innovation. | Olsson & Spaan, 2021 |
| 31 | Lack of Pilot Projects | A shortage of successful pilot projects in Industry 4.0 technologies in construction | Hartmann & Fischer, 2018 |

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| | | makes it difficult for companies to evaluate potential benefits. | |
| 32 | Environmental and Sustainability Concerns | Integrating Industry 4.0 technologies while adhering to environmental regulations and sustainable practices is a challenge for construction firms. | Kamarudin et al., 2019 |
| 33 | Lack of Digital Twins Expertise | Digital twins, which are essential for Industry 4.0, require specialized knowledge and expertise, which many construction firms currently lack. | Amiri et al., 2022 |
| 34 | Stakeholder Reluctance | Some stakeholders in construction projects are hesitant to invest in Industry 4.0 technologies due to perceived risks and uncertainties. | Kumar et al., 2021 |
| 35 | Supply Chain Disruption Risk | The integration of digital technologies can lead to disruptions in traditional supply chains, creating resistance from suppliers and partners. | Spaan & Abraham, 2023 |
| 36 | Difficulty in Measuring ROI | Firms often struggle to measure the long-term return on investment for Industry 4.0 technologies, leading to delays in adoption. | Olsson & Spaan, 2021 |

### 2.3 Industry 4.0 Challenges and Opportunities

The construction industry is "undergoing a profound transformation driven by the adoption of advanced technologies. These technologies, often associated with Industry 4.0, offer the potential to enhance efficiency, safety, and overall productivity in construction projects. However, their implementation is not without challenges. This chapter provides a detailed examination of various technologies currently being integrated into the construction industry, discussing their meanings, associated challenges, and opportunities for improvement. The discussion is supported by relevant literature, providing a comprehensive overview of each technology's role in modern construction practices. **Table 3** illustrates summary of Industry 4.0 challenges and opportunities associated with various Industry 4.0 technologies.

Supervised machine learning (SML) represents an advanced facet of machine learning where algorithms are trained on labeled datasets to develop predictive models that can solve complex problems. In the construction industry, SML can significantly enhance decision-making processes, particularly in managing complex datasets and nonlinear equations. As noted by Rawson and Brito (2023) and Baduge et al. (2022), SML offers improved accuracy and safety by enabling real-time analysis of construction activities. However, the deployment of SML is hampered by challenges such as the availability of appropriate datasets and the need for robust frameworks to ensure transparency in outcomes (Mirzaei et al., 2022; Xu et al., 2021). Blockchain technology is increasingly recognized as a secure digital ledger for storing and sharing data across networks. In construction, blockchain offers a trusted platform for data sharing, which is crucial for the efficient operation of digital technologies that rely on large datasets (Chen et al., 2023). Despite its potential, blockchain faces challenges related to data manipulation, transparency, and security, which can undermine the trust in transactions (Wu et al., 2023; Kang et al., 2022). Nevertheless, the technology remains a promising solution for improving data management and enhancing the overall transparency of construction operations (Teisserenc & Sepasgozar, 2021). Sensors are technological devices designed to collect data and trigger remedial actions based on the information gathered. They play a critical role in monitoring construction activities, offering real-time analysis that ensures safety and efficiency on construction sites (Rosário & Dias, 2023). However, the effective use of sensors depends on the accuracy and reliability of the data collected. Challenges include the need for physical contact with objects and the potential for technical glitches, which can lead to incorrect decisions (Fugate & Alzraiee, 2023). Despite these challenges, sensors are integral to enhancing construction monitoring and decision-making processes

(Rao et al., 2022; Nogueira et al., 2019). Smart industrial robots, which combine manipulators, sensors, and control systems, are increasingly used in construction to automate complex tasks. These robots are capable of learning and making decisions in dynamic environments, offering significant opportunities for market exploration and improved operational efficiency (Arents & Greitans, 2022). However, their implementation is constrained by the lack of skilled operators, operational accuracy issues, and the inherent risks associated with robot-human interactions (Dörfler et al., 2022). As noted by Zhu et al. (2021), addressing these challenges requires a concerted effort to enhance the credibility and safety of robotic systems in construction (Turner et al., 2020). Digital twin technology involves creating a virtual replica of a physical environment or object to analyze its performance in real time. In construction, digital twins are valuable for planning, resource management, and maintenance, as they provide a comprehensive view of project progress and performance (Honghong et al., 2023). However, the adoption of digital twins is often limited by technical resource inefficiencies, security concerns, and the high costs associated with application and skill development (Sanabria et al., 2022; Teisserenc & Sepasgozar, 2021). Despite these barriers, digital twins offer a promising avenue for improving project lifecycle management and operational safety (Brum et al., 2021; Hou et al., 2020).

Building Information Modeling (BIM) is an automated platform that integrates various data related to construction projects throughout their lifecycle. BIM enables better visualization, simulation, and coordination of construction processes, making it an essential tool for modern project management (Honghong et al., 2023). However, BIM implementation faces challenges such as insufficient data availability, information misinterpretation, and unexpected complications that can arise during the project's execution (Porwal et al., 2023; Khoshfetrat et al., 2022). Nonetheless, BIM remains a powerful tool for improving construction outcomes by integrating critical project data, such as geometry, material specifications, and cost estimates (Lee et al., 2021; Hoang et al., 2020; Craveiro et al., 2019). Drones, or Unmanned Aerial Vehicles (UAVs), are increasingly used in construction for site monitoring, inspection, surveying, and maintenance. These devices offer real-time insights into construction progress, enhancing safety and efficiency while reducing operational costs (Albeaino et al., 2022). However, the use of drones is not without risks, including the potential for accidents and damage during operations, especially in challenging environments or at greater heights (Adepoju et al., 2022). Additionally, technological constraints and airspace regulations can limit the effective deployment of drones in construction projects (Outay et al., 2020; Kas & Johnson, 2019). Exoskeletons are robotic devices designed to enhance human strength, allowing construction workers to lift heavy loads with significantly reduced effort. These devices have the potential to prevent injuries and improve safety on construction sites (Nnaji et al., 2023). However, the continuous use of exoskeletons can lead to muscle-related injuries, particularly if not properly managed or if workers are required to exert extreme effort for prolonged periods (Mahmud et al., 2022). Despite these concerns, exoskeletons represent a significant advancement in reducing the physical strain on workers and improving overall site safety (Okpala et al., 2022; Salvadore et al., 2019).

Augmented Reality (AR) technology enables the creation of virtual environments that mirror real-world settings, allowing for enhanced visualization and planning in construction projects. AR is particularly useful for designing complex structures and managing risks through real-time information (Kolaei et al., 2022). However, the development and implementation of AR frameworks can be challenging, particularly when dealing with intricate designs and data integration (Oke et al., 2022). Despite these challenges, AR offers significant opportunities for improving project documentation, monitoring, and overall performance (Alirezaei et al., 2022; Bademosi et al., 2019; Castronovo et al., 2018). Big Data refers to the large volumes of data generated and collected during construction projects. This data can be analyzed to improve safety, reduce waste, and enhance quality standards on construction sites (Jiang et al., 2023). However, the integration of data from various machinery and processing devices can be complex, often leading to unpredictable and substandard outputs (Munawar et al., 2022). Nevertheless, the effective use of Big Data can support the development of future strategies, ensuring more informed decision-making and improved project outcomes (Shooshtarian et al., 2022; Lezoche et al., 2020; Lu et al., 2018). 3D Printing technology involves the creation of physical objects by layering materials using specialized printers. In construction, 3D printing offers the potential for faster project completion, reduced waste, and enhanced design capabilities (Salazar et al., 2023). However, the adoption of 3D printing is often limited by the absence of automated business frameworks and operational constraints (Kazemian et al., 2022). Despite these limitations, 3D printing remains a promising technology for improving construction processes by ensuring design reliability and reducing risks through early-stage design verification (Buchanan & Gardner, 2019; Ngo et al., 2018). Artificial Intelligence (AI) in construction involves the use of computers to recognize patterns, process data, and develop solutions in real-time. AI has the potential to revolutionize construction by improving planning, cost estimation, waste reduction, and risk assessment (Saka et al., 2023). However, challenges such as data storage, cleaning, and handling in an integrated form can hinder the effective deployment of AI (Baduge et al., 2022). Nonetheless, AI continues to offer significant opportunities for enhancing project efficiency and reducing operational risks (Regona et al., 2022; Abioye et al., 2021; Winsun, 2016).

The adoption of advanced technologies in the construction industry presents both significant opportunities and formidable challenges. While these technologies have the potential to enhance efficiency, safety, and overall project outcomes, their implementation is often hindered by technical, operational, and regulatory barriers. Addressing these challenges requires a concerted effort from industry stakeholders to develop robust frameworks, improve skills, and ensure the availability of reliable data. As the industry continues to evolve, the successful integration of these technologies will be critical to achieving sustainable growth and competitiveness in the global construction

Table 3 Industry 4.0 challenges and opportunities

| S.No. | Technology | Meaning | Challenges | Opportunities | References |
|---|---|---|---|---|---|
| 1 | Supervised machine learning | Advanced version of machine learning where machines are upskilled with suitable set of data to develop and | Presence of appropriate datasets, framework and outcome assessment methods to ensure transparency | Capability of dealing complex datasets and non linear equations, Enhances safety and accuracy in decision | Rawson and Brito, 2023; Baduge *et al.*, 2022; Mirzaei *et al.*, 2022; Xu *et al.* 2021 |

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| | | design output solutions | | process using real time analysis | |
| 2 | Blockchain | Digital register for storing data that can be shared via network | Data shared are on risk of manipulation creating issues of transparency, safety and privacy related to transactions | Most trusted system for data sharing so huge data can be shared and stored for effective operation of further digital technologies based on datasets | Chen *et al*., 2023; Wu *et al*., 2023; Kang *et al*., 2022; Teisserenc and sepasgozar, 2021 |
| 3 | Sensors | technological based devices established to gather data and initiate remedial application effectively | Analysis and effective implementation of data depends on physical contact of object, however, lack of appropriate data, technical glitches can result in incorrect decision | Capable of monitoring construction activities, real time analysis and mapping, ensuring safety and efficiency | Rosário and Dias, 2023; Fugate and Alzraiee, 2023; Rao *et al.,* 2022; Nogueira *et al.,* 2019 |
| 4 | Smart Industrial Robot | Intelligent industrial robots, which combine a manipulator, sensors, and | Absence of skills, operational accuracy and credibility, danger of accidents that requires human | Capable of investigating potential markets and methods to absorb market factors and | Arents and Greitans, 2022; Dörfler *et al*., 2022; Zhu *et al*., 2021; |

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| | | controls, are smart industrial robots. | judgment and intervention | master in decision making and learning in dynamic challenges | Turner *et al.*, 2020 |
| 5 | Digital Twin | Duplicate of the real environment or object to analyze real time operation and performance | Inefficient technical resources, security issues, poor standards, High application cost and skills in construction creates hindrance in improving project lifecycle | Capable of performing real time analysis of progress ensuring safety and standards, planning for resources and maintenance | Honghong *et al.,* 2023; Sanabria *et al.*, 2022; Teisserenc and sepasgozar, 2021; Brum *et al.*, 2021; Hou *et al.*, 2020 |
| 6 | Building Information Modeling (BIM) | Automated platform that uses various virtualization and simulation methods to combine information relevant to construction during project's life cycle. | Insufficient availability of data , Information misinterpretation, unpredicted complications | Integrate data related to projects like geometry, material specification, structure design, output and cost of production | Honghong *et al.,* 2023; Porwal *et al.*, 2023; Khoshfetrat *et al.*, 2022; Lee *et al.*, 2021; Hoang *et al.*, 2020; Craveiro *et al.*, 2019 |
| 7 | Drones/UAVs | Teleoperated devices similar to mini aircraft | Risk involved in operations and danger of accidents or damage in space or greater heights, Constraints of technology and airspace norms | Real time monitoring of site work, Inspection, surveying and maintenance with cost effectiveness and safety | Albeaino *et al.*, 2022; Adepoju *et al.*, 2022; Outay *et al.*, 2020; Kas and Johnson *et al.*, 2019 |

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| 8 | Exoskeletons | Robotic device which on wearing boosts human power 20 times | Muscle related Injuries on construction sites due to continuous operations of extreme efforts | Aids in uplifting heavy loaded infrastructure on construction sites to eliminate serious accidents and injuries | Nnaji *et al.*, 2023; Mahmud *et al.*, 2022; Okpala *et al.*, 2022; Salvadore *et al.*, 2019 |
| 9 | Augmented Reality | Developing virtual surroundings of the real environment | Designing framework of complex structures in virtual form instead of conventional method and equipment through data collection and implementation | Capable of improving performance through effective documentation and monitoring, managing risk through real time information | Kolaei *et al.*, 2022; Oke *et al.*, 2022; Alirezaei *et al.*, 2022; Bademosi *et al.*, 2019; Castronovo *et al.*, 2018 |
| 10 | Big Data | Huge construction data gathering and storing | Disintegration of data from machinery and processing devices resulting in unpredictable and substandard outputs | Significantly ensures safety on construction sites, waste minimization, Improving quality standards, | Jiang et al., 2023; Munawar *et al.*, 2022; Shooshtarian *et al.*, 2022; Lezoche *et al.*, 2020; |

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| | | | | data collection and support for developing future strategies | Lu *et al*., 2018 |
| 11 | 3D Printing | Designing of products by continuous addition of layers through specialized printers | Limited automated business frameworks and operations | Aids in faster construction, limiting waste, design enhancement, ensuring process reliability and reducing risks through design verification | Salazar *et al*., 2023; Kazemian *et al*., 2022; Buchanan and Gardner, 2019; Ngo *et al*., 2018 |
| 12 | Artificial Intelligence (AI) | computers absorbing and recognizing operations for developing solutions in real time | Difficulties in storing, cleaning and handling of data in integrated form to execute remedial steps in real time | Promote Highly efficient planning and designing of project in terms of event occurrence, cost estimation, waste reduction and risk assessment | Saka *et al*., 2023; Baduge *et al*., 2022; Regona *et al*., 2022; Abioye *et al*., 2021; Winsun, 2016 |

## 2.4 Industry 4.0 Impacts in achieving sustainability

Industry 4.0 encompasses a wide range of advanced technologies that are revolutionizing the construction industry, with significant implications for sustainability. These technologies, such as supervised machine learning, blockchain, sensors, smart industrial robots, digital twins, and more, contribute to the achievement of the triple bottom line—social, economic, and environmental sustainability—by enhancing decision-making processes, reducing costs, and minimizing environmental impacts.

Sustainability refers to the development and implementation of strategies that meet current needs without compromising the ability of future generations to meet their own needs. It encompasses three interconnected dimensions: social, economic, and environmental. These dimensions are often represented as the triple bottom line (TBL), a framework that encourages businesses and organizations to consider the broader impact of their operations.

a) **Social Sustainability** focuses on maintaining and improving the well-being of individuals and communities. It involves ensuring fair labor practices, promoting health and safety, and supporting equitable access to resources and opportunities (Elkington, 1997; Sachs, 2015).
b) **Economic Sustainability** emphasizes the efficient and responsible use of resources to ensure long-term financial stability and economic growth. It involves cost-effective operations, financial transparency, and the creation of value for stakeholders, including customers, employees, and shareholders (Savitz & Weber, 2013; Schaltegger et al., 2017).
c) **Environmental Sustainability** is concerned with minimizing negative impacts on the environment. It involves the responsible use of natural resources, reducing carbon footprints, preventing pollution, and promoting biodiversity and ecosystem health (Bansal & DesJardine, 2014; Adams et al., 2016).

The integration of Industry 4.0 technologies into the construction industry supports the achievement of the triple bottom line by enabling more efficient, cost-effective, and environmentally friendly practices.” These technologies help organizations to balance social, economic, and environmental objectives, leading to more sustainable and resilient business models (Elkington, 1997; Savitz & Weber, 2013). **Table 4** illustrates summary of Industry 4.0 technologies impacts on social, economic and environment dimensions in achieving sustainability. **Supervised Machine Learning** plays a critical role in real-time data analysis, enabling better decision-making that improves societal well-being and individual lifestyles. Economically, it aids in the reduction of direct and indirect costs, resource management, and the reliability of supply chains through accurate cost estimation. Environmentally, it helps in reducing waste generation, developing climate change strategies, and fostering sustainable development while addressing the rebound effect on the environment (Lakhouit et al., 2023; Shinde et al., 2022; Shoar et al., 2022; Sharma et al., 2020). **Blockchain technology** enhances transparency and collaboration among stakeholders, ensuring data reliability and the efficient handling of hazardous materials. This results in reduced overhead costs and improved circular economy practices. Environmentally, blockchain supports the use of reusable and recyclable materials, contributing to effective waste management and sustainable building design (Elghaish et al., 2023; Figueiredo et al., 2022; Woo et al., 2021; Teisserenc & Sepasgozar, 2021). **Sensors** are increasingly used to prevent ergonomic injuries and monitor environmental health factors, thus contributing to social sustainability by protecting workers and communities. Economically, sensors are crucial in pollutant monitoring, particularly on construction sites, where they detect harmful contaminants, thereby playing a significant role in sustainable development (Xu et al., 2022; Fokaides et al., 2020; Santos et al., 2019; Ahmad et al., 2016). **Smart Industrial Robots** enhance the quality of work and reduce human risk in construction by enabling human-robot collaboration. These robots improve economic efficiency by reducing labor costs, minimizing resource waste, and streamlining supply chain operations. From an environmental perspective, they support the implementation of green technologies, contributing to the reduction of carbon emissions (Wang et al., 2023; Li et al., 2022; Dzedzickis et al., 2021). **Digital Twins** improve societal well-being by optimizing designs that reduce carbon emissions and mitigate greenhouse effects. Economically, digital twins eliminate resource, time, and environmental challenges through pre-analysis of product designs, leading to intelligent and sustainable green structures (Yang et al., 2022; Sepasgozar, 2021; Teisserenc & Sepasgozar, 2021; Fokaides et al., 2020). **Building Information Modeling (BIM)** enhances workplace safety through rigorous safety analysis, supports population stability by identifying suitable construction sites, and improves economic outcomes by increasing productivity, reducing waste, and ensuring timely project delivery. Environmentally, BIM helps in energy management, reducing carbon emissions, conserving resources, and improving waste management (Verdaguer et al., 2023; Sahu et al., 2023; Filho et al., 2022; Norouzi et al., 2021; Panteli et al., 2021; Slivkova et al., 2020; Lekan et al., 2020; Ghosh et al., 2020). **Drones and UAVs** have economic advantages as cost-effective technical systems, although their social and regulatory measures for safe operation are still lacking. Environmentally, they are instrumental in using additional cameras and sensors to monitor and address various environmental challenges (Lima et al., 2022; Mahroof et al., 2021; Jeelani & Gheisari, 2021). **Exoskeletons** minimize workplace injuries and ensure the health and safety of workers. Economically, they optimize the cost of training and skilled manpower, while environmentally, they facilitate the implementation of complex architectural designs and enhance risk management, contributing to sustainable regeneration and the lifecycle of projects (Labò et al., 2023; Vita et al., 2022; Brum et al., 2021; Bellini, 2020). **Augmented Reality (AR)** supports employee training and reduces workplace risks, leading to financial optimization through virtual resource management. Environmentally, AR helps in preventing resource wastage, reducing accidental disasters, and implementing sustainable strategies through pre-visualization of the project environment (Senanayake et al., 2023; Franco et al., 2022; Rodrigues, 2021; Delgado et al., 2020; Ahmed, 2019). **Big Data** is crucial for efficient project management, reliable supply chains, and smooth financial operations. Economically, big data provides competitive business advantages, while environmentally, it tracks, analyzes, and controls the impacts of ongoing construction activities, supporting the formulation of sustainable strategies (Woo et al., 2023; Yevu et al., 2021; Choi et al., 2021; Sivarajah et al., 2017; Wong & Zhou, 2015). **3D Printing** offers “economical and affordable housing by enabling mass customization, quick deployment, and reduced construction costs. It also minimizes waste through material planning and limited transportation, contributing to the circular economy. Environmentally, 3D printing supports the use of reusable and green materials, waste reduction, and efficient resource planning, thereby easing the environmental burden (Gopal et al., 2023; Ibrahim et al., 2022; Caldona et al., 2022; Žujović et al., 2022; Volpe et al., 2021; Aghimien et al., 2021; Akyazi et al., 2020; Tahmasebinia et al., 2020). **Artificial Intelligence (AI)** enhances social sustainability by improving efficiency, reducing the need for continuous manual labor, and transferring expertise across industries. Economically, AI helps in predicting and mitigating project risks, optimizing costs, and enhancing sustainable strategies, contributing to overall project success and sustainability (Kulejewski & Roslon, 2023; Debrah et al., 2022; Nagy et al., 2021; Choi et al., 2021).

Table 4. **Industry 4.0 Impacts** in achieving sustainability

<table>
<tr><th>S.No.</th><th>Industry 4.0 Technologies</th><th>Social</th><th>Economic</th><th>Environmental</th><th>Reference</th></tr>
<tr><td>1</td><td>supervised machine learning</td><td>Analysis of real time scenario for taking data based decisions for betterment of society and life style of an individual</td><td>Effective decision making algorithms to reduce direct or indirect costs, reliable supply chain and resource management through appropriate cost estimation</td><td>Reduces waste generation, develop strategies for changing climate, sustainable development and tackle rebound effect of environment</td><td>Lakhouit *et al.*, 2023; Shinde *et al.*, 2022; Shoar *et al.*, 2022; Sharma *et al.*, 2020</td></tr>
<tr><td>2</td><td>Blockchain</td><td>Expanded association and clarity between collaborator, Data reliability, building information sharing, monitor and handling of harmful matter</td><td>Limiting down excessive expenses by reducing in competencies and overhead costs, improves circular economy</td><td>Application of reusable and recyclable materials through effective analysis promotes management of waste in lifecycle of project, sustainable building design including resource management</td><td>Elghaish *et al.*, 2023; Figueiredo *et al.*, 2022; Woo *et al.*, 2021; Teisserenc and sepasgozar, 2021</td></tr>
<tr><td>3</td><td>Sensors</td><td>Sensors preventing ergonomic injuries and the discharge of dangerous substances by tracking worker and environmental health factors</td><td colspan="2">Pollutant monitoring systems are gaining popularity since presence of dangerous contaminants on construction sites are rising, therefore, low-cost sensor technology plays a very crucial role</td><td>Xu *et al.*, 2022; Fokaides *et al.*, 2020; Santos *et al.*, 2019; Ahmad *et al.*, 2016</td></tr>
<tr><td>4</td><td>Smart Industrial Robot</td><td>Human robot collaboration enhances quality of work, reduces risk to human life involved in construction, reliable decision making</td><td>Saves cost associated with labor, reduces resource wastage, efficient operations improves supply chain</td><td>Promotes effective implementation of green technologies and reduces carbon emissions</td><td>Wang *et al.*, 2023; Li *et al.*, 2022; Dzedzickis *et al.*, 2021</td></tr>
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| 5 | Digital Twin | Improving quality of life in society by enhancing designs that reduces carbon emissions and greenhouse effect | Elimination of wastage of resources, funds, time and environmental challenges through pre analysis of product design using digital twin technology, Intelligent and smart green structures | | Yang *et al*., 2022; Sepasgozar, 2021; Teisserenc and sepasgozar, 2021; Fokaides *et al*., 2020 |
| 6 | Building Information Modeling (BIM) | Limiting workplace accidents through safety analysis and ensure population stability by suggesting suitable sites of construction | Enhances operations performance and productivity, Reducing wastages, timely delivery of projects, economical housing, cost estimation and schedule management | Evaluate and control energy output, carbon emissions, conserve resources and enhances waste management | Verdaguer *et al*., 2023; Sahu *et al*., 2023; Filho *et al*., 2022; Norouzi *et al*., 2021; Panteli *et al*., 2021; Slivkova *et al*., 2020; Lekan *et al*., 2020; Ghosh *et al*., 2020 |
| 7 | Drones/UAVs | Lack of regulatory and managerial measures for safer operation | Economical technical system | Additional use of cameras and sensors to analyze and address numerous environmental issues | Lima *et al*., 2022; Mahroof *et al*., 2021; Jeelani and Gheisari, 2021 |
| 8 | Exoskeletons | Minimizing organizational tragedies and ensuring health and security | Optimizes cost of training and skilled man power | Makes feasible implementation of complex architectural design, enhances risk management, sustainable regeneration and up gradation life cycle of project | Labò *et al*., 2023; Vita *et al*., 2022; Brum *et al*., 2021; Bellini, 2020 |
| 9 | Augmented Reality | Training employees and reducing workplace risks | Financial optimization of resources and efficient budgeting using virtual framework of future operations | Curtailing wastage of resources, accidental disasters, sustainable strategies through pre virtual realization of environment | Senanayake *et al*., 2023; Franco *et al*., 2022; Rodrigues, 2021; Delgado *et al*., 2020; Ahmed, 2019 |
| 10 | Big Data | Efficient project management, reliable supply chain, smooth financial operations and easily available information to monitor project progress, competitive benefits in business | | Track, Analyze and control effects of ongoing construction and supports in formulating sustainable strategies using data sets | Woo *et al*., 2023; Yevu *et al*., 2021; Choi *et al*., 2021; Sivarajah *et al*., 2017; Wong and Zhou, 2015 |

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| 11 | 3D Printing | Economical and affordable housing | Mass customization and quick deployment, reduces construction cost, no wastage, material planning and limited transportation, improved circular economy | Application of reusable, recyclable and green material, waste reduction and efficient resource planning reduces burden on environment | Gopal *et al*., 2023; Ibrahim *et al*., 2022; Caldona *et al*., 2022; Žujović *et al*., 2022; Volpe *et al*., 2021; Aghimien *et al*., 2021; Akyazi *et al*., 2020; Tahmasebinia *et al*., 2020 |
| 12 | Artificial Intelligence (AI) | Switching from manual to digital improves overall efficiency, hiring continuous labor, and social transferring of expertise from other industries and significant trusted experience of customers | Predict and react to probable risks in project lifecycle, design evaluation, cost optimization, risk elimination, maintenance forecasting and enhancing potential sustainable strategies for construction | | Kulejewski and Roslon, 2023; Debrah *et al*., 2022; Nagy *et al*., 2021; Choi *et al*., 2021 |

### 2.5 Industry 4.0 : Perceived Risks

The adoption of Industry 4.0 technologies in construction industries is hindered by several perceived risks that significantly impact decision-making and implementation processes. Table 5 illustrates summary of 20 perceived risks of Industry 4.0 in construction industry identified through systematic literature review."

One of the major concerns is **cybersecurity risks**, which involve potential threats like data breaches, hacking, and unauthorized access to sensitive project information (Patel et al., 2023; Liu et al., 2019). Alongside this, **data privacy issues** also present a major challenge due to the risks associated with the collection, storage, and management of sensitive and personal data (Liu et al., 2019; Gupta & Jain, 2021). These concerns are amplified by **interoperability challenges**, where companies struggle to integrate new technologies with existing systems and processes, posing operational difficulties (Khosrowshahi & Arayici, 2012).

The complexity of **technological advancements** adds another layer of difficulty, as these technologies demand specialized training and knowledge, resulting in a steep learning curve for employees (Sharma & Sharma, 2022). Moreover, **resistance to change** remains a significant issue, where employees and stakeholders are reluctant to adopt new technologies due to uncertainties about disruptions or potential risks (Kumar et al., 2020; Gupta & Jain, 2021). Additionally, the **lack of a skilled workforce** further complicates the situation, as there is a shortage of professionals capable of operating and managing advanced Industry 4.0 technologies (Kumar et al., 2020; Gupta & Jain, 2021).

**Infrastructure limitations** also contribute to the barriers, as inadequate technological infrastructure in many organizations hinders the effective deployment and integration of Industry 4.0 solutions (Gupta & Jain, 2021; Sharma & Sharma, 2022). This is compounded by the challenges of **compliance with evolving standards**, where organizations struggle to keep pace with rapidly changing regulations and standards related to Industry 4.0 (Khosrowshahi & Arayici, 2012). **Data privacy regulations** further complicate compliance efforts, requiring adherence to strict laws and regulations concerning the protection of sensitive information (Liu et al., 2019; Patel et al., 2023).

Moreover, **safety and liability issues** create additional barriers, as companies must ensure compliance with stringent safety standards while addressing liability concerns (Kumar et al., 2020; Sharma & Sharma, 2022). The **high initial costs** associated with the adoption of Industry 4.0 technologies represent another significant risk, particularly for smaller firms that may struggle to allocate the necessary capital (Patel et al., 2023; Liu et al., 2019). Closely related to this are **cost overruns**, where unforeseen expenses during technology implementation can push projects over budget (Gupta & Jain, 2021). Furthermore, **ROI uncertainty** makes firms hesitant to invest in these technologies, as the long-term return on investment remains unclear (Kumar et al., 2020; Sharma & Sharma, 2022).

Additional risks include **vendor lock-in**, where companies become dependent on specific vendors for technological solutions, limiting flexibility and scalability (Hartmann & Fischer, 2018). **Market volatility** also affects investment decisions, as the construction industry is highly sensitive to market fluctuations, reducing confidence in long-term technological investments (Nagy et al., 2021). Moreover, the **integration of Industry 4.0**

**technologies with legacy systems** can be challenging for firms relying on outdated infrastructure, leading to disruptions (Amiri et al., 2022). **Cybersecurity threats** are another key risk, as the increasing reliance on interconnected systems exposes companies to potential cyberattacks (Jayaraman et al., 2018).

Culturally, there is **resistance within organizations**, especially in traditional industries like construction, where the fear of job displacement and change hampers the adoption of new technologies (Hartmann & Fischer, 2018). Furthermore, **insufficient government support**, such as inadequate incentives, policies, or funding, slows down the transition to Industry 4.0 (Kumar et al., 2021). The **aging workforce** in the construction industry also presents challenges, as older employees may be less inclined to adopt new digital tools and technologies (Zhang et al., 2022).

In conclusion, the adoption of Industry 4.0 technologies is fraught with multiple risks spanning cybersecurity, workforce skills, costs, and compliance issues, making it crucial for organizations to strategize carefully in mitigating these barriers.

Table 5. Perceived Risks of Industry 4.0 in construction

| **S.No.** | **Name of Risk** | **Description** | **Citation** |
|---|---|---|---|
| 1 | Cybersecurity Risks | Threats related to data breaches, hacking, and unauthorized access to sensitive project information. | Patel et al. (2023); Liu et al. (2019) |
| 2 | Data Privacy Issues | Risks associated with the collection, storage, and management of sensitive and personal data. | Liu et al. (2019); Gupta & Jain (2021) |
| 3 | Interoperability Challenges | Difficulties in integrating new technologies with existing systems and processes. | Khosrowshahi & Arayici (2012) |

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| 4 | Technological Complexity | Complexity of new technologies leading to a steep learning curve and increased training requirements. | Sharma & Sharma (2022) |
| 5 | Resistance to Change | Employee and stakeholder resistance to adopting new technologies due to fear of disruption or uncertainty. | Kumar et al. (2020); Gupta & Jain (2021) |
| 6 | Lack of Skilled Workforce | Shortage of skilled professionals capable of operating and managing advanced Industry 4.0 technologies. | Kumar et al. (2020); Gupta & Jain (2021) |
| 7 | Infrastructure Limitations | Inadequate technological infrastructure to support the deployment and integration of Industry 4.0 solutions. | Gupta & Jain (2021); Sharma & Sharma (2022) |
| 8 | Compliance with Evolving Standards | Uncertainty and challenges in adhering to new and evolving regulations and standards for Industry 4.0 technologies. | Khosrowshahi & Arayici (2012) |
| 9 | Data Privacy Regulations | Challenges related to compliance with data privacy laws and regulations. | Liu et al. (2019); Patel et al. (2023) |
| 10 | Safety and Liability Issues | Risks related to ensuring compliance with safety standards and handling liability issues. | Kumar et al. (2020); Sharma & Sharma (2022) |

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| 11 | High Initial Costs | Significant capital investment required for the adoption of Industry 4.0 technologies. | Patel et al. (2023); Liu et al. (2019) |
| 12 | Cost Overruns | Risk of exceeding the budget due to unforeseen expenses related to technology implementation. | Gupta & Jain (2021) |
| 13 | ROI Uncertainty | Uncertainty regarding the return on investment and long-term benefits of adopting new technologies. | Kumar et al. (2020); Sharma & Sharma (2022) |
| 14 | Vendor Lock-In | Dependency on a specific vendor for technological solutions limits flexibility and scalability in Industry 4.0 implementations. | Hartmann & Fischer (2018) |
| 15 | Market Volatility | Industry 4.0 adoption is impacted by the high sensitivity of the construction sector to market fluctuations, limiting technology investments. | Nagy et al. (2021) |
| 16 | Integration with Legacy Systems | Outdated legacy systems in companies make it difficult to integrate new Industry 4.0 technologies without disrupting current operations. | Amiri et al. (2022) |
| 17 | Cybersecurity Threats | Increased exposure to cyberattacks due to greater use of interconnected | Jayaraman et al. (2018) |

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| | | Industry 4.0 technologies. | |
| 18 | Cultural Resistance | Organizational culture, especially in traditional industries, can resist adopting Industry 4.0 technologies due to fear of job loss and change. | Hartmann & Fischer (2018) |
| 19 | Insufficient Government Support | Limited government incentives, policies, or funding for the construction sector in adopting Industry 4.0 technologies slows down the transformation. | Kumar et al. (2021) |
| 20 | Aging Workforce | The aging workforce in the construction sector poses challenges, as older workers may resist adopting new digital tools and technologies. | Zhang et al. (2022) |

### 2.6 Overview of Research Studies on Industry 4.0 in Construction

The integration of Industry 4.0 technologies into the construction industry has brought significant advancements, particularly through Building Information Modeling (BIM) and the Internet of Things (IoT). This section reviews various studies that explore the barriers, benefits, and challenges associated with these technologies. It aims to provide a comprehensive understanding of how these technologies are being adopted and the factors influencing their implementation. Table 6 illustrates Contemporary work of Industry 4.0 technologies in construction industry.

**Nikooravan and Golabchi (2023)** conducted a case study in Iran to explore the barriers associated with BIM in the Architectural, Engineering, and Construction (AEC) industry.

They identified several impediments, including resistance to change, high initial costs, and a lack of skilled personnel. Their qualitative analysis revealed that overcoming these barriers requires targeted strategies and robust support systems (Nikooravan & Golabchi, 2023). **Hall et al. (2023)** performed a literature review combined with the Analytical Hierarchy Process (AHP) in New Zealand. Their study identified several barriers to the adoption of BIM within Small and Medium-sized Enterprises (SMEs), such as limited financial resources and insufficient technical expertise. The study provided a detailed hierarchical framework to prioritize these barriers and suggested potential solutions (Hall et al., 2023). **Hwang et al. (2022)** utilized a comprehensive literature review and pilot interviews in Singapore to examine challenges associated with BIM adoption. They proposed strategies to address these challenges, including enhanced training programs and better stakeholder engagement. Their qualitative data highlighted the importance of organizational perceptions and attitudes towards BIM (Hwang et al., 2022). **Yami and Anibire (2021)** conducted a case study in Saudi Arabia to investigate the benefits and barriers of BIM implementation. Their study concluded that while BIM offers significant benefits, such as improved project coordination and reduced costs, barriers like lack of technical knowledge and high implementation costs remain significant challenges (Yami & Anibire, 2021). **Bajpai and Misra (2022)** employed Fuzzy-DEMATEL and Interpretive Structural Modeling (ISM) in India to analyze critical barriers to BIM adoption. Their mixed-methods approach identified 14 critical barriers, with the most influential being resistance to change and inadequate training. Their model provides a framework for addressing these barriers effectively (Bajpai & Misra, 2022). **Zhou et al. (2021)** proposed an IoT-enabled BIM platform in Hong Kong, focusing on improving decision-making for on-site assembly services. Their qualitative analysis highlighted the potential of IoT to enhance real-time data collection and communication, although challenges such as integration with existing systems and data security need to be addressed (Zhou et al., 2021). **Gamil et al. (2020)** used SPSS Software 22.0 in Malaysia to identify major challenges in the acceptance of IoT in the construction industry. They found that issues such as lack of safety and security, undocumented standards, and inadequate connectivity are major obstacles. Their quantitative analysis provided insights into the technical and operational challenges faced by the industry (Gamil et al., 2020). **Chan et al. (2019)** conducted a structured empirical survey in Hong Kong to examine the benefits and challenges of BIM implementation. Their quantitative data revealed that while BIM offers considerable benefits, such as improved efficiency and accuracy, challenges related to technology adoption and integration persist (Chan et al., 2019). **Mathiyazhagan et al. (2019)** developed a sustainable material assessment model using Fuzzy TOPSIS in India. Their study examined various material selection variables, such as environmental impact and cost, and proposed a model to select the most appropriate materials based on sustainability criteria. Their approach integrates both quantitative and qualitative analyses to enhance decision-making in material selection (Mathiyazhagan et al., 2019). The reviewed studies provide a comprehensive overview of the barriers, benefits, and challenges associated with BIM and IoT technologies in the construction industry. While these technologies offer substantial improvements in "efficiency, safety, and sustainability, their adoption is impeded by various barriers such as high costs, lack of skilled personnel, and integration challenges. Addressing these barriers requires targeted strategies, including improved training, financial support, and enhanced stakeholder engagement.

Table 6 Contemporary work of Industry 4.0 technologies in construction industry

| **S.No.** | **Authors** | **Country** | **Method/ Model/Tool** | **Analysis Type** | **Contribution** |
|---|---|---|---|---|---|
| 1 | Nikooravan and Golabchi, 2023 | Iran | Case study Method | Qualitative data | Examine and analyze various barriers of Building Information Modeling (BIM) in Architectural, Engineering and construction industry |

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| 2 | Hall *et al.*, 2023 | New Zealand | Literature Review and Analytical Hierarchy Process (AHP) | Both quantitative and qualitative | Identified barriers in adoption of Industry 4.0 technology i.e. BIM within SMEs |
| 3 | Hwang *et al.*,2022 | Singapore | comprehensive literature review and pilot interviews | Qualitative data | Examined challenges, propose efficient strategies, investigate perceptions of organizations |
| 4 | Bajpai and Misra, 2022 | India | Fuzzy-DEMATEL and interpretive structural modeling (ISM) | Both quantitative and qualitative | Examined 14 critical barriers and identified most influencing critical barrier |
| 5 | Ogunsanya *et al.*,2022 | Nigeria | exploratory factor analysis | Qualitative data | Examined the barriers of public aided construction in context of sustainable procurement |

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| 6 | Yami and Anibire, 2021 | Saudi Arabia | Case study Method | Qualitative data | Concluded most important benefits and dominating barriers in implementation of BIM in construction Industry |
| 7 | Zhou *et al.,*2021 | Hong Kong | IOT enabled BIM Platform | Qualitative data | Proposed a IOT enabled smart BIM platform to take effective decision for providing on site assembly services on time |
| 8 | Gamil *et al*., 2020 | Malaysia | SPSS Software 22.0 | Quantitative | Identified that absence of safety and security, documented standards, benefit awareness, improper introduction of IOT and robustness in connectivity are major challenges in acceptance of IOT in |

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| | | | | | construction Industry |
| 9 | Chan *et al*., 2019 | Hong Kong | structured empirical survey | Quantitative | Examined the distinguish benefits and challenges in implementation of BIM in construction industry |
| 10 | Mathiyazhagan *et al*., 2019 | India | sustainable material assessment model & Fuzzy TOPSIS | Both quantitative and qualitative | Examined the material selection variables, analyzed them and propose model for selecting most appropriate material in terms of sustainability |
| 11 | Zou et al., 2021 | China | Multi-Criteria Decision-Making (MCDM) | Both quantitative and qualitative | Developed a framework to evaluate the readiness of construction companies for Industry 4.0 technologies, identifying key |

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| | | | | | enablers and barriers. |
| 12 | Sanchez & Roberts, 2020 | United States | Case Study and SWOT Analysis | Qualitative | Investigated blockchain adoption in construction, identifying strengths, weaknesses, opportunities, and threats in its implementation. |
| 13 | Bhattacharya et al., 2022 | India | Structural Equation Modeling (SEM) | Quantitative | Analyzed factors affecting AI adoption in construction and proposed a predictive model for successful AI implementation. |
| 14 | Tomić & Stojanović, 2021 | Serbia | Delphi Technique | Both quantitative and qualitative | Developed a Delphi-based consensus model to prioritize Industry 4.0 technologies for smart construction in Serbia. |

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| 15 | Bui et al., 2020 | Vietnam | Digital Twin and BIM integration | Both quantitative and qualitative | Explored the integration of Digital Twin and BIM for real-time monitoring and predictive maintenance in construction projects. |
| 16 | Jallow et al., 2021 | United Kingdom | System Dynamics Modeling | Quantitative | Developed a system dynamics model to simulate the impact of Industry 4.0 technologies on construction project performance and cost efficiency. |
| 17 | Li & Yang, 2021 | China | Blockchain-enabled BIM | Qualitative | Proposed a blockchain-enabled BIM framework to enhance transparency, data security, and collaboration in |

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| | | | | | construction projects. |
| 18 | Noghabaei et al., 2021 | United States | Augmented Reality (AR) and Virtual Reality (VR) tools | Both quantitative and qualitative | Investigated the use of AR and VR tools for improving safety training and on-site visualization in the construction industry. |
| 19 | Rajak & Vinodh, 2020 | India | Lean Construction and Industry 4.0 integration | Both quantitative and qualitative | Proposed an integrated approach combining lean construction principles with Industry 4.0 technologies to improve efficiency and reduce waste in construction. |
| 20 | Shojaei et al., 2020 | Australia | Geographic Information Systems (GIS) and BIM integration | Qualitative | Examined the integration of GIS and BIM for enhanced urban planning, infrastructure management, and construction site analysis. |

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| 21 | Becerik-Gerber et al., 2020 | United States | Digital Twin and Predictive Analytics | Both quantitative and qualitative | Analyzed the potential of Digital Twins integrated with predictive analytics for optimizing facility management and operational efficiency. |
| 22 | Kumar et al., 2021 | India | Machine Learning and IoT integration | Quantitative | Explored the integration of machine learning algorithms with IoT devices for real-time monitoring and predictive maintenance in construction sites. |
| 23 | Trinh et al., 2021 | Vietnam | Blockchain Technology for Construction Management | Qualitative | Proposed a blockchain-based construction management system to improve transparency, reduce delays, and enhance collaboration |

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| | | | | | among stakeholders. |
| 24 | Wuni & Shen, 2020 | China | Hybrid Simulation Modeling | Both quantitative and qualitative | Developed a hybrid simulation model to assess the impact of adopting Industry 4.0 technologies on project delivery and cost management in construction. |
| 25 | Pagani & Alvisi, 2022 | Italy | Cloud-Based BIM Platform | Qualitative | Investigated the use of cloud-based BIM platforms to enhance collaboration, data sharing, and decision-making processes in the construction industry. |

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| 26 | Pereira et al., 2021 | Portugal | Smart Sensors and IoT | Quantitative | Analyzed the role of smart sensors and IoT in monitoring construction site conditions and improving safety protocols and environmental management. |
| 27 | Dallasega et al., 2020 | Italy | Cyber-Physical Systems (CPS) | Qualitative | Explored the application of Cyber-Physical Systems (CPS) in construction supply chain management, improving real-time communication and decision-making. |
| 28 | Sawhney et al., 2020 | India | 4D BIM and Lean Principles | Both quantitative and qualitative | Integrated 4D BIM with lean construction principles to enhance project scheduling, reduce delays, and improve |

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| | | | | | resource allocation. |
| 29 | Marzouk & Zaher, 2021 | Egypt | BIM-GIS Integration | Qualitative | Examined the integration of BIM and GIS for improving site analysis, environmental impact assessments, and urban infrastructure management in construction. |
| 30 | Gade et al., 2020 | India | Artificial Neural Networks (ANN) | Quantitative | Implemented Artificial Neural Networks (ANN) to predict construction project outcomes, focusing on cost estimation and schedule forecasting. |

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| 31 | Li et al., 2020 | China | Smart Contracts and Blockchain | Qualitative | Investigated the use of smart contracts enabled by blockchain technology to automate and secure payment processes in construction projects. |
| 32 | Parn et al., 2020 | United Kingdom | Mixed Reality (MR) Tools | Both quantitative and qualitative | Explored the adoption of Mixed Reality (MR) tools for enhancing collaboration, design visualization, and stakeholder engagement in construction projects. |
| 33 | Kopsida et al., 2021 | Greece | Digital Twin and IoT Integration | Qualitative | Proposed a Digital Twin and IoT integration framework to monitor and manage the lifecycle of construction |

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| | | | | | assets, improving operational efficiency. |
| 34 | Bastian et al., 2021 | Germany | Autonomous Robotics | Quantitative | Investigated the use of autonomous robots for construction site automation, focusing on tasks such as bricklaying, material handling, and site inspection. |
| 35 | Farooq et al., 2020 | Pakistan | Lean Six Sigma and Industry 4.0 | Both quantitative and qualitative | Integrated Lean Six Sigma methodologies with Industry 4.0 technologies to enhance quality control, reduce waste, and improve process efficiency in construction. |
| 36 | Chen et al., 2021 | Taiwan | UAVs (Unmanned Aerial Vehicles) and BIM | Quantitative | Studied the integration of UAVs with BIM for real-time site monitoring, progress tracking, and |

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| | | | | | data collection in construction projects. |
| 37 | Mokhtar et al., 2021 | Malaysia | Smart Sensors and Predictive Maintenance | Qualitative | Developed a framework for using smart sensors to enable predictive maintenance in construction equipment, reducing downtime and maintenance costs. |
| 38 | Shakil et al., 2020 | Bangladesh | Big Data Analytics and AI | Both quantitative and qualitative | Explored the application of Big Data Analytics and AI in construction project management, focusing on risk assessment and decision-making processes. |

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| 39 | Olawumi & Chan, 2021 | Nigeria | Sustainability Assessment Model | Qualitative | Proposed a sustainability assessment model for evaluating the environmental, economic, and social impacts of Industry 4.0 technologies in construction. |
| 40 | Abd El-Razek & Abo Elnasr, 2020 | Egypt | IoT-Based Energy Management | Quantitative | Investigated IoT-based energy management systems in construction sites to monitor and optimize energy consumption, contributing to sustainable construction. |
| 41 | Perera et al., 2021 | Sri Lanka | Smart Wearables and Worker Safety | Qualitative | Examined the role of smart wearables in enhancing worker safety, monitoring health metrics, and reducing |

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| | | | | | accidents on construction sites. |
| 42 | Duan et al., 2021 | China | Augmented Reality (AR) for On-site Training | Both quantitative and qualitative | Explored the use of AR for on-site worker training, improving skills acquisition, and reducing errors during construction activities. |
| 43 | Ogunbiyi et al., 2021 | Nigeria | Modular Construction and Digital Twins | Qualitative | Investigated the potential of combining modular construction with Digital Twins to improve construction speed, reduce costs, and enhance quality control. |

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| 44 | Ali et al., 2020 | Pakistan | Smart Cities and BIM Integration | Both quantitative and qualitative | Proposed a framework for integrating BIM with smart city initiatives, focusing on urban planning, infrastructure management, and sustainable development. |
| 45 | Jang & Lee, 2021 | South Korea | Machine Learning for Construction Safety | Quantitative | Developed a machine learning model to predict and prevent safety incidents on construction sites, using real-time data from IoT devices. |
| 46 | Freitas et al., 2020 | Brazil | Digital Fabrication and 3D Printing | Both quantitative and qualitative | Explored the application of 3D printing and digital fabrication technologies in construction, focusing on their potential to reduce material waste and costs. |

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| 47 | Pärn & Edwards, 2021 | United Kingdom | Cybersecurity for BIM and IoT | Qualitative | Investigated the cybersecurity challenges associated with the integration of BIM and IoT, proposing strategies to enhance data security in construction projects. |
| 48 | Keskin et al., 2021 | Turkey | AI-Driven Project Scheduling | Quantitative | Developed an AI-driven project scheduling tool that optimizes resource allocation, timelines, and cost efficiency in construction projects. |
| 49 | Dias et al., 2021 | Portugal | Blockchain for Supply Chain Management | Both quantitative and qualitative | Explored the use of blockchain technology to enhance transparency, traceability, and security in construction |

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| | | | | | supply chain management. |
| 50 | Martínez et al., 2021 | Spain | IoT and BIM for Facility Managem ent | Qualitative | Proposed a framework for integrating IoT with BIM to improve facility management, focusing on real-time monitoring and predictive maintenance. |
| 51 | Rahman et al., 2020 | Malaysia | Cloud Computin g and BIM | Both quantitative and qualitative | Investigated the integration of cloud computing with BIM to enhance collaboration, data sharing, and project management in construction projects. |
| 52 | Wang et al., 2021 | China | Digital Twin and Smart Constructi on | Qualitative | Proposed a Digital Twin framework for smart construction, focusing on |

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| | | | | | real-time monitoring, simulation, and optimization of construction processes. |
| 53 | Zhong et al., 2021 | China | IoT and Blockchain Integration | Qualitative | Explored the integration of IoT and blockchain technologies to improve transparency, data security, and automation in construction supply chains. |
| 54 | Kaushik & Banerjee, 2020 | India | GIS-Based Construction Management | Quantitative | Developed a GIS-based tool for construction project management, emphasizing site selection, resource allocation, and risk assessment. |
| 55 | Hassan et al., 2021 | Egypt | Robotics and AI for Construction | Both quantitative and qualitative | Examined the use of robotics and AI in automating construction |

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| | | | Automation | | tasks such as bricklaying, plastering, and quality control, improving efficiency and accuracy. |
| 56 | Alaloul et al., 2021 | United Arab Emirates | Construction 4.0 Framework | Qualitative | Proposed a comprehensive Construction 4.0 framework, integrating various Industry 4.0 technologies such as BIM, IoT, and AI to enhance construction processes. |
| 57 | Babatunde et al., 2020 | Nigeria | VR for Construction Safety Training | Quantitative | Investigated the application of Virtual Reality (VR) for construction safety training, focusing on hazard identification and risk mitigation. |

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| 58 | Yahya et al., 2021 | Indonesia | Predictive Analytics for Construction Delays | Both quantitative and qualitative | Developed a predictive analytics model to identify and mitigate potential delays in construction projects, using historical data and machine learning. |
| 59 | Kamardeen & Rameezdeen, 2021 | Sri Lanka | Sustainable Construction Practices with BIM | Qualitative | Explored the role of BIM in promoting sustainable construction practices, focusing on energy efficiency, material optimization, and waste reduction. |
| 60 | Pedro & Meireles, 2020 | Portugal | Smart Contracts in Construction | Qualitative | Investigated the potential of smart contracts to automate contractual obligations, payments, and compliance in |

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| | | | | | construction projects, improving transparency. |
| 61 | Bressanelli et al., 2020 | Italy | Circular Economy and Industry 4.0 | Both quantitative and qualitative | Examined how Industry 4.0 technologies can support circular economy practices in construction, emphasizing waste reduction, recycling, and resource efficiency. |
| 62 | Gupta & Rathore, 2021 | India | AI-Based Construction Project Risk Management | Quantitative | Developed an AI-based tool for managing risks in construction projects, focusing on early detection and proactive mitigation of potential issues. |

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| 63 | Navarro et al., 2021 | Spain | Digital Twin and Augmented Reality (AR) | Qualitative | Proposed the integration of Digital Twin and AR for real-time visualization and management of construction projects, improving decision-making and coordination. |
| 64 | Rana et al., 2020 | Pakistan | IoT-Based Smart Construction Site | Both quantitative and qualitative | Investigated the use of IoT to create a smart construction site, focusing on real-time monitoring, safety management, and resource optimization. |
| 65 | Ahmed & Ahmed, 2021 | Bangladesh | BIM and Lean Construction Integration | Qualitative | Explored the integration of BIM with lean construction principles to enhance project efficiency, |

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| | | | | | reduce waste, and improve collaboration. |
| 66 | Oliveira et al., 2020 | Brazil | AI-Driven Predictive Maintenance in Construction | Quantitative | Developed an AI-driven predictive maintenance model to optimize the lifespan of construction equipment, reduce downtime, and improve overall project efficiency. |
| 67 | Kivrak et al., 2021 | Turkey | Smart Building Technologies and BIM | Qualitative | Examined the role of smart building technologies integrated with BIM in enhancing building performance, energy efficiency, and occupant comfort. |

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| 68 | He & Zhang, 2020 | China | Smart Sensors for Structural Health Monitoring (SHM) | Quantitative | Investigated the application of smart sensors in SHM systems to monitor the integrity and safety of construction structures in real-time. |
| 69 | Phung et al., 2021 | Vietnam | AI-Based Construction Resource Allocation | Both quantitative and qualitative | Developed an AI-based model to optimize resource allocation in construction projects, focusing on cost efficiency and timely project completion. |
| 70 | Franco & Blanes, 2021 | Spain | Blockchain for Construction Contract Management | Qualitative | Investigated the use of blockchain technology to manage and automate construction contracts, ensuring transparency |

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| | | | | | and reducing disputes. |
| 71 | Moreno et al., 2020 | Mexico | IoT and Cloud Computing for Construction Data Management | Quantitative | Proposed a framework for integrating IoT with cloud computing to enhance data management, storage, and sharing in construction projects. |

**2.7 Industry 4.0 and Multi Criteria Decision Making**

The application of Multi-Criteria Decision Making (MCDM) methods in Industry 4.0 has gained significant attention in recent years, helping organizations optimize complex decision-making processes in areas such as technology selection, supplier evaluation, and risk management. Baskar, Kumar, and Krishnamoorthy (2021) offer an overview of various MCDM approaches like AHP (Analytic Hierarchy Process), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), and Fuzzy MCDM, demonstrating their importance in solving decision-making challenges specific to Industry 4.0 environments. The study highlights how these tools support firms in evaluating alternatives by accounting for factors such as automation, digitalization, and overall technological integration in manufacturing systems. Similarly, Luthra, Mangla, and Sadhu (2019) explored how Industry 4.0 enhances supplier selection processes through MCDM techniques. In their research, the AHP and TOPSIS methods are applied to prioritize suppliers based on new performance indicators like agility and digitalization, which are central to Industry 4.0's operational dynamics.

In addition to decision-making in supply chain and operations, MCDM is also critical for fostering sustainability within Industry 4.0 practices. Govindan, Shankar, and Kannan (2020) integrate sustainability with smart manufacturing systems, using methods like Fuzzy AHP and VIKOR (VIsekriterijumska optimizacija I Kompromisno Resenje). Their research emphasizes how MCDM tools can guide organizations in adopting green technologies and implementing sustainable manufacturing strategies while navigating the complexities of digital transformation. The use of these techniques enables businesses to weigh multiple criteria—such as environmental impact, cost-efficiency, and technological innovation—thus promoting sustainable growth in the Industry 4.0 era. Overall, MCDM methods provide a structured approach to decision-making, helping firms evaluate competing alternatives in a multi-faceted and data-driven manner, which is especially crucial in the fast-evolving landscape of Industry 4.0. Table 7 illustrates extended table with scholarly works that focus on the use of Multi-Criteria Decision Making (MCDM) for technology adoption in Industry 4.0.

Table 7. works related to Industry 4.0 and Multi Criteria Decision Making

| Reference | MCDM Technology Used | Brief Research Description |
|---|---|---|
| Baskar, P., Kumar, S. S., & Krishnamoorthy, V. (2021) | AHP, TOPSIS, Fuzzy MCDM | The study explores the application of MCDM methods for Industry 4.0 technology selection, risk management, and process optimization in manufacturing. |
| Luthra, S., Mangla, S. K., & Sadhu, R. (2019) | AHP, TOPSIS | This paper uses AHP and TOPSIS to address supplier selection challenges in Industry 4.0 environments, focusing on agility, automation, and digitalization criteria. |

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| Govindan, K., Shankar, M., & Kannan, D. (2020) | Fuzzy AHP, VIKOR | The research employs Fuzzy AHP and VIKOR to prioritize sustainable Industry 4.0 manufacturing practices, focusing on green technology adoption and sustainability. |
| Jovanović, B., Rajković, M., & Brković, N. (2020) | Hybrid MCDM (AHP, TOPSIS) | This study proposes a hybrid AHP-TOPSIS model to evaluate the adoption of Industry 4.0 technologies, considering factors like cost, flexibility, and readiness. |
| Németh, T., & Kiss, A. (2021) | PROMETHEE, AHP | The paper examines Industry 4.0 technology adoption in a case study setting, using PROMETHEE and AHP to assess different technologies' suitability based on multiple criteria. |
| Zavadskas, E. K., Turskis, Z., & Kildienė, S. (2014) | TOPSIS, SAW | The paper explores the use of TOPSIS and SAW (Simple Additive Weighting) for selecting the most suitable Industry 4.0 technologies in the construction sector. |
| Rezaei, J. (2015) | Best-Worst Method (BWM) | This research develops the Best-Worst Method (BWM) to improve decision-making in the context of Industry 4.0 by identifying the best and worst criteria for technology adoption. |
| Varela, L., Araújo, A., & Ferreira, L. (2019) | AHP, DEMATEL | The study applies AHP and DEMATEL (Decision Making Trial and Evaluation Laboratory) to identify the interdependencies among Industry 4.0 technologies and evaluate their adoption. |
| Favi, C., Germani, M., & Mandolini, M. (2020) | AHP, TOPSIS | This paper applies AHP and TOPSIS to select technologies for additive manufacturing in Industry 4.0, considering cost, material efficiency, and process optimization. |
| Vinodh, S., & Ramesh, V. (2018) | Fuzzy AHP, VIKOR | The study integrates Fuzzy AHP and VIKOR to evaluate the adoption of sustainable manufacturing technologies in Industry 4.0. It emphasizes energy efficiency, automation, and production flexibility. |
| Raj, A., Dwivedi, G., Sharma, A., & Lopes de Sousa Jabbour, A. B. (2020) | AHP, Fuzzy TOPSIS | This research uses AHP and Fuzzy TOPSIS to assess the readiness of Indian manufacturing industries for Industry 4.0, focusing on organizational and technological factors. |
| Machado, C. G., Winroth, M., & da Silva, E. L. (2019) | AHP, DEMATEL | The study employs AHP and DEMATEL to analyze the barriers to adopting Industry 4.0 technologies in manufacturing sectors, identifying and ranking critical challenges. |
| Pham, H., Nguyen, T., & Huynh, P. (2021) | Fuzzy TOPSIS, SWARA | The paper focuses on the use of Fuzzy TOPSIS and SWARA (Step-wise Weight Assessment Ratio Analysis) to assess Industry 4.0 technologies for smart logistics and supply chain management. |

## 2.8 Research Gaps

The identified research gaps highlight significant shortcomings in the existing literature on Industry 4.0 (I4.0) in the construction industry, which require further exploration and analysis to bridge theoretical and practical insights.

Firstly, while numerous studies have identified a wide range of enablers for the adoption of I4.0 technologies in construction, there is a noticeable lack of logical prioritization of these complex enablers." For instance, factors such as technological readiness, governmental policies, and stakeholder collaboration are often discussed but not ranked systematically based on their importance or influence (Zhou et al., 2020; Oesterreich & Teuteberg, 2016). The absence of prioritization creates challenges for practitioners in focusing on the most critical enablers for successful implementation.

Secondly, the literature provides insights into the barriers to adopting I4.0 technologies, such as high costs, skill gaps, and resistance to change (Mollah et al., 2021; Sawhney et al., 2020). However, studies lack significant discussion on the prioritization of these barriers, making it difficult to address the most critical obstacles hindering adoption. A structured ranking or hierarchical analysis would be instrumental in guiding policymakers and industry leaders to allocate resources effectively.

Thirdly, the research highlights the importance of the social, economic, and environmental dimensions of I4.0 in achieving sustainable construction practices. While the literature outlines these dimensions, it does not adequately categorize I4.0 technologies under these dimensions or provide a logical ranking of their contributions. For example, technologies like BIM, IoT, and AI contribute variably to each sustainability dimension, but the literature does not establish their hierarchical impact (Martek et al., 2019). Such categorization and ranking are essential for aligning technological investments with sustainability goals.

Finally, the literature acknowledges the perceived risks of I4.0 technologies from the customer's perspective, such as cybersecurity, data privacy, and ROI uncertainty (Chauhan et al., 2022; Bojanova, 2017). However, there is a need to prioritize these risks to identify the most influential ones, which are critical for market expansion of I4.0-based construction projects. Without this prioritization, stakeholders cannot effectively mitigate the risks that may deter adoption.

Addressing these gaps by employing methodologies such as Analytic Hierarchy Process (AHP), Delphi techniques, or fuzzy logic-based prioritization models can provide actionable insights for practitioners and researchers. Systematic prioritization and categorization of enablers, barriers, sustainability dimensions, and risks are crucial to advancing the theoretical understanding and practical application of Industry 4.0 in the construction industry.

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# 3 Research Methodology

This chapter outlines the research methodology adopted for studying the integration of Industry 4.0 technologies in the Indian construction sector. The research aims to address gaps in the literature by exploring the enablers, barriers, sustainability impacts, and perceived risks associated with these technologies. It defines clear research objectives, such as ranking enablers, barriers, and risks, and emphasizes sustainability dimensions. The study employs a mixed-methods approach, combining qualitative methods like expert interviews with quantitative tools, including Multi-Criteria Decision-Making (MCDM) techniques like Fuzzy AHP, SWARA, and COPRAS. The research design features iterative feedback loops, ensuring refinement of tools and strategies. Sampling targets industry experts using purposive and judgment sampling, while a robust questionnaire incorporates pairwise comparisons and fuzzy logic to handle uncertainty. Pre-testing and pilot studies ensure reliability and validity, with methods like Cronbach's alpha verifying internal consistency. Overall, the chapter presents a systematic framework to analyze Industry 4.0 adoption and its implications for sustainability in construction.

### 3.1 Research Purpose

The primary purpose of this research is to address significant gaps in the literature surrounding the application of Industry 4.0 technologies in the construction industry. While Industry 4.0 technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and big data analytics have revolutionized various sectors, their integration into the construction industry remains underexplored, particularly in terms of sustainability and practical implementation (Oesterreich & Teuteberg, 2016; Liao et al., 2017). This study is designed to explore how these technologies can be applied to enhance sustainable practices and streamline project management within the construction industry.

Industry 4.0 promises a transformative shift toward more efficient, digital, and interconnected processes, but its application in the construction industry has been slower than in other industries (Li et al., 2020). Therefore, this study seeks to evaluate the integration of Industry 4.0 technologies from a sustainability perspective and provide insights into practical implementation strategies.

### 3.2 Research Objectives

The research objectives were developed following a comprehensive review of existing literature and extensive consultations with experts in both academia and the construction industry. The intent is to understand how Industry 4.0 technologies can be effectively incorporated into the construction sector, particularly in the Indian context, where challenges such as inadequate infrastructure, regulatory hurdles, and socio-economic diversity present unique barriers (Li et al., 2020). The specific research objectives are outlined below:

1. **To study and analyze various factors in construction from Industry 4.0 perspectives:** aims to identify and examine various factors such as enablers, barriers, challenges and opportunities, impacts on sustainability dimensions and perceived risks that can influence adoption of Industry 4.0 technologies in construction industries. By studying these factors, the objective aims to provide a

holistic understanding of how Industry 4.0 can transform the construction industry, overcome challenges, and contribute to sustainable development.

2. **To identify and rank significant Industry 4.0 Enablers in Indian construction industry:** focuses on systematically prioritizing the key factor (enablers) that drive the adoption of **Industry 4.0 (I4.0)** technologies in construction. It aims to provide a **systematic framework** to evaluate multiple enablers simultaneously, ensuring that decisions are well-structured and based on logical criteria.
3. **To identify and prioritize significant Industry 4.0 Barriers in Indian construction industry:** focuses on systematically assessing and ranking the challenges that hinder the adoption of **Industry 4.0 (I4.0)** technologies in the construction industry. It aims to provide a **framework to analyze and prioritize barriers** logically, ensuring that the most critical challenges are systematically identified.
4. **To identify and prioritize sustainability criterias for Industry 4.0 adoption in Indian construction industry:** aims to evaluate and rank various technologies based on sustainability impacts (social, economic, and environmental) that are critical for the successful implementation of **Industry 4.0 (I4.0)** technologies in the Indian construction industry. It aims at **comprehensive evaluation** of multiple sustainability criterias, covering **economic, environmental,** and **social** factors simultaneously.
5. **To analyze and rank perceived risks of Industry 4.0 adoption from Indian Customer Perspectives:** Customer perspectives are critical in shaping the adoption of new technologies, particularly in developing countries where concerns about costs, technology reliability, and safety are prevalent (Khan et al., 2021). This objective aims to analyze and rank the perceived risks associated with Industry 4.0 adoption from the perspective of Indian customers in **logical, systematic,** and **comprehensive manner**, rather than based on intuition or isolated judgments.

### 3.3 Research Questions

- RQ1: What are key operational factors that influence Industry 4.0 adoption in the construction industry?

- RQ2: What are the critical enablers that facilitate the successful adoption of Industry 4.0
technologies in the Indian construction industry?

- RQ3: What are the most significant barriers to the integration of Industry 4.0 technologies in the Indian construction sector?

- RQ4: What sustainability criterias should be prioritized for the implementation of Industry 4.0 technologies in construction?

- RQ5: What are the key risks perceived by Indian customers regarding Industry 4.0 adoption in construction, and how can these risks be ranked to foster greater acceptance and trust in these technologies?

### 3.4 Research Design

The flowchart in figure 1 illustrates a proposed PhD research design, which shows a cyclical and iterative research process. The Prior Phase, which occurs before feedback, and the Post Feedback Loops, which occur after feedback integration, make up its two primary stages. Below is an explanation of each step:

Prior Phase:

This is the initial phase of the research, involving the foundational steps of idea formulation, literature survey, and preliminary research design.

a. **Literature Survey, Idea Acquisition, Expert Consultation, and Problem Identification**: This step emphasizes exploring existing literature and gathering insights from experts to identify the problem and research gaps in Industry 4.0 in construction. The focus is on framing an initial understanding of the domain.

b. **Preliminary Research Assessment and Gap Identification**: A thorough assessment of the existing body of knowledge to pinpoint specific gaps in the field of Industry 4.0 in construction. It highlights unaddressed areas of concern.

c. **Formulation of Research Questions and Objectives**: Based on the identified gaps, the research questions and objectives are developed. These guide the entire research process, ensuring that the investigation remains focused and aligned with the gaps found.

d. **Literature Review, Concept Definition, Industry 4.0 Analysis in Construction**: more in-depth review of literature follows, which includes defining key concepts and further analysis of how Industry 4.0 has been applied in construction, ensuring a comprehensive understanding of the context.

e. **Research Design & Process, Data Collection Tool Preparation**: At this stage, a detailed research methodology is designed. This includes planning how data will be collected and developing appropriate tools (e.g., surveys, interview guides) for gathering this data.

f. **Data Collection, Data Sources, Population and Study Area Decision, Sample Size Determination**: Data collection begins here. The study area, population, and sample size are determined based on the research questions. This is the practical stage where fieldwork, surveys, or interviews take place to gather raw data.

g. **Variable Discussion, Data Analysis**: The data collected is analyzed based on identified variables. This may involve statistical or content analysis to interpret the results.

h. **Result Synthesis, Conclusions, and Recommendations**: The results are synthesized to draw conclusions. Recommendations for the industry or future research are based on the findings. This section consolidates everything learned from the research.

Post Feedback Loops:

This section includes continuous feedback loops to refine and improve the research framework and findings.

1. **Literature Gaps and Assumptions, Developing Objectives, Problem Statement Formulation, Forecasting Expected Results**: This stage allows the research process to evolve by addressing any new gaps or assumptions that might arise from the initial literature review or feedback received from peers and experts. It helps in refining the objectives and expectations from the research.
2. **Conceptual Reasoning, Gap Assessment, Identify Improvement Strategies**: As more insights are gained, the conceptual framework may be adjusted, and improvement strategies may be identified to bridge gaps that the research uncovers.
3. **Data Collection Process, Data Collection Tools Pretest, Data Collection Start**: Once new insights are incorporated, data collection tools may need testing (pretesting), and the actual data collection process is initiated. This may include making adjustments to earlier tools for better data accuracy.
4. **Tools Modification as per Contemplated Data, Data Cleaning and Entry into Analytical Tools**: After gathering the data, tools are modified as necessary to better suit the new findings. The collected data is cleaned and entered into software or other analysis tools for deeper interpretation.
5. **Data Analysis and Presentation, Content Analysis, Descriptive Analysis, MCDM Techniques**: This is the stage where the data is deeply analyzed using

methods like content analysis or MCDM (Multi-Criteria Decision Making) techniques to rank or prioritize risks, ideas, or strategies.

6. **Determining Priority and Ranking, Concluding Results for Further Action, Entry to MCDM Techniques like Fuzzy AHP, SWARA AND COPRAS**: Based on the analysis, priorities and rankings are determined. Techniques such as Fuzzy AHP, SWARA AND COPRAS can be employed to deal with complex multi-criteria decision-making problems, particularly in ranking risks or other factors in Industry 4.0 in construction.
7. **Substantial Findings through Empirical Results and Interviews, Proposing New Conceptual Frameworks**: After empirical analysis and interviews, new insights are likely to emerge, allowing for the proposal of novel conceptual frameworks that better capture the realities of Industry 4.0 in construction.
8. **Highlighting Benefits, Recommendations, Future Research Area**: The final stage emphasizes the benefits and contributions of the research. Recommendations for future research are made based on the findings, ensuring that further investigation can build upon the current work.

In conclusion, this framework is robust, involving iterative processes of literature review, methodology development, data collection, analysis, and feedback integration, with the ultimate goal of addressing the research gaps in the application of Industry 4.0 in construction.

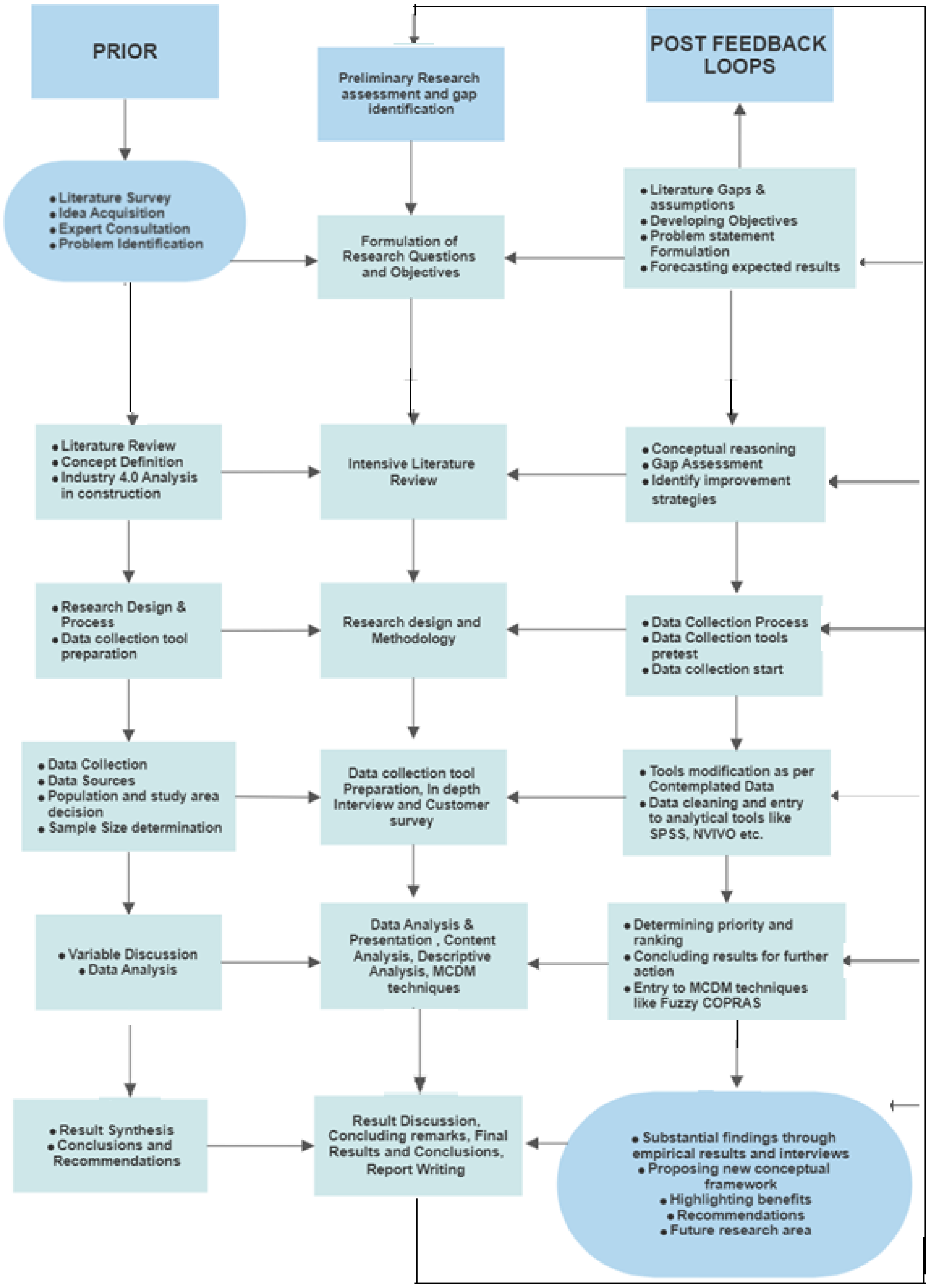


**Fig 1. Research Design**

## 3.5 Sampling

### 3.5.1 Sampling Frame

The target population for this study comprises professionals from the Indian construction industry who are involved or have expertise in Industry 4.0 technology adoption. This includes construction managers, engineers, technology providers, researchers, and policymakers. In the first stage of the research, the study captures demographic data, the level of Industry 4.0 implementation in their organizations, and which technologies (such as IoT, AI, robotics, etc.) are being used most frequently. The study also explores the factors driving or hindering Industry 4.0 adoption in the Indian construction sector.

### 3.5.2 Sampling Technique

The study employs **purposive sampling** in the first phase for the selection of industry experts and stakeholders with experience in Industry 4.0. In the second phase, **judgment sampling** is used to gather responses from individuals capable of providing valuable insights for the FAHP-based ranking of various factors. This technique ensures that the respondents possess relevant knowledge and experience in the construction and technological domains.

### 3.5.3 Data Collection

- **Qualitative Data**:
    - **Semi-structured Interviews**: These will be conducted with 15-20 experts from the construction industry, academia, and technology providers. The interviews will explore key enablers,barriers, risks, and sustainability dimensions related to Industry 4.0 adoption.
    - **Literature Review**: Extensive literature review to identify existing barriers, enablers, and sustainability criteria from global and local contexts.
- **Quantitative Data**:
    - **MCDM-Based Questionnaire**: The quantitative phase will involve Multi-Criteria-Decision-Making techniques based questionnaire designed to prioritize factors. The questionnaire will collect expert judgments on the

relative importance of these elements using pairwise comparisons based on a triangular fuzzy scale .

- **Survey Methodology**:
    - The questionnaire will be distributed both electronically and through in-person interactions to ensure high participation rates from experts. It will also incorporate closed-ended questions for clarity.

### 3.5.4 Sample Size

- **Qualitative Phase**: A target sample size of **15-20 participants** for in-depth interviews, as this range is typically sufficient for capturing detailed qualitative insights from industry experts and practitioners .

- **Quantitative Phase**: A larger sample size of **20-30 experts** will be required for the FAHP-based questionnaire phase. This will ensure sufficient statistical rigor for conducting the FAHP analysis and ranking the barriers and enablers of Industry 4.0 in construction .

## 3.6 Nature of Questionnaire

The questionnaire will be structured into two key sections:

- **Section 1: Expert Demographics**
  This section will gather details about the respondents, such as their role, experience level, organization type, and familiarity with Industry 4.0 technologies in construction.
- **Section 2: MCDM-Based Pairwise Comparisons**
    - **Pairwise Comparisons**: The MCDM methods will require experts to provide pairwise comparisons of the identified barriers, enablers, risks, and sustainability criteria using **Triangular Fuzzy Numbers (TFNs)** to handle uncertainty in judgment. The comparison will be based on linguistic scales such as Low, Moderate, and High, corresponding to fuzzy values .
    - **Closed-Ended Questions**: Questions will include multiple-choice options to rate the importance of various enablers and barriers, followed by ranking these factors based on their significance.

- **Sensitivity Analysis**: The questionnaire will also include questions related to the sensitivity of the results to ensure robustness in the MCDM rankings.

### 3.7 Scale/Measurement Design

The research employs a detailed **Fuzzy Analytical Hierarchy Process (FAHP)**, which integrates fuzzy logic into traditional multi-criteria decision-making (MCDM) methods to handle uncertainty in expert judgments. The FAHP process involves pairwise comparisons and uses **Triangular Fuzzy Numbers (TFNs)** to assess the relative importance of various factors in complex decision-making scenarios. The fuzzy approach is particularly useful in Industry 4.0 applications, where uncertainty and subjective judgments dominate decision-making.

- **Triangular Fuzzy Numbers (TFN)**

In the study, **Triangular Fuzzy Numbers (TFN)** are used to quantify subjective judgments in the decision-making process. A TFN is defined by three parameters: a lower bound (l), a middle value (m), and an upper bound (u), which are denoted as (l, m, u). These three values represent the range of possible outcomes, helping decision-makers express uncertainty in their comparisons.

- **Example from the Study**: If experts are comparing two barriers to Industry 4.0 adoption, the TFN allows them to express a range of possibilities such as Low, Moderate, and High importance:
    - **Equal Importance**: (1, 1, 1)
    - **Moderate Importance**: (3, 4, 5)
    - **Extreme Importance**: (7, 8, 9)

The use of fuzzy logic helps address imprecise and uncertain expert evaluations, offering a more flexible and realistic approach.

- **Pairwise Comparison and Fuzzy Synthesis**

The **pairwise comparison** method is central to the MCDM process. Experts evaluate two factors simultaneously, such as two barriers or enablers of Industry 4.0, by comparing their relative importance using a TFN scale. After the comparisons are made, the fuzzy values are converted (defuzzified) into crisp values to facilitate final ranking and decision-making.

- **Fuzzy Weight Calculation**

The MCDM method involves calculating **fuzzy synthetic extent values** for each criterion or barrier. These are aggregated into a final weight vector, which reflects the overall importance of each criterion.

- **Linguistic Variables**

The TFN scale used in the manuscripts is closely tied to linguistic variables that help quantify expert judgments. These variables range from Very Low to Extreme, offering a flexible method for rating factors.

- **Example of Scale Used**:
  - **Very Low**: (1, 2, 3)
  - **Low**: (2, 3, 4)
  - **Moderate**: (3, 4, 5)
  - **High**: (4, 5, 6)
  - **Extreme**: (7, 8, 9)(Revised Manuscript 1)(Revised Manuscript 1)

- **Sensitivity Analysis**

In MCDM, after the weights are calculated, sensitivity analysis is often performed to verify the stability and robustness of the results. This step ensures that small changes in the input values (expert judgments) do not significantly alter the final rankings.

### 3.8 Pre-Test of Questionnaire

Industry 4.0 specialists, construction industry professionals, researchers, and academic professors comprised the expert group in the current study. The participants were asked to review and provide feedback on the questionnaire's layout and the overall study methodology. The experts thoroughly examined the scope, content, and purpose of each item related to the barriers, enablers, and risks associated with Industry 4.0 adoption in the construction sector. Preliminary tests were conducted to ensure the questionnaire's content validity. After discussions with the experts, several items were removed, and new ones that were more relevant to the Indian construction industry were added. This iterative process helped refine the questionnaire to better capture the complexities of Industry 4.0 implementation.

### 3.9 Pilot Study

The reliability of the instrument was assessed using **Cronbach's alpha** to ensure internal consistency. All constructs achieved values above the 0.7 cutoff, indicating that the questionnaire is reliable (Hair et al., 2006). After analyzing the pilot test results, adjustments were made to improve the clarity and relevance of the questions, based on expert feedback. The refined questionnaire was then distributed to the respondents for the main study. All constructs demonstrated strong internal consistency, with Cronbach's alpha values ranging from 0.883 (minimum) to 0.945 (maximum). This confirms that the items within each construct are reliable, supporting the internal consistency and reliability of the instrument used in the study.

### 3.10 Multi Criteria Decision Making Techniques

#### 3.10.1 Fuzzy AHP (Analytic Hierarchy Process)

The Fuzzy Analytic Hierarchy Process (Fuzzy AHP) is a Multi-Criteria Decision-Making (MCDM) technique that extends the traditional AHP by incorporating fuzzy logic to handle the uncertainty and vagueness associated with human judgment. The standard AHP, developed by Thomas Saaty in the 1970s, is widely used for solving complex decision-making problems by structuring them into a hierarchy of goals, criteria, and alternatives. It employs pairwise comparisons to calculate the relative importance of criteria and the performance of alternatives concerning those criteria (Saaty, 1980). However, AHP assumes that decision-makers provide precise judgments, which can be problematic when dealing with subjective or imprecise information. This is where Fuzzy AHP comes into play, offering a solution to incorporate uncertainty by using fuzzy numbers to represent subjective judgments.

Fuzzy logic, introduced by Zadeh (1965), is a mathematical framework for representing uncertainty and ambiguity, which is inherent in many real-world situations. In the context of decision-making, fuzzy logic allows for a range of truth values, rather than just binary true or false judgments. It is particularly useful when human judgments are imprecise, such as when decision-makers use terms like fairly important or very important. These linguistic terms can be modeled using fuzzy numbers, allowing for a more flexible and realistic representation of human preferences (Zadeh, 1965).

Fuzzy AHP integrates fuzzy logic into the traditional AHP framework to handle the vagueness in pairwise comparison judgments. The core idea of Fuzzy AHP is to replace the crisp values used in AHP's pairwise comparisons with fuzzy numbers, typically triangular or trapezoidal fuzzy numbers, which are defined by a triplet (l, m, u) representing the lower, middle, and upper bounds of a fuzzy number. This enables decision-makers to express their preferences with greater flexibility and reduces the risk of inconsistency in pairwise comparisons (Van Laarhoven & Pedrycz, 1983).

The Fuzzy AHP process generally involves the following steps:

1. **Problem Structuring**: The decision problem is structured into a hierarchy, with the main goal at the top, followed by criteria, sub-criteria, and alternatives at lower levels, similar to the traditional AHP.

In Fuzzy AHP, decision-makers' judgments are expressed as fuzzy numbers. The most common representation is the **Triangular Fuzzy Number (TFN)**, which is represented as $\tilde{a} = (l, m, u)$, where:

- $l$: Lower bound (the smallest possible value),
- $m$: Middle value (the most likely or expected value),
- $u$: Upper bound (the largest possible value).

2. **Pairwise Comparisons Using Fuzzy Numbers**: Decision-makers conduct pairwise comparisons between the criteria and alternatives using linguistic terms (e.g., slightly more important, equally important) that are then converted into fuzzy numbers (Chan & Kumar, 2007).

   The fuzzy comparison matrix for n criteria is defined as:

$$\begin{pmatrix} (1,1,1) & \cdots & \tilde{a}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \cdots & (1,1,1) \end{pmatrix}$$

where each $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ is the triangular fuzzy number representing the relative importance of criterion $i$ to criterion $j$.

3. **Fuzzy Pairwise Comparison Matrix**: The fuzzy comparison matrices are constructed for each level of the hierarchy. Instead of crisp values, fuzzy numbers are used to capture the uncertainty in the decision-makers' judgments.

For triangular fuzzy numbers $\tilde{a} = (l_a, m_a, u_a)$and $\tilde{b} = (l_b, m_b, u_b)$, basic operations like addition, subtraction, and multiplication are defined as:

- **Addition**:

$$\tilde{a} + \tilde{b} = (l_a + l_b, m_a + m_b, u_a + u_b)$$

- **Multiplication**:

$$\tilde{a}\, X\, \tilde{b} = (l_a X\, l_b, m_a\, X\, m_b, u_a\, X\, u_b)$$

- **Reciprocal of a TFN**:

$$\tilde{a}^{-1} = (\frac{1}{u_a}, \frac{1}{m_a}, \frac{1}{l_a})$$

4. **Synthesis of Priorities**: The fuzzy pairwise comparison matrices are synthesized to calculate the relative weights of the criteria and alternatives. These fuzzy weights can be defuzzified using methods such as the centroid method or the alpha-cut method to obtain crisp priority values (Buckley, 1985).

   The fuzzy weights of each criterion can be calculated using the geometric mean method for fuzzy numbers. For a fuzzy comparison matrix $\widetilde{A}$, the fuzzy weight $\widetilde{W}_i$ for criterion $i$ is calculated as:

$$\widetilde{W}_i = (\prod_{j=1}^{n} \tilde{a}_{ij})^{\frac{1}{n}} = ((\prod_{j=1}^{n} \tilde{l}_{ij})^{\frac{1}{n}}, (\prod_{j=1}^{n} \widetilde{m}_{ij})^{\frac{1}{n}}, (\prod_{j=1}^{n} \tilde{u}_{ij})^{\frac{1}{n}})$$

5. **Consistency Check**: Similar to the traditional AHP, a consistency check is performed to ensure that the judgments are not highly inconsistent. Fuzzy AHP allows for a higher tolerance of inconsistency due to the flexibility of fuzzy numbers.

   The fuzzy weights need to be normalized. The normalized fuzzy weight $\widetilde{w}_i$ for criterion $i$ is calculated as:

$$\widetilde{w}_i = \left(\frac{l_i}{\sum_{k=1}^{n} u_k}, \frac{m_i}{\sum_{k=1}^{n} m_k}, \frac{u_i}{\sum_{k=1}^{n} l_k}\right)$$

6. **Ranking of Alternatives**: The alternatives are ranked based on the calculated weights, allowing decision-makers to choose the best option while considering the inherent uncertainty in the decision-making process (Mikhailov & Singh, 2003).

To convert fuzzy numbers into crisp values, defuzzification is required. A common defuzzification method is the **Centroid Method** or **Center of Gravity Method**, which calculates the crisp value $C(\widetilde{w}_i)$ as:

$$C(\widetilde{w}_i) = \frac{l_i + m_i + u_i}{3}$$

This converts the fuzzy weights into crisp weights for decision-making.

Fuzzy AHP has been applied in various fields, including supply chain management, project selection, environmental management, and construction (Onut et al., 2009). For instance, in supply chain management, Fuzzy AHP has been used to rank suppliers based on multiple criteria such as cost, quality, and delivery performance, where decision-makers' judgments may be uncertain (Chan & Kumar, 2007). In construction, it has been applied to prioritize project risks, where the uncertainty in risk assessments can be modeled using fuzzy numbers (Cheng et al., 2002).

One of the primary advantages of Fuzzy AHP is its ability to manage the uncertainty and imprecision in decision-makers' judgments, making it a more realistic approach compared to traditional AHP (Van Laarhoven & Pedrycz, 1983). Fuzzy AHP allows decision-makers to express their preferences using linguistic terms, which can be more intuitive than providing exact numerical values (Buckley, 1985). The flexibility of fuzzy numbers allows for a higher tolerance of inconsistency in judgments, which can be particularly useful in complex decision-making scenarios involving multiple criteria and alternatives (Mikhailov & Singh, 2003).

### 3.10.2 Fuzzy SWARA (Step-wise Weight Assessment Ratio Analysis)

Fuzzy SWARA (Step-wise Weight Assessment Ratio Analysis) is a Multi-Criteria Decision-Making (MCDM) technique that extends the classical SWARA method by incorporating fuzzy logic to handle uncertainty and subjectivity in expert judgments. This approach is especially useful in decision-making scenarios where criteria weights need to be determined, and the opinions of experts are imprecise or uncertain. Fuzzy SWARA enables the assignment of criteria weights based on subjective judgments, which are modeled using fuzzy numbers.

The classical SWARA method, developed by Kersuliene, Zavadskas, and Turskis (2010), involves a structured process in which decision-makers assign relative importance to various criteria in a step-by-step manner. Fuzzy SWARA, introduced later to handle vagueness in human judgment, replaces the crisp values used in traditional SWARA with fuzzy numbers.

In Fuzzy SWARA, experts use linguistic terms (such as very important, important, moderately important, etc.) that are translated into fuzzy numbers, often represented by **Triangular Fuzzy Numbers (TFNs)**. These fuzzy numbers account for the inherent uncertainty in decision-making, making Fuzzy SWARA a powerful tool for prioritizing criteria in complex, uncertain environments.

The Fuzzy SWARA process follows these main steps:

***1.*** *Identify the Criteria*

The first step involves identifying the set of criteria relevant to the decision-making problem. These criteria are typically identified through literature reviews or expert input.

Let:

$C_1$,$C_2$…………………,$C_n$ represent the criteria to be evaluated.

***2.*** *Expert Evaluation Using Fuzzy Numbers*

Experts express their judgments on the relative importance of criteria using linguistic variables, which are converted into **Triangular Fuzzy Numbers (TFNs)**. The most common form of TFN is $\tilde{a} = (l, m, u)$, where:

- $l$: Lower bound (the smallest possible value),
- $m$: Middle value (the most likely or expected value),
- $u$: Upper bound (the largest possible value).

For example, the linguistic term Very Important can be represented as a fuzzy number (0.7,0.9,1.0)(0.7, 0.9, 1.0)(0.7,0.9,1.0).

***3.*** *Determine the Comparative Importance (SI) of Criteria*

Experts are asked to compare each criterion $C_i$ with the previous one $C_{i-1}$, expressing the comparative importance $\widetilde{SI}_i$ as a fuzzy number.

Let:

- $\widetilde{SI}_i$ = ($l_{SI_i}, m_{SI_i}, u_{SI_i}$)be the fuzzy importance of criterion $C_i$ relative to $C_{i-1}$, where $i$ =2,3,..., n.

***4.*** *Calculate the Fuzzy Coefficient* $\tilde{\boldsymbol{k}}_{\boldsymbol{i}}$

The coefficient $\tilde{k}_i$ for each criterion is computed using the following equation:

$$\tilde{k}_i = 1 + \widetilde{SI}_i$$

This coefficient represents the adjusted importance of each criterion.

*5. Determine the Fuzzy Recalculated Weights* $\tilde{\boldsymbol{q}}_{\boldsymbol{i}}$

The recalculated fuzzy weight $\tilde{q}_i$ for each criterion is computed by dividing the recalculated weight of the previous criterion by the fuzzy coefficient:

$$\tilde{q}_i = \frac{\tilde{q}_i - 1}{\tilde{k}_i} \; for\; i = 2,3, \dots \dots, n$$

For the first criterion, the fuzzy recalculated weight is $\tilde{q}_i = (1,1,1)$.

***6.** Normalize the Fuzzy Weights*

The fuzzy recalculated weights are then normalized to obtain the final fuzzy weights. The normalization is done by dividing each fuzzy recalculated weight by the sum of all fuzzy recalculated weights:

$$\widetilde{W}_i = \frac{\tilde{q}_i}{\sum_{i=1}^{n} \tilde{q}_i}$$

Where $\widetilde{W}_i = (l_{w_i}, m_{w_i}, u_{w_i})$ represents the normalized fuzzy weight of criterion $C_i$.

***7.** Defuzzification*

After the fuzzy weights are calculated, they need to be converted into crisp values using a defuzzification method. One of the most commonly used methods is the **Centroid Method**, which calculates the crisp weight $W_i$ of each criterion as follows:

$$W_i = \frac{l_{w_i} + m_{w_i} + u_{w_i}}{3}$$

This process yields the final crisp weights, which can then be used in further decision-making steps, such as ranking alternatives or selecting the best course of action.

Fuzzy SWARA has been successfully applied in various fields, such as supplier selection, sustainable construction, and project management. In supplier selection, for example, criteria like cost, quality, and delivery time can be evaluated under uncertainty, and experts' judgments are captured using fuzzy numbers (Büyüközkan & Güleryüz, 2016).

Fuzzy SWARA is a robust MCDM technique that addresses the limitations of the traditional SWARA method by incorporating fuzzy logic. It is particularly useful in situations where expert judgments are subjective and imprecise, providing a more flexible and realistic decision-making framework. By integrating fuzzy numbers into the SWARA process, decision-makers can better handle uncertainty, leading to more accurate and reliable results.

### 3.10.3 Fuzzy Complex Proportional Assessment of Alternatives (COPRAS)

Fuzzy Complex Proportional Assessment (Fuzzy COPRAS) is a method that incorporates fuzzy logic to handle the inherent uncertainty in decision-making processes. It effectively combines the principles of proportional assessment with fuzzy set theory to rank alternatives based on multiple criteria.

Fuzzy COPRAS provides a structured approach for evaluating and prioritizing alternatives by converting qualitative assessments into quantitative measures. This method is particularly useful in situations where the data is imprecise or uncertain.

***Steps of Fuzzy COPRAS***

1. **Establish the Decision Matrix**: Define the set of alternatives $A = \{a_1, a_2 \dots \dots .., a_n\}$ and criteria $C = \{c_1, c_2 \dots \dots .., c_n\}$. The initial decision matrix can be represented as:

$$D = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}$$

   where $x_{ij}$ represents the performance of alternative $a_i$ under criterion $c_j$.

2. **Convert to Fuzzy Values**: Transform the crisp decision matrix into a fuzzy decision matrix using fuzzy numbers (e.g., triangular fuzzy numbers).
3. **Normalize the Fuzzy Decision Matrix**: Normalize the fuzzy decision matrix $D_f$:

$$x_{ij} = \frac{x_{ij}}{\max(x_{ij})}$$

for benefit criteria. For cost criteria, it can be expressed as:

$$x_{ij} = \frac{min(x_{ij})}{x_{ij}}$$

4. **Determine the Weights of Criteria**: Assign weights wjw_jwj to each criterion based on their importance, ensuring $w_j \in [0,1] and \ \sum_{j=1}^{n} w_j = 1$
5. **Calculate the Fuzzy Performance Values**: Compute the fuzzy performance value for each alternative $P_i$:

$$P_i = \sum_{j=1}^{n} w_j \, \tilde{x}_{ij}$$

6. **Compute the Complex Proportional Assessment**: The final performance value is obtained by assessing the positive and negative impacts of each alternative, defined as:

$$P_i^+ = \sum_{j=1}^{n} w_j \, \tilde{x}_{ij}$$

$$P_i^- = \sum_{j=1}^{n} w_j \, (1 - \tilde{x}_{ij})$$

The overall performance can then be represented as:

$$P_i = P_i^+ - P_i^-$$

7. **Defuzzification**: Convert fuzzy performance values into crisp values using a defuzzification method, such as the centroid method.
8. **Rank the Alternatives**: Rank the alternatives based on their defuzzified performance values $P_i$ .

***Mathematical Formulation***

- **Fuzzy Numbers**: A triangular fuzzy number $\tilde{x} = (l, m, u)$ is defined by its lower bound $l$, mode $m$, and upper bound $u$.
- **Fuzzy Addition and Multiplication**: The operations for triangular fuzzy numbers are defined as follows:

$$\tilde{x}_1 + \tilde{x}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$$

$$\tilde{x}_1 . \tilde{x}_2 = (l_1 . l_2, m_1 . m_2, u_1 . u_2)$$

Fuzzy COPRAS has been applied in various fields, including environmental assessments, supplier selection, and project management. For instance, in a study by Zhang et al. (2020), Fuzzy COPRAS was utilized to evaluate green suppliers, demonstrating its capability to handle uncertainties in environmental criteria.

Fuzzy COPRAS is a robust MCDM technique that integrates fuzzy logic with proportional assessment principles. By effectively dealing with uncertainty and allowing for a comprehensive evaluation of alternatives based on multiple criteria, it serves as a valuable tool for decision-makers in complex environments.

# 4 Ranking of Industry 4.0 Enablers: A Fuzzy SWARA-COPRAS Approach

This chapter focuses on the identification, prioritization, and ranking of enablers for adopting Industry 4.0 technologies in the Indian construction industry. From an initial pool of 35 enablers, the chapter narrows down to 12 key enablers categorized under organizational, economic, and technological criteria. Economic factors, particularly profitability and stakeholder investment, are identified as the most influential, followed by government regulations and market demand. Technologies like BIM, 3D printing, and IoT are acknowledged but ranked lower due to challenges in adoption. Using Fuzzy SWARA and Fuzzy COPRAS methodologies, the chapter evaluates these enablers' relative importance and performs sensitivity analysis to validate the robustness of the rankings. The findings emphasize the critical role of financial and regulatory support in driving Industry 4.0 adoption, while technological enablers require further development to realize their full potential.

The literature review in Section 2.1 outlines 35 enablers of Industry 4.0 adoption in construction industry. These domains play a critical role in facilitating the integration of Industry 4.0 technologies in the construction industry, particularly in developing countries like India. To further refine and prioritize these enablers, insights were gathered from a panel of five experts from the case organization. These experts: “Head (Projects), Head (Architecture), Head (Construction Engineering), Head (Technological), and Senior Manager (Design and Layout) possessing expertise and more than ten years of professional experience.

Based on the recommendations of the expert panel and the findings from the literature review, 3 major criterias (Organizational, Economic, Technological) and 12 key enablers were selected from an initial pool of 35 enablers identified during the analysis. The panel’s inputs ensured that the selected enablers were the most relevant and impactful for the context of Industry 4.0 in the Indian construction industry. The finalized criteria and enablers, along with their corresponding codes, are presented in **Table 8**.

### 4.1 Enablers Identification:

#### 1. Organizational Enablers

Organizational enablers are essential for creating an environment conducive to adopting Industry 4.0 technologies. These include:

- **Employers' Training with Corporate Ethics (E1):** Training employees to understand and adopt ethical practices within Industry 4.0 is crucial for aligning technological advances with corporate responsibility. Corporate ethics ensure that the integration of new technologies meets organizational goals while maintaining social responsibility (Shayganmehr et al., 2021).

- **Organization Strategic Planning (E2):** This refers to the structured and long-term planning required to adopt Industry 4.0 technologies. Strategic planning ensures that the company can achieve its business objectives efficiently and respond to technological advancements (Devi et al., 2021).

- **Risk-Taking Behavior (E3):** Implementing new technologies involves risks related to social, economic, and environmental factors. Organizations that foster a culture of risk-taking are more likely to adopt innovative solutions, driving the successful integration of Industry 4.0 (Newaz et al., 2023).

- **Governmental Regulations (E4):** Regulatory frameworks and legal policies are critical for ensuring that the adoption of Industry 4.0 complies with governmental guidelines, particularly in the construction industry. Governments play a crucial role in promoting technology integration through incentives and regulations (Olsson et al., 2021).

**2. Economic Enablers**

Economic enablers focus on financial considerations and incentives that encourage the adoption of new technologies:

- **Rewards and Incentives (E5):** Incentives for employees and stakeholders can motivate the adoption of Industry 4.0 technologies, encouraging them to align their efforts with sustainable strategies (Famakin et al., 2023).

- **Profitability (E6):** Profitability, ranked as the top enabler in the study, highlights the financial benefits of adopting Industry 4.0 technologies. Increased efficiency, reduced operational costs, and higher productivity are key economic drivers for the construction industry to adopt these technologies (Bamgbade et al., 2017).

- **Stakeholders' Investment (E7):** The active involvement of stakeholders is vital for the successful adoption of Industry 4.0. Their investment in technology adoption ensures that projects are well-funded and supported at all levels (Aghimien et al., 2021).

- **Market Demand (E8):** Consumer demand for Industry 4.0-generated designs drives market growth. Market willingness to adopt new construction technologies can significantly impact the implementation of Industry 4.0 in construction (Oke et al., 2022).

**3. Technological Enablers**

Technological enablers relate to the capabilities and innovations that facilitate the practical implementation of Industry 4.0:

- **Artificial Intelligence (AI) (E9):** AI enhances productivity by automating processes, reducing manual interventions, and enabling predictive analytics to optimize construction workflows (Shayganmehr et al., 2021).

- **3D Printing (E10):** This technology enables the creation of complex structures efficiently, reducing costs and construction time. 3D printing optimizes material use, making it a key enabler of Industry 4.0 (Subramanya et al., 2020).
- **Building Information Modeling (BIM) and Digital Twin (E11):** These technologies provide real-time data on construction processes, allowing for better project planning, execution, and maintenance. BIM and Digital Twins play a significant role in improving construction efficiency and sustainability (Hossain & Nadeem, 2019).
- **Internet of Things (IoT) (E12):** IoT connects physical devices across the construction site, allowing for real-time monitoring and data collection. This technology improves decision-making, resource allocation, and safety in construction (Ghosh et al., 2021).

Table 8. Finalized criterias and Enablers with their codes

| **Criteria** | Enablers | Code | **Criteria** | Enablers | Code | **Criteria** | Enablers | Code |
|---|---|---|---|---|---|---|---|---|
| **Organizational** | Employers training with corporate ethics | E1 | **Economic** | Rewards and Incentives | E5 | **Technological** | Artificial intelligence | E9 |
| | Organization strategic planning | E2 | | Profitability | E6 | | 3D printing | E10 |
| | Risk-taking behavior | E3 | | Stakeholders Investment | E7 | | Building information modeling(BIM) and Digital Twin | E11 |
| | Governmental regulations | E4 | | Market Demand | E8 | | Internet of Things (IOT) | E12 |

## 4.2 Analysis of weights using Fuzzy SWARA

The final weights of the three primary criteria (Economic, Organizational, and Technological) that were derived using the **Fuzzy SWARA** method are represented in table 9. Each criterion was evaluated based on expert input, with their relative importance assigned through linguistic scales. The computed weights for each category indicate the level of influence these criteria have on Industry 4.0 adoption in construction projects.

- **Economic Criteria**: This category holds the highest weight, suggesting that financial enablers, such as profitability, are critical to adopting Industry 4.0.
- **Organizational Criteria**: This includes aspects like strategic planning and risk-taking behavior, with a moderate weight.
- **Technological Criteria**: While important, this criterion received the lowest weight, indicating that although technology enablers are critical, economic factors often take precedence.

Table 9. Final Weights of Main Criteria's

| Criteria | $\tilde{s}_j$ | | | $\tilde{K}_j$ | | | $\tilde{Q}_j$ | | | $\tilde{W}_j$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Economic | | | | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.478 | 0.526 | 0.584 |
| Organizational | 0.667 | 1.000 | 1.500 | 1.667 | 2.000 | 2.500 | 0.400 | 0.500 | 0.600 | 0.191 | 0.263 | 0.351 |
| Technological | 0.222 | 0.250 | 0.286 | 1.222 | 1.250 | 1.286 | 0.311 | 0.400 | 0.491 | 0.149 | 0.211 | 0.287 |

Table 10 focuses on the economic enablers identified, such as **Profitability, Stakeholder Investment, Rewards, and Market Demand**. The **local weights** represent the importance of each enabler within the economic category, while the **global weights** reflect their overall contribution when compared to enablers across all criteria.

- **Profitability (E6)** emerged as the most influential enabler, given its significant impact on the overall adoption of Industry 4.0. It indicates that the financial gains from adopting these technologies are pivotal.
- **Stakeholders' Investment (E7)** also scored high, showcasing the necessity of financial backing from stakeholders in pushing for digital transformation.

Table 10. Local weight and Global weight of enablers under economic criteria

| Criteria | $\tilde{s}_j$ | | | $\tilde{K}_j$ | | | $\tilde{q}_j$ | | | Local Weight $\tilde{w}_j$ | | | Global Weight $\tilde{w}_j$ | | | Non Fuzzy wj |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **E6:Profitability** | | | | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.396 | 0.443 | 0.496 | 0.189 | 0.233 | 0.289 | 0.237 |
| **E7:Stakeholders coordination** | 0.667 | 1.000 | 1.500 | 1.667 | 2.000 | 2.500 | 0.400 | 0.500 | 0.600 | 0.155 | 0.233 | 0.337 | 0.023 | 0.049 | 0.097 | 0.056 |
| **E5:Rewards and Incentives** | 0.667 | 1.000 | 1.500 | 1.667 | 2.000 | 2.500 | 0.200 | 0.250 | 0.300 | 0.079 | 0.111 | 0.149 | 0.038 | 0.058 | 0.087 | 0.061 |
| **E8:Market demand** | 0.400 | 0.500 | 0.667 | 1.400 | 1.500 | 1.667 | 0.043 | 0.074 | 0.109 | 0.017 | 0.033 | 0.054 | 0.008 | 0.017 | 0.032 | 0.019 |

Table 11 ranks organizational enablers like **Strategic Planning, Government Regulations, Employers' Training**, and **Risk-taking Behavior**. Similar to the previous table, local and global weights are assigned to each enabler.

- **Strategic Planning (E2)** holds the highest weight within this category, emphasizing the need for clear long-term strategies when adopting new technologies.
- **Government Regulations (E4)** was also ranked high, demonstrating the role of regulatory frameworks in facilitating technological adoption.

Table 11. Local weight and Global weight of enablers under organizational criteria

| Criteria | $\tilde{s}_j$ | | | $\tilde{K}_j$ | | | $\tilde{q}_j$ | | | Local Weight $\tilde{w}_j$ | | | Global Weight $\tilde{w}_j$ | | | Non Fuzzy wj |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **E2:Organization strategic planning** | | | | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.388 | 0.467 | 0.562 | 0.058 | 0.099 | 0.161 | 0.106 |
| **E4:Governmental regulations** | 0.400 | 0.500 | 0.667 | 1.400 | 1.500 | 1.667 | 0.096 | 0.167 | 0.257 | 0.037 | 0.078 | 0.145 | 0.006 | 0.016 | 0.041 | 0.021 |
| **E1: Employers training with corporate ethics** | 0.286 | 0.333 | 0.400 | 1.286 | 1.333 | 1.400 | 0.069 | 0.125 | 0.200 | 0.027 | 0.058 | 0.112 | 0.004 | 0.012 | 0.032 | 0.016 |
| **E3:Risk-taking behavior** | 0.222 | 0.25 | 0.286 | 1.222 | 1.250 | 1.286 | 0.053 | 0.100 | 0.164 | 0.021 | 0.047 | 0.092 | 0.003 | 0.010 | 0.026 | 0.013 |

Table 12 evaluates technological enablers such as **BIM (Building Information Modeling), 3D Printing, AI (Artificial Intelligence)**, and **IoT (Internet of Things)**.

- **BIM (E11)** and **3D Printing (E10)** are the top enablers within this category, reflecting their transformational potential in improving construction practices.
- **AI (E9)** and **IoT (E12)**, although important, are ranked lower, possibly due to their relative novelty in the industry.

Table 12. Local weight and Global weight of enablers under Technological criteria

| Criteria | s̃j | | | K̃j | | | q̃j | | | Local Weight w̃j | | | Global Weight w̃j | | | Non Fuzzy wj |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **E11:Building information modeling (BIM) and Digital Twin** | | | | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.429 | 0.479 | 0.528 | 0.082 | 0.126 | 0.185 | 0.131 |
| **E10: 3D printing** | 1.000 | 1.000 | 1.000 | 2.000 | 2.000 | 2.000 | 0.500 | 0.500 | 0.500 | 0.215 | 0.239 | 0.264 | 0.041 | 0.063 | 0.093 | 0.066 |
| **E12: Internet of Things (IOT)** | 0.400 | 0.500 | 0.667 | 1.400 | 1.500 | 1.667 | 0.029 | 0.056 | 0.092 | 0.012 | 0.027 | 0.048 | 0.002 | 0.007 | 0.017 | 0.009 |
| **E9: Artificial intelligence** | 0.286 | 0.333 | 0.400 | 1.286 | 1.333 | 1.400 | 0.021 | 0.042 | 0.071 | 0.009 | 0.02 | 0.038 | 0.002 | 0.005 | 0.013 | 0.007 |

Table 13 shows the **Fuzzy Decision Matrix** as rated by the first expert. The matrix represents the linguistic scales used by the expert to evaluate each enabler against the criteria. Each entry in the table is expressed as a triangular fuzzy number, reflecting the range of possible values assigned to the importance of each enabler based on the expert's judgment.

Table 13**.** Fuzzy decision matrix between enablers and criteria (Expert 1)

| Enabler Code | Organizational criteria | Enabler Code | Economic criteria | Enabler Code | Technological Criteria |
|---|---|---|---|---|---|
| **E1** | (0.286,0.0.333,0.4) | **E5** | (0.667,1,1.5) | **E9** | (1.5,2,2.5) |
| **E2** | (0.4,0.5,0.667) | **E6** | (1.5,2,2.5) | **E10** | (1.5,2,2.5) |
| **E3** | (0.4,0.5,0.667) | **E7** | (1.5,2,2.5) | **E11** | (0.667,1,1.5) |
| **E4** | (0.286,0.333,0.4) | **E8** | (0.667,1,1.5) | **E12** | (1.5,2,2.5) |

The **Aggregate Fuzzy Decision Matrix** illustrated in table 14 combines the evaluations from all experts, providing a consolidated view of how each enabler is assessed across different criteria. The aggregation is crucial to minimize individual biases and ensure a comprehensive evaluation.

Table 14. Aggregate fuzzy decision matrix between enablers and criteria

| Enabler Code | Organizational criteria | Enabler Code | Economic criteria | Enabler Code | Technological Criteria |
|---|---|---|---|---|---|
| E1 | (0.2647, 0.3053, 0.3620) | E5 | (0.2433, 0.2777, 0.3240) | E9 | (1.2223, 1.6667, 2.1667) |
| E2 | (0.3620, 0.4443, 0.5780) | E6 | (0.2647, 0.3053, 0.3620) | E10 | (1.2223, 1.6667, 2.1667) |
| E3 | (0.2647, 0.3053, 0.3620) | E7 | (0.2647, 0.3053, 0.3620) | E11 | (0.5780, 0.8333, 1.2223) |
| E4 | (0.3620, 0.4443, 0.5780) | E8 | (0.5780, 0.8333, 1.2223) | E12 | (1.2223, 1.6667, 2.1667) |

In table 15, the aggregated fuzzy values from Table 14 are normalized. This normalization step ensures that the values are standardized and comparable across different criteria, allowing for a fair ranking of enablers.

Table 15. Normalized fuzzy decision matrix between enablers and criteria

| Enabler Code | Organizational criteria | Code | Economic criteria | Code | Technological Criteria |
|---|---|---|---|---|---|
| E1 | (0.0860, 0.0993, 0.1177) | E5 | (0.1258, 0.1452, 0.1721) | E9 | (0.1403, 0.1913, 0.2487) |
| E2 | (0.1177, 0.1445, 0.1879) | E6 | (0.1721, 0.2112, 0.2748) | E10 | (0.0664, 0.0957, 0.1403) |
| E3 | (0.1177, 0.1445, 0.1879) | E7 | (0.0860, 0.0993, 0.1177) | E11 | (0.1403, 0.1913, 0.2487) |
| E4 | (0.0860, 0.0993, 0.1177) | E8 | (0.1157, 0.1320, 0.1540) | E12 | (0.1403, 0.1913, 0.2487) |

Table 16 presents the Weighted Normalized Fuzzy Decision Matrix, which is obtained by multiplying the normalized values from Table 15 with the weights computed through the Fuzzy SWARA method. The resulting values provide a clearer picture of how each enabler contributes to the overall objective of Industry 4.0 adoption.

Table 16. Weighted Normalized fuzzy decision matrix between enablers and criteria

| Code | Organizational criteria | Code | Economic criteria | Code | Technological Criteria |
|---|---|---|---|---|---|
| **E1** | (0.0006, 0.0007, 0.0008) | E5 | (0.0014, 0.0016, 0.0019) | E9 | (0.0007, 0.0009, 0.0011) |
| **E2** | (0.0008, 0.0010, 0.0013) | E6 | (0.0019, 0.0023, 0.0030) | E10 | (0.0024, 0.0033, 0.0042) |
| **E3** | (0.0008, 0.0010, 0.0013) | E7 | (0.0008, 0.0010, 0.0013) | E11 | (0.0011, 0.0016, 0.0024) |
| **E4** | (0.0006, 0.0007, 0.0008) | E8 | (0.0013, 0.0015, 0.0017) | E12 | (0.0018, 0.0026,0.0036) |

### 4.3 Final results and ranking using Fuzzy COPRAS

**Table 17** presents the final results and ranking of the **12 Industry 4.0 enablers** for adoption in the Indian construction industry. The enablers were evaluated using the **Fuzzy COPRAS** method, which is a multi-criteria decision-making (MCDM) tool that assigns rankings to alternatives based on their performance across various criteria.

- **Enablers and their Significance**

The **12 enablers** identified and ranked in Table 8 are categorized under **organizational, economic, and technological criteria**, and the table presents their final **Pj**, **Rj**, and **Nj** scores.

- **Pj** represents the sum of the normalized performance values of the enabler, where higher values are preferred.
- **Rj** represents the sum of the inverse normalized performance values, where lower values are preferable.
- **Qj** is the ratio that combines both Pj and Rj to give the overall performance score for each enabler.

- **Nj (%)** represents the normalized final score and indicates the percentage ranking of each enabler.

➢ **Top-Ranked Enablers**

- **Profitability (E6)**: Ranked as the top enabler with an **Nj** value of **100%**, profitability is identified as the most significant factor for Industry 4.0 adoption in the construction industry. This suggests that financial gains and cost-efficiency derived from adopting new technologies are critical motivators for stakeholders.
- **Stakeholders' Investments (E7)**: With an **Nj** score of **93.78%**, this enabler highlights the importance of investments from various stakeholders, including contractors, clients, and financial institutions, to support the digital transformation of construction projects.
- **Governmental Regulations (E4)**: This enabler scored **87.57%** and is ranked third, indicating the crucial role that policies, legal frameworks, and government incentives play in facilitating Industry 4.0 adoption.

➢ **Mid-Ranked Enablers**

- **Market Demand (E8)**: Market demand ranked fourth with a score of **86.46%**, emphasizing that consumer and client willingness to adopt innovative, technology-driven solutions is a key driver for technological integration in construction.
- **Building Information Modeling (BIM) and Digital Twin (E11)**: BIM and Digital Twins, widely recognized for their ability to enhance construction design and real-time project management, are ranked fifth with a score of **83.83%**. This reflects their importance in improving construction project efficiency and decision-making processes.
- **Organization Strategic Planning (E2)**: Ranked sixth with **74.97%**, this enabler emphasizes the need for strategic foresight and careful planning within organizations to successfully integrate Industry 4.0 technologies.

➢ **Lower-Ranked Enablers**

- **Artificial Intelligence (E9)**: Although AI has the potential to revolutionize construction through automation and data analytics, it ranked lower with an **Nj** value of **70.75%**, indicating its relative novelty and the need for further development in construction-specific applications.
- **Internet of Things (IoT) (E12)**: IoT ranked last with a score of **63.47%**, suggesting that while IoT can greatly enhance connectivity and monitoring in construction, its adoption is still in the early stages, particularly in India, where challenges like infrastructure readiness and security concerns may hinder its full integration.

Table 17. Final results and rank of the Enablers

| Enabler code | Enablers | $P_j$ | | | $R_j$ | | | De-fuzzy $P_j$ | De-fuzzy $R_j$ | $Q_j$ | $N_j$ (%) | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E1 | Employers training with corporate ethics | 0.0814 | 0.1131 | 0.1580 | 0.0236 | 0.0418 | 0.0633 | 0.1175 | 0.0429 | 0.1534 | 71.00 | 10 |
| E2 | Organization strategic planning | 0.0760 | 0.1005 | 0.1319 | 0.0176 | 0.0261 | 0.0344 | 0.1028 | 0.0260 | 0.1620 | 74.97 | 6 |
| E3 | Risk-taking behavior | 0.0703 | 0.0935 | 0.1236 | 0.0173 | 0.0234 | 0.0298 | 0.0958 | 0.0235 | 0.1614 | 74.66 | 7 |
| E4 | Governmental regulations | 0.1201 | 0.1632 | 0.2144 | 0.0159 | 0.0687 | 0.1137 | 0.1659 | 0.0661 | 0.1892 | 87.57 | 3 |
| E5 | Rewards and Incentives | 0.0961 | 0.1296 | 0.1710 | 0.0188 | 0.0721 | 0.1165 | 0.1322 | 0.0691 | 0.1545 | 71.51 | 9 |
| E6 | Profitability | 0.1267 | 0.1734 | 0.2316 | 0.0212 | 0.0387 | 0.0595 | 0.1774 | 0.0398 | 0.2161 | 100.00 | 1 |
| E7 | Stakeholders Investments | 0.1257 | 0.1710 | 0.2248 | 0.0306 | 0.0520 | 0.0776 | 0.1738 | 0.0534 | 0.2027 | 93.78 | 2 |
| E8 | Market demand | 0.0945 | 0.1251 | 0.1611 | 0.0174 | 0.0258 | 0.0340 | 0.1269 | 0.0257 | 0.1869 | 86.46 | 4 |
| E9 | Artificial intelligence | 0.0758 | 0.1045 | 0.1457 | 0.0171 | 0.0335 | 0.0539 | 0.1087 | 0.0348 | 0.1529 | 70.75 | 11 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E10 | 3D printing | 0.0970 | 0.1315 | 0.1756 | 0.0136 | 0.0651 | 0.1079 | 0.1347 | 0.0622 | 0.1595 | 73.79 | 8 |
| E11 | Building information modeling (BIM) and Digital Twin | 0.0946 | 0.1290 | 0.1743 | 0.0154 | 0.0307 | 0.0494 | 0.1328 | 0.0319 | 0.1812 | 83.83 | 5 |
| E12 | Internet of Things (IOT) | 0.0633 | 0.0817 | 0.1070 | 0.0211 | 0.0289 | 0.0369 | 0.0840 | 0.0290 | 0.1372 | 63.47 | 12 |

**4.4 Sensitivity Analysis**

The sensitivity analysis is a critical step in evaluating the robustness of the **ARank-FSC** method, which was used to rank enablers for adopting Industry 4.0 technologies in the Indian construction industry. Sensitivity analysis is employed to examine the stability of the final rankings by altering the weights of the criteria and observing how these changes influence the ranking of enablers.

## Purpose of Sensitivity Analysis

The primary objective of sensitivity analysis is to verify the reliability of the rankings produced through the ARank-FSC approach. It allows decision-makers to understand how small changes in the importance of the criteria affect the overall ranking of enablers, thus ensuring that the results are not overly dependent on any specific weighting scheme.

## Sensitivity Runs and Weight Modifications

In total, **19 sensitivity runs** were conducted, each with different weight configurations for the three main criteria: **Economic, Organizational, and Technological**. The changes in the criteria weights aimed to simulate real-world scenarios where the focus might shift from one criterion to another, depending on the organizational or project needs.

- For the **first three runs**, one criterion was given a significantly lower weight (0.015) while the others were assigned larger weights (0.6). This allowed the analysis to observe how each enabler performs when a particular criterion is de-emphasized.

- In **experiments 4 through 17**, the weights of certain criteria were kept constant, while others were varied significantly.
- The final two experiments (**18 and 19**) set some of the criteria weights to zero while increasing others to moderate values, such as 0.3, to further explore extreme scenarios.

## Results of Sensitivity Analysis

Table 18 and Figure 2 present the results of the sensitivity analysis, showing how the rankings of the 12 enablers shifted under different weight configurations. The findings are summarized as follows:

- **Profitability (E6)**: This enabler ranked first in **8 of the 19 tests**, confirming that it is the most robust enabler across a variety of weighting scenarios. Profitability consistently emerged as the top enabler when economic factors were emphasized, underscoring the importance of financial returns for adopting Industry 4.0 technologies.
- **Stakeholders' Investments (E7)**: This enabler performed well in **5 sensitivity tests**, ranking first when the focus shifted towards organizational factors such as stakeholder engagement and investment.
- **Market Demand (E8)**: Ranked first in **5 tests**, particularly when market-driven criteria were prioritized. This suggests that consumer and market demand is a strong driver for Industry 4.0 adoption in construction.
- **3D Printing (E10)**: This technological enabler ranked first in one experiment, highlighting its importance when technological capabilities were prioritized over economic and organizational factors.
- **Internet of Things (IoT) (E12)**: Throughout the analysis, IoT consistently ranked as the lowest enabler, indicating that its adoption is less critical when compared to other factors, especially in scenarios where economic and organizational factors are prioritized.

The sensitivity analysis confirms the robustness of the ARank-FSC method by demonstrating that the top-ranked enablers, particularly **Profitability (E6)** and

**Stakeholders' Investments (E7)**, maintained high rankings across a variety of scenarios. This suggests that these enablers are universally critical, regardless of the specific focus of the decision-makers. The analysis also reveals that while technological enablers like **3D Printing (E10)** and **BIM (E11)** are important, they tend to become more influential only when economic and organizational factors are less emphasized. The sensitivity analysis provides valuable insights into the stability of the enabler rankings, reinforcing the importance of economic factors such as profitability and stakeholder investment. It also highlights that while technological enablers like IoT and 3D printing are important, they are less critical in scenarios where financial and organizational concerns dominate. The robust performance of the top enablers across different scenarios confirms the reliability of the ARank-FSC approach for decision-making in Industry 4.0 adoption in construction.

Table 18. Sensitivity Analysis

| Expt. No. | $N_j$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 | E9 | E10 | E11 | E12 |
| 1 | 69.25 | 80.27 | 73.10 | 93.82 | 88.11 | 100.00 | 96.50 | 83.30 | 90.23 | 71.90 | 71.25 | 52.21 |
| 2 | 79.12 | 80.05 | 67.02 | 90.25 | 87.5 | 100.00 | 97.36 | 83.25 | 92.3 | 72.08 | 72.42 | 48.12 |
| 3 | 78.25 | 78.87 | 67.55 | 92.12 | 92.85 | 98.96 | 100.00 | 82.80 | 93.54 | 71.55 | 72.07 | 62.70 |
| 4 | 32.41 | 28.18 | 36.28 | 30.50 | 58.75 | 63.98 | 100.00 | 39.65 | 30.50 | 40.23 | 31.82 | 38.71 |
| 5 | 62.5 | 86.49 | 49.60 | 89.90 | 48.60 | 100.00 | 50.31 | 50.12 | 90.8 | 49.50 | 60.71 | 39.41 |
| 6 | 51.75 | 57.09 | 68.91 | 90.32 | 65.62 | 70.07 | 100.00 | 65.03 | 91.23 | 63.49 | 93.23 | 97.65 |
| 7 | 86.39 | 80.12 | 82.07 | 67.05 | 62.03 | 94.05 | 93.56 | 100.00 | 65.90 | 89.80 | 59.20 | 49.23 |
| 8 | 35.25 | 27.45 | 40.10 | 32.58 | 97.42 | 46.78 | 100.00 | 44.65 | 40.18 | 43.81 | 41.60 | 62.47 |
| 9 | 94.02 | 54.87 | 97.80 | 89.25 | 65.25 | 100.00 | 67.23 | 60.80 | 55.45 | 93.52 | 61.25 | 52.25 |
| 10 | 44.65 | 47.13 | 41.90 | 90.45 | 64.13 | 100.00 | 48.36 | 48.09 | 90.35 | 47.42 | 60.23 | 41.40 |
| 11 | 42.25 | 29.25 | 39.24 | 56.89 | 62.21 | 100.00 | 39.00 | 51.24 | 56.79 | 90.65 | 41.27 | 37.65 |
| 12 | 60.14 | 51.12 | 49.60 | 84.72 | 80.29 | 95.27 | 93.65 | 100.00 | 84.55 | 56.23 | 57.85 | 49.06 |
| 13 | 87.45 | 79.25 | 51.80 | 82.36 | 91.48 | 93.84 | 93.21 | 100.00 | 83.26 | 59.70 | 85.38 | 51.18 |
| 14 | 59.36 | 81.70 | 93.06 | 55.35 | 45.85 | 63.45 | 93.76 | 54.20 | 55.27 | 100.00 | 41.63 | 41.61 |
| 15 | 62.26 | 55.36 | 66.87 | 57.85 | 97.25 | 68.90 | 100.00 | 56.70 | 91.11 | 51.20 | 60.57 | 41.36 |
| 16 | 87.69 | 79.80 | 51.20 | 82.70 | 91.28 | 94.93 | 93.45 | 100.00 | 83.362 | 53.90 | 57.36 | 50.62 |
| 17 | 43.02 | 52.32 | 47.45 | 39.25 | 80.28 | 95.36 | 94.42 | 100.00 | 52.15 | 48.50 | 54.90 | 59.36 |
| 18 | 76.25 | 78.29 | 71.41 | 96.95 | 88.24 | 100.00 | 95.52 | 82.30 | 93.14 | 69.55 | 71.45 | 67.30 |
| 19 | 82.57 | 67.75 | 82.15 | 78.90 | 92.3 | 100.00 | 96.13 | 99.90 | 79.12 | 94.52 | 75.12 | 75.82 |

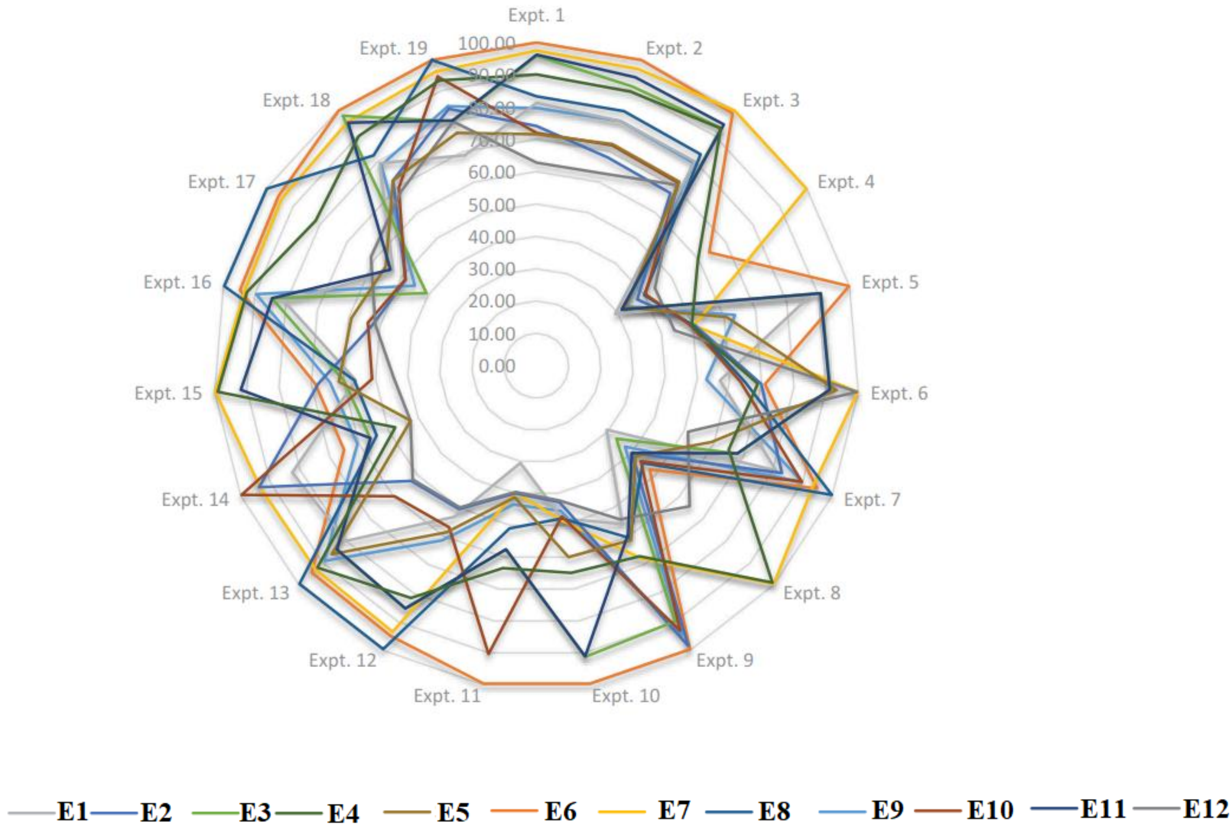


Fig 2. Results of sensitivity analysis ($N_j$ scores)

### 4.5 Discussions

The results of this study focus on identifying and ranking the enablers for the adoption of Industry 4.0 technologies in the construction industry, specifically within the Indian context. The study employs the ARank-FSC (Assessment and Ranking of Industry 4.0 Enablers using Fuzzy SWARA and Fuzzy COPRAS)" method to systematically evaluate these enablers.

- Key Enablers and Their Rankings

Based on the Fuzzy SWARA and Fuzzy COPRAS methodologies, the enablers were ranked to determine their significance in facilitating the adoption of Industry 4.0 technologies in construction. The rankings of these enablers provide valuable insights into which factors are most critical for stakeholders to focus on when integrating these advanced technologies.

1. Profitability (E6): Ranked as the top enabler with an Nj score of 100%, this highlights that financial viability is the most significant driver for adopting Industry 4.0. Profitability ensures that technological investments in the construction industry are sustainable and offer a competitive edge.
2. Stakeholders' Investments (E7): This enabler was ranked second with an Nj score of 93.78%. It emphasizes the importance of collaboration and investment from various stakeholders, such as contractors, suppliers, and clients, to successfully implement Industry 4.0 technologies.
3. Governmental Regulations (E4): Government support through regulations, policies, and incentives was ranked third with an Nj score of 87.57%. This demonstrates the essential role that regulatory frameworks play in encouraging the adoption of smart technologies in construction.
4. Market Demand (E8): Market willingness and demand for innovative construction solutions were ranked fourth with an Nj score of 86.46%. Consumer and client preferences for sustainable and efficient construction projects act as strong motivators for adopting Industry 4.0 technologies.
5. Building Information Modeling (BIM) and Digital Twins (E11): Ranked fifth with an Nj score of 83.83%, BIM and digital twins provide significant advantages in terms of improving design accuracy, construction management, and real-time project monitoring.
6. Organizational Strategic Planning (E2): This enabler, ranked sixth with an Nj score of 74.97%, highlights the need for long-term strategic planning within organizations to ensure the smooth integration of Industry 4.0 technologies.
7. Risk-Taking Behavior (E3): Ranked seventh with an Nj score of 74.66%, this enabler emphasizes that organizations need to foster a culture of innovation and risk-taking to embrace new technologies.
8. 3D Printing (E10): Ranked eighth with an Nj score of 73.79%, 3D printing is gaining attention as a transformative technology for creating complex structures more efficiently, using less material and time.
9. Rewards and Incentives (E5): Ranked ninth with an Nj score of 71.51%, offering rewards and incentives can encourage employees and stakeholders to adopt new technologies and align with Industry 4.0 practices.

10. Employers’ Training with Corporate Ethics (E1): This enabler, ranked tenth with an Nj score of 71.00%, indicates the importance of training employees to develop the necessary skills to work with Industry 4.0 technologies while adhering to corporate ethics.
11. Artificial Intelligence (AI) (E9): Ranked eleventh with an Nj score of 70.75%, AI holds potential but remains underutilized due to technical challenges and its relative novelty in construction.
12. Internet of Things (IoT) (E12): The lowest-ranked enabler, with an Nj score of 63.47%, IoT offers significant opportunities for real-time data collection and communication but faces challenges related to integration and security.

➢ Key Findings

- Profitability emerged as the most critical enabler, indicating that financial returns are the top priority for stakeholders in the construction industry when adopting new technologies.
- Stakeholder investment and government regulations were also ranked highly, suggesting that financial backing and regulatory support are essential for successful Industry 4.0 adoption.
- Technological enablers, such as BIM, 3D printing, and AI, were ranked lower than economic and organizational factors. This suggests that while these technologies have significant potential, their adoption is still contingent on overcoming financial and organizational barriers.
- IoT and AI were the least prioritized enablers, possibly due to the relative novelty of these technologies in the construction industry and the challenges of integrating them with existing systems.

➢ Sensitivity Analysis

A sensitivity analysis was conducted to verify the robustness of the rankings. The weights of the criteria were varied in multiple experiments, and the rankings of the enablers were recalculated. The results from the sensitivity analysis indicate that Profitability (E6) consistently ranked as the top enabler across most experiments, reaffirming its critical importance. Other enablers such as Stakeholders' Investments (E7) and Governmental Regulations (E4) also maintained high rankings in several experiments, further confirming their significance. The sensitivity analysis helps to ensure that the ranking methodology is reliable and robust, even when the weights of the criteria are changed. This provides decision-makers with confidence in the results of the ARank-FSC method.

# 5 Prioritizing Barriers to Industry 4.0 in Construction Industry

This chapter examines the barriers to adopting Industry 4.0 technologies in the Indian construction industry, categorizing them into financial, technological, organizational, regulatory, and market-related barriers. From an initial list of 36 barriers, 20 key barriers were finalized based on expert input. Financial barriers, particularly high initial investment and lack of funding, emerged as the most critical obstacles, followed by technological barriers like data management challenges and complexity of technologies. Regulatory issues, such as poor tax rebates, and organizational factors, including a lack of leadership and resistance to change, were also significant. Market-related barriers were deemed less influential. Using the Fuzzy AHP methodology, the study prioritized these barriers and performed a sensitivity analysis to validate the rankings. The findings highlight the need for financial support, government incentives, and strong leadership to facilitate Industry 4.0 adoption in construction.

The literature review in Section 2.2 identifies 36 key barriers to the implementation of Industry 4.0 technologies in the construction industry, particularly within the Indian context. These barriers are categorized into five primary groups: "**Financial, Technological, Organizational, Market-related, and Regulatory barriers.** To refine and prioritize these barriers, insights were gathered from an expert panel. Based on the panel's recommendations, a total of 20 significant barriers were finalized for further analysis.

The **Fuzzy Analytical Hierarchy Process (FAHP)** method was applied to evaluate the relative importance of these barriers, effectively addressing the uncertainty and complexity inherent in their identification and ranking. The proposed model was implemented in a construction company located in northern India (the organization's identity is withheld for confidentiality reasons). The findings provide a comprehensive understanding of the most critical barriers, offering actionable insights to facilitate the adoption of Industry 4.0 technologies in the Indian construction industry.

## 5.1 Barriers Identification

A survey was developed with insights from the literature study and disseminated to experts and decision-makers. Their expertise was used to explore common barriers in the construction industry to the acceptance of I4.0 technologies. The study considers decision-makers from both industry and academia to mitigate potential biases toward their respective organizations. Eight professionals with over 15 years of experience in the construction industry were chosen to refine identified barriers and construct a pairwise decision matrix. Twenty barriers were eventually classified into five major categories based on both literature research findings and expert opinions, as detailed in Table 19.

### Financial Barriers

Financial barriers represent the most critical obstacle to I4.0 adoption in the construction industry. These barriers are primarily associated with the costs and uncertainties related to technology investments:

- **FI1 - High Initial Investment**: The cost of acquiring and implementing new technologies, such as IoT devices, Building Information Modeling (BIM) software, and automation machinery, presents a significant barrier. Many construction firms, especially small and medium enterprises (SMEs), find it difficult to allocate the necessary financial resources for these upfront costs.
- **FI2 - Uncertain Return on Investment (ROI)**: This barrier arises from the difficulty in predicting the financial benefits of adopting I4.0 technologies. Due to long project cycles and dynamic market conditions, companies face uncertainty in calculating ROI, making it harder to justify investments.
- **FI3 - Lack of Funding**: Many construction firms struggle with securing external funding for technology investments, either due to the lack of investor confidence in the sector or the limited availability of venture capital or government-backed incentives.
- **FI4 - Cost-Benefit Analysis Challenges**: This barrier reflects the complexity of conducting comprehensive cost-benefit analyses for I4.0 technologies. Given the long-term nature of returns and the difficulty in quantifying intangible benefits (e.g., enhanced decision-making through real-time data), many firms struggle to make informed investment decisions.

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**Technological Barriers**

Technological barriers focus on the inherent complexities of adopting I4.0 technologies within construction projects. These include both operational challenges and limitations related to industry standards:

- **TE1 - Complexity of Technologies**: I4.0 technologies, including BIM, AI, and IoT, are often complex and require substantial technical expertise for integration into construction workflows. The fragmented nature of the construction industry exacerbates these complexities.
- **TE2 - Poor Standards and Protocols**: The lack of established industry-wide standards and protocols for technology integration creates significant barriers. Poor

interoperability between various systems leads to delays, increased costs, and potential technical failures.

- **TE3 - Data Management and Security**: The large volume of data generated by I4.0 technologies poses challenges in terms of storage, management, and security. Ensuring data privacy, integrity, and compliance with regulations like the General Data Protection Regulation (GDPR) is crucial but difficult to manage.
- **TE4 - Skill Gaps and Training Needs**: Construction workers often lack the technical skills required to operate and manage advanced digital tools. Training programs are limited, and the slow pace of skill development further hampers the effective adoption of these technologies.

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**Regulatory Barriers**

Regulatory barriers encompass legal and compliance challenges that construction companies face when adopting new technologies. These barriers often involve concerns about safety, liability, and ethical implications:

- **RE1 - Privacy Regulations**: Strict regulations on data handling and privacy, such as the GDPR, make it difficult for construction companies to collect, share, and store data securely. Non-compliance with these regulations can lead to legal and financial consequences.
- **RE2 - Safety and Liability Regulations**: Automation technologies, including drones and robotics, introduce new safety concerns. Ensuring that these technologies meet existing safety standards and liability requirements adds complexity to the adoption process.
- **RE3 - Ethical and Social Implications**: The introduction of I4.0 technologies often leads to job displacement and raises concerns about labor rights and social equity. Ethical considerations around the human impact of automation act as significant barriers to adoption.
- **RE4 - Poor Tax Rebates**: A lack of government-provided financial incentives, such as tax rebates, discourages firms from investing in I4.0 technologies. Without

these incentives, the financial risks associated with technological investments remain high.

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**Organizational Barriers**

Organizational barriers pertain to the internal dynamics and leadership challenges within construction firms that hinder the adoption of I4.0:

- **OR1 - Lack of Leadership and Vision**: The absence of strong, visionary leadership within construction companies prevents the development of strategic goals related to digital transformation. Without clear direction from management, firms struggle to allocate resources and drive technological change.
- **OR2 - Resistance to Change**: Employees and managers may resist the adoption of new technologies due to fear of job loss, a preference for traditional practices, or skepticism about the benefits of I4.0.
- **OR3 - Short-Term Focus and Risk Aversion**: Many construction firms prioritize short-term gains over long-term investments in technology. This risk-averse mentality prevents companies from making the necessary investments in I4.0 (Revised Manuscript 1).
- **OR4 - Lack of Performance Measures**: The absence of well-defined metrics to assess the performance and impact of I4.0 technologies makes it difficult for firms to justify investments and track progress.

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**Market-Related Barriers**

Market barriers focus on external factors, including the behavior of customers, suppliers, and competitors, that influence the adoption of I4.0 technologies:

- **MR1 - Market Fragmentation**: The construction industry is highly fragmented, with many small and medium-sized enterprises (SMEs) operating independently.

This fragmentation limits the ability of firms to invest in and adopt new technologies on a large scale.

- **MR2 - Limited Customer Awareness**: Clients and customers often lack awareness of the benefits of I4.0 technologies. Without customer demand, construction firms may be reluctant to invest in these technologies.
- **MR3 - Vendor Lock-In**: Dependence on a single technology provider can limit a firm's flexibility and increase costs. Firms are often hesitant to adopt I4.0 technologies due to the fear of becoming locked into specific platforms or systems (Revised Manuscript 1).
- **MR4 - Market Volatility**: Economic fluctuations, regulatory changes, and political instability can disrupt investment cycles and delay projects, making firms less willing to adopt expensive new technologies.

**Table 19** Finalized Barriers of I4.0 in Construction Industry

| Major Barriers/Criteria | Barriers Code | Sub-Criterias |
|---|---|---|
| Financial Barriers | FI1 | High Initial Investment |
| | FI2 | Uncertain Return on Investment |
| | FI3 | Lack of Funding |
| | FI4 | Cost-Benefit Analysis Challenges |
| Technological Barriers | TE1 | Complexity of Technologies |
| | TE2 | Poor Standards and Protocols |
| | TE3 | Data Management and Security |
| | TE4 | Skill Gaps and Training needs |
| Regulatory Barriers | RE1 | Privacy Regulations |
| | RE2 | Safety and Liability regulations |
| | RE3 | Ethical and Social Implications |
| | RE4 | Poor tax rebates |
| Organizational Barriers | OR1 | Lack of leadership and Vision |
| | OR2 | Resistant to change |
| | OR3 | Short term focus and Risk Aversion |
| | OR4 | Lack of performance measures |
| Market Barriers | MR1 | Market Fragmentation |
| | MR2 | Limited Customer Awareness |
| | MR3 | Vendor Lock-In |
| | MR4 | Market Volatility |

## 5.2 Pairwise Assessment of Major and Sub Criterias

Table 20 evaluates the comparative importance of these major barriers by assigning fuzzy values to each pair. The comparison shows that financial barriers are considered the most significant, as they are rated highly against all other criteria. Technological and regulatory barriers also score relatively high, indicating their strong influence on I4.0 adoption.

**Table 20** Pairwise Assessment of Major Barriers

| | FI | OR | TE | MR | RE |
|---|---|---|---|---|---|
| FI | (1.00,1.00,1.00) | (1.00,2.00,3.00) | (1.00,2.00,3.00) | (2.00,3.00,4.00) | (2.00,3.00,4.00) |
| OR | (0.33,0.50,1.00) | (1.00,1.00,1.00) | (0.33,0.50,1.00) | (3.00,4.00,5.00) | (0.25,0.33,0.50) |
| TE | (1.00,0.50,0.33) | (1.00,2.00,3.00) | (1.00,1.00,1.00) | (1.00,2.00,3.00) | (2.00,3.00,4.00) |
| MR | (0.25,0.33,0.50) | (0.20,0.25,0.33) | (0.33,0.50,1.00) | (1.00,1.00,1.00) | (0.33,0.50,1.00) |
| RE | (0.25,0.33,0.50) | (2.00,3.00,4.00) | (0.25,0.33,0.50) | (1.00,2.00,3.00) | (1.00,1.00,1.00) |

Table 21 presents the normalized weights and ranking of the major barriers. It reveals that financial barriers (FI) have the highest relative weight (0.655), followed by technological barriers (TE) with a weight of 0.520, and regulatory barriers (RE) with a weight of 0.399. Market barriers (MR) are considered the least important.

**Table 21** Relative Weight and Ranks of major Barriers

| Criteria | Relative Weights | Rank |
|---|---|---|
| FI | 0.655 | 1 |
| OR | 0.372 | 4 |
| TE | 0.520 | 2 |
| MR | 0.021 | 5 |
| RE | 0.399 | 3 |

Likewise, the pairwise assessment of sub-barriers was conducted as illustrated in Table 22-26

**Table 22** Pairwise Assessment of Financial Sub-Barrier (FI)

| | FI1 | FI2 | FI3 | FI4 |
|---|---|---|---|---|
| FI1 | (1.00,1.00,1.00) | (2.00,3.00,4.00) | (0.33,0.50,1.00) | (3.00,4.00,5.00) |
| FI2 | (0.25,0.33,0.50) | (1.00,1.00,1.00) | (0.33,0.50,1.00) | (1.00,2.00,3.00) |
| FI3 | (1.00,2.00,3.00) | (1.00,2.00,3.00) | (1.00,1.00,1.00) | (0.25,0.33,0.50) |
| FI4 | (0.2,0.25,0.33) | (0.33,0.50,1.00) | (2.00,3.00,4.00) | (1.00,1.00,1.00) |

**Table 23** Pairwise Assessment of Organizational Sub-Barrier (OR)

| | OR1 | OR2 | OR3 | OR4 |
|---|---|---|---|---|
| OR1 | (1.00,1.00,1.00) | (3.00,4.00,5.00) | (0.33,0.50,1.00) | (2.00,3.00,4.00) |
| OR2 | (0.20,0.25,0.33) | (1.00,1.00,1.00) | (2.00,3.00,4.00) | (0.25,0.33,0.50) |
| OR3 | (1.00,2.00,3.00) | (0.25,0.33,0.50) | (1.00,1.00,1.00) | (1.00,2.00,3.00) |
| OR4 | (0.25,0.33,0.50) | (2.00,3.00,4.00) | (0.33,0.50,1.00) | (1.00,1.00,1.00) |

**Table 24** Pairwise Assessment of Technological Sub-Barrier (TE)

| | TE1 | TE2 | TE3 | TE4 |
|---|---|---|---|---|
| TE1 | (1.00,1.00,1.00) | (2.00,3.00,4.00) | (1.00,2.00,3.00) | (0.20,0.25,0.33) |
| TE2 | (0.25,0.33,0.50) | (1.00,1.00,1.00) | (0.33,0.50,1.00) | (3.00,4.00,5.00) |
| TE3 | (0.33,0.50,1.00) | (1.00,2.00,3.00) | (1.00,1.00,1.00) | (2.00,3.00,4.00) |
| TE4 | (3.00,4.00,5.00) | (0.20,0.25,0.33) | (0.25,0.33,0.50) | (1.00,1.00,1.00) |

**Table 25** Pairwise Assessment of Market Sub-Barrier (MR)

| | MR1 | MR2 | MR3 | MR4 |
|---|---|---|---|---|
| MR1 | (1.00,1.00,1.00) | (0.25,0.33,0.50) | (0.20,0.25,0.33) | (3.00,4.00,5.00) |
| MR2 | (2.00,3.00,4.00) | (1.00,1.00,1.00) | (2.00,3.00,4.00) | (0.33,0.50,1.00) |
| MR3 | (3.00,4.00,5.00) | (0.25,0.33,0.50) | (1.00,1.00,1.00) | (1.00,2.00,3.00) |
| MR4 | (0.20,0.25,0.33) | (1.00,2.00,3.00) | (0.33,0.50,1.00) | (1.00,1.00,1.00) |

**Table 26** Pairwise Assessment of Regulatory Sub-Barrier (RE)

| | RE1 | RE2 | RE3 | RE4 |
|---|---|---|---|---|
| RE1 | (1.00,1.00,1.00) | (0.20,0.25,0.33) | (3.00,4.00,5.00) | (0.25,0.33,0.50) |
| RE2 | (3.00,4.00,5.00) | (1.00,1.00,1.00) | (0.33,0.50,1.00) | (0.20,0.25,0.33) |
| RE3 | (0.20,0.25,0.33) | (1.00,2.00,3.00) | (1.00,1.00,1.00) | (2.00,3.00,4.00) |
| RE4 | (2.00,3.00,4.00) | (3.00,4.00,5.00) | (0.25,0.33,0.50) | (1.00,1.00,1.00) |

### 5.3 Final results and ranking using Fuzzy AHP

Table 27 presents the final ranking and global weights of sub-barriers that influence the adoption of Industry 4.0 (I4.0) in the construction industry. These sub-barriers are classified under five major categories: financial (FI), organizational (OR), technological (TE), market (MR), and regulatory (RE). The Fuzzy Analytical Hierarchy Process (FAHP) was employed to assess and rank these sub-barriers, accounting for uncertainties in expert judgments through the use of fuzzy logic.

1. **Financial Barriers (FI)**

Financial barriers dominate the overall ranking, with two of the top three sub-barriers being financial in nature.

**FI1: High Initial Investment (Global Weight: 0.489, Rank: 1)**

This is the highest-ranked sub-barrier, indicating that the high cost of initial investment in I4.0 technologies is the most critical challenge. It reflects the substantial upfront costs of acquiring advanced technologies, training personnel, and upgrading infrastructure, which may discourage construction firms from adopting I4.0.

**FI3: Lack of Funding (Global Weight: 0.309, Rank: 2)**

This sub-barrier highlights the difficulties construction firms face in securing external financial support from banks or investors to implement I4.0 technologies.

**FI4: Cost-Benefit Analysis Challenges (Global Weight: 0.248, Rank: 8)**

This sub-barrier points to the complexity in evaluating the long-term benefits of investing in I4.0 technologies, given the evolving nature of technology and market conditions.

**FI2: Uncertain Return on Investment (Global Weight: 0.181, Rank: 11)**

Uncertainty regarding the profitability of I4.0 investments makes it harder for companies to commit resources.

2. **Technological Barriers (TE)**

Technological sub-barriers also rank highly, with the focus on data management and security.

**TE3: Data Management and Security (Global Weight: 0.277, Rank: 3)**

This sub-barrier reflects concerns about managing and securing vast amounts of data in an interconnected I4.0 environment. The construction industry deals with sensitive data, making this a critical issue.

**TE1: Complexity of Technologies (Global Weight: 0.268, Rank: 4)**

The complex and interconnected nature of I4.0 technologies like IoT, robotics, and BIM can be overwhelming for companies lacking technical expertise.

**TE2: Poor Standards and Protocols (Global Weight: 0.253, Rank: 7)**

The lack of standardized protocols and interoperability among I4.0 technologies presents a significant challenge.

**TE4: Skill Gaps and Training Needs (Global Weight: 0.240, Rank: 9)**

This barrier highlights the shortage of skilled personnel required to operate advanced technologies and the need for extensive training.

3. **Organizational Barriers (OR)**

Leadership and vision within organizations play a crucial role in I4.0 adoption.

**OR1: Lack of Leadership and Vision (Global Weight: 0.268, Rank: 5)**

The absence of strong leadership to drive digital transformation initiatives is a key organizational barrier. This sub-barrier underscores the need for visionary leadership to guide companies through the complexities of I4.0 implementation.

**OR3: Short-term Focus and Risk Aversion (Global Weight: 0.173, Rank: 12)**

Many companies are focused on short-term gains, which prevents long-term investment in transformative technologies.

**OR4: Lack of Performance Measures (Global Weight: 0.145, Rank: 15)**

The absence of clear metrics for measuring the success of I4.0 projects makes it difficult to evaluate progress and justify further investment.

**OR2: Resistance to Change (Global Weight: 0.124, Rank: 16)**

Resistance from employees or management towards technological change can be a major barrier to I4.0 adoption, especially in traditionally operated construction firms.

4. **Market Barriers (MR)**

Market-related barriers rank the lowest in the overall assessment, suggesting that other barriers are more critical to address for I4.0 adoption in construction.

**MR1: Market Fragmentation (Global Weight: 0.009, Rank: 19)**

The fragmented nature of the construction industry, composed of numerous small firms, makes it challenging to scale I4.0 technologies.

**MR2: Limited Customer Awareness (Global Weight: 0.013, Rank: 17)**

This highlights that many clients are unaware of the benefits of I4.0 technologies, which hampers adoption.

**MR3: Vendor Lock-in (Global Weight: 0.012, Rank: 18)**

Companies face the risk of becoming dependent on specific vendors for I4.0 technologies, reducing flexibility and increasing costs.

**MR4: Market Volatility (Global Weight: 0.006, Rank: 20)**

Economic fluctuations and changes in the construction market can deter investment in new technologies.

5. **Regulatory Barriers (RE)**

Regulatory barriers are moderately ranked but still pose significant challenges.

**RE4: Poor Tax Rebates (Global Weight: 0.260, Rank: 6)**

Companies are reluctant to invest in I4.0 technologies without adequate financial incentives such as tax rebates.

**RE3: Ethical and Social Implications (Global Weight: 0.195, Rank: 10)**

Concerns about the social and ethical implications of I4.0 technologies, such as job displacement due to automation, hinder widespread adoption.

**RE2: Safety and Liability Regulations (Global Weight: 0.170, Rank: 13)**

Strict regulations around safety and liability make companies cautious about adopting new technologies.

**RE1: Privacy Regulations (Global Weight: 0.158, Rank: 14)**

Data privacy regulations, like the GDPR, require companies to adopt stringent data protection measures, adding complexity to I4.0 adoption.

**Table 27** Final Ranks and Global weights of Sub- barriers

| Criteria | Relative weights | Barriers | Relative weights | Global Weights | Rank |
|---|---|---|---|---|---|
| FI | 0.655 | FI1 | 0.746 | 0.489 | 1 |
| | | FI2 | 0.276 | 0.181 | 11 |
| | | FI3 | 0.471 | 0.309 | 2 |
| | | FI4 | 0.379 | 0.248 | 8 |
| OR | 0.372 | OR1 | 0.720 | 0.268 | 5 |
| | | OR2 | 0.334 | 0.124 | 16 |
| | | OR3 | 0.464 | 0.173 | 12 |
| | | OR4 | 0.391 | 0.145 | 15 |
| TE | 0.520 | TE1 | 0.516 | 0.268 | 4 |
| | | TE2 | 0.486 | 0.253 | 7 |
| | | TE3 | 0.532 | 0.277 | 3 |
| | | TE4 | 0.461 | 0.240 | 9 |
| MR | 0.021 | MR1 | 0.444 | 0.009 | 19 |
| | | MR2 | 0.607 | 0.013 | 17 |
| | | MR3 | 0.595 | 0.012 | 18 |
| | | MR4 | 0.281 | 0.006 | 20 |
| RE | 0.399 | RE1 | 0.395 | 0.158 | 14 |
| | | RE2 | 0.425 | 0.170 | 13 |
| | | RE3 | 0.488 | 0.195 | 10 |
| | | RE4 | 0.651 | 0.260 | 6 |

## 5.4 Sensitivity Analysis

Sensitivity analysis in the manuscript evaluates the robustness of the rankings derived from the Fuzzy Analytical Hierarchy Process (FAHP) by observing how minor variations in the relative weights of criteria influence the prioritization of barriers to Industry 4.0 (I4.0) implementation. This step is crucial for verifying whether the rankings of barriers remain stable when subjected to changes in weighting.

***Key Points of Sensitivity Analysis:***

1. **Impact of Financial Barriers:**
   - The sensitivity analysis focuses primarily on financial barriers (FI), which are recognized as the most critical barriers to I4.0 adoption. The weights of financial barriers are systematically increased in increments (from 0.1 to 0.9) to assess how other barrier rankings respond to these changes. This process helps determine if the dominance of financial barriers significantly affects the prioritization of other barriers.
   - Table 28 illustrates the impact of incremental increases in the weight of financial barriers on the ranking of other major criteria, including organizational (OR), technological (TE), market (MR), and regulatory (RE) barriers. As the weight of the financial barrier increases, notable shifts are observed in the rankings of technological and organizational barriers. This implies that technological and organizational concerns are also crucial but may be overshadowed by financial issues when given greater emphasis.
2. **Observations on Sub-barriers:**
   - The sensitivity analysis revealed that as the weight of financial barriers increases, the **high initial investment (FI1)** becomes increasingly significant, consistently maintaining its rank as the most important barrier as the weight approaches a normalized value of 0.665. Conversely, sub-barriers such as **data management and security (TE3)** initially hold high importance but lose rank as financial barriers gain more weight.

3. **Ranking Variations:**
   - Table 29 and Figure 3, included in the manuscript, visually demonstrates how the rankings of sub-barriers fluctuate with variations in the financial barrier's weight. The technological sub-barriers, particularly **TE3 (Data Management and Security)**, exhibit the most variability, indicating their sensitivity to changes in the weight of financial concerns. On the other hand, market-related barriers (MR) show minimal change, emphasizing that market factors are less influential in comparison to financial and technological issues.
4. **Conclusion of Sensitivity Analysis:**
   - The sensitivity analysis confirms that financial barriers, specifically high initial investment costs and funding challenges, are the most influential in determining the overall prioritization of barriers to I4.0. The findings suggest that while technological and organizational barriers are critical, their ranking depends heavily on the weight assigned to financial constraints. This insight is vital for decision-makers in the construction industry, indicating that efforts to mitigate financial risks could significantly alter the perceived importance of other barriers.

**Table 28** Impact of Incremental Increase (0.1 to 0.9) in FI Barrier Values on Other Criterias

| Criteria | Normalized Weight | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6 | Run 7 | Run 8 | Run 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| FI | 0.655 | 0.100 | 0.200 | 0.300 | 0.400 | 0.500 | 0.600 | 0.700 | 0.800 | 0.900 |
| OR | 0.372 | 0.618 | 0.577 | 0.536 | 0.495 | 0.454 | 0.413 | 0.330 | 0.288 | 0.246 |
| TE | 0.520 | 0.862 | 0.805 | 0.748 | 0.691 | 0.634 | 0.577 | 0.462 | 0.404 | 0.346 |
| MR | 0.021 | 0.033 | 0.031 | 0.029 | 0.027 | 0.025 | 0.023 | 0.018 | 0.015 | 0.012 |
| RE | 0.399 | 0.663 | 0.619 | 0.575 | 0.531 | 0.487 | 0.443 | 0.399 | 0.399 | 0.399 |

**Table 29** Barriers rank after sensitivity analysis

| | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.665 (Normalized) | 0.7 | 0.8 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|---|
| FI1 | 13 | 13 | 11 | 7 | 1 | 1 | 1 | 1 | 1 | 1 |
| FI2 | 16 | 16 | 16 | 16 | 16 | 14 | 11 | 10 | 4 | 4 |
| FI3 | 14 | 14 | 14 | 13 | 9 | 6 | 2 | 2 | 2 | 2 |
| FI4 | 15 | 15 | 15 | 15 | 13 | 9 | 8 | 3 | 3 | 3 |
| OR1 | 4 | 3 | 3 | 3 | 4 | 4 | 5 | 6 | 7 | 7 |
| OR2 | 12 | 12 | 13 | 14 | 15 | 16 | 16 | 16 | 16 | 16 |
| OR3 | 9 | 8 | 8 | 9 | 10 | 11 | 12 | 12 | 12 | 12 |
| OR4 | 11 | 11 | 12 | 12 | 14 | 15 | 15 | 15 | 15 | 15 |
| TE1 | 3 | 2 | 2 | 2 | 3 | 3 | 4 | 5 | 6 | 6 |
| TE2 | 5 | 5 | 5 | 5 | 6 | 7 | 7 | 8 | 9 | 9 |
| TE3 | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 4 | 5 | 5 |
| TE4 | 6 | 6 | 6 | 6 | 7 | 8 | 9 | 9 | 10 | 10 |
| MR1 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 |
| MR2 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 |
| MR3 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| MR4 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| RE1 | 10 | 10 | 10 | 11 | 12 | 13 | 14 | 14 | 14 | 14 |
| RE2 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 13 | 13 | 13 |
| RE3 | 7 | 7 | 7 | 8 | 8 | 10 | 10 | 11 | 11 | 11 |
| RE4 | 2 | 4 | 4 | 4 | 5 | 5 | 6 | 7 | 8 | 8 |

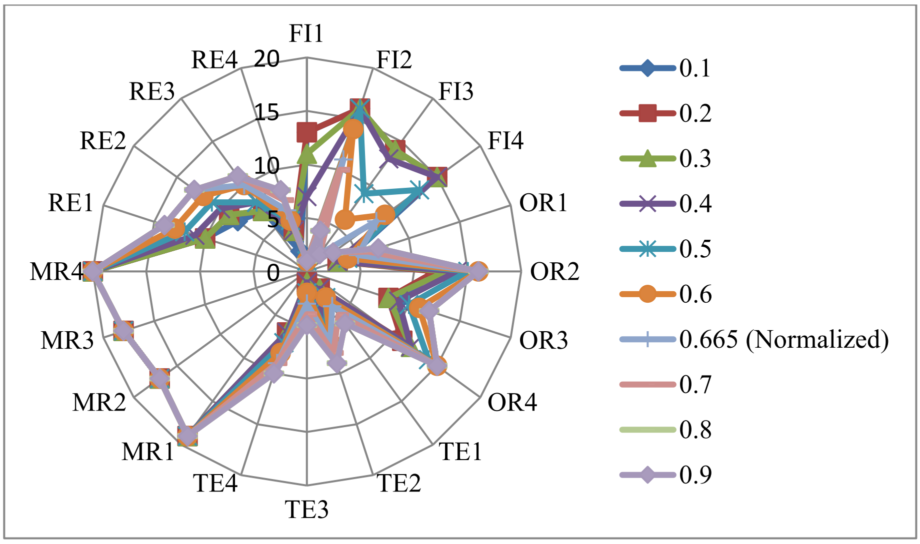


**Fig. 3** Ranking variations after sensitivity analysis

## 5.5 Discussions

The results section of the manuscript provides an in-depth analysis of the barriers to Industry 4.0 (I4.0) adoption in the Indian construction industry. The Fuzzy Analytical Hierarchy Process (FAHP) model used in the study enables decision-makers to prioritize the barriers and sub-barriers based on their relative significance, offering a structured way to tackle the most critical challenges first.

- *Barriers Prioritization*

The prioritization of barriers through FAHP provides valuable insights into which factors are most obstructive to the adoption of I4.0 technologies. The results show that **financial barriers (FI)** are the most significant, followed by **technological barriers (TE)**, **regulatory barriers (RE)**, **organizational barriers (OR)**, and **market-related barriers (MR)**." The relative weight of financial barriers, as shown in Table 5, is **0.655**, making them the most critical area for intervention.

- **FI1 (High Initial Investment)** emerged as the most significant sub-barrier, with a **global weight of 0.489**, underscoring the immense costs associated with implementing I4.0 technologies. This finding is consistent with literature that highlights the high capital expenditure required for advanced technologies in construction(Revised Manuscript 1).
- **FI3 (Lack of Funding)** ranked second overall, with a **global weight of 0.309**, reflecting the need for external financing or government subsidies to support I4.0 initiatives.
- Other significant sub-barriers include **TE3 (Data Management and Security)**, with a **global weight of 0.277**, indicating concerns about handling vast amounts of data securely, and **RE4 (Poor Tax Rebates)**, which ranked 6th overall with a **global weight of 0.260**, reflecting the lack of governmental financial incentives for I4.0 adoption.

- *Technological and Organizational Challenges*

Technological barriers ranked second in the overall prioritization, emphasizing the complexity of I4.0 technologies and the skill gaps within the construction workforce. The study found that:

- **TE3 (Data Management and Security)**, with a **global weight of 0.277**, is a major concern due to the increasing reliance on digital platforms and the risks associated with cybersecurity.
- **TE1 (Complexity of Technologies)**, which ranked fourth overall with a **global weight of 0.268**, highlights the challenges that firms face in integrating various digital tools and systems.

In the organizational category, **OR1 (Lack of Leadership and Vision)** was the most significant barrier, ranking fifth overall. This finding suggests that strong leadership is crucial for driving the cultural and operational shifts necessary for successful I4.0 implementation.

- *Market and Regulatory Barriers*

Market-related barriers were found to have the lowest impact, with **MR4 (Market Volatility)** ranked last. This suggests that, although market conditions affect the adoption of I4.0, they are less significant compared to financial and technological factors.

However, regulatory barriers, particularly **RE4 (Poor Tax Rebates)**, ranked high among sub-barriers, indicating that inadequate financial incentives from the government are a major obstacle.

- *Sensitivity Analysis*

The sensitivity analysis was conducted to test the robustness of the FAHP results by varying the relative weights of the major criteria. The findings indicate that **financial barriers** consistently remained the most critical, even when their weights were reduced. **Technological barriers** showed the most significant fluctuation in ranking when subjected to changes in their weight, further confirming their importance.

# 6 Assessment of Sustainability Impacts of Industry 4.0 Technologies

This chapter evaluates the sustainability impacts of Industry 4.0 technologies in the construction industry across three dimensions: economic, environmental, and social. Using the Fuzzy AHP method, the study identifies and ranks 12 sub-criteria under these dimensions based on their importance. Economic sustainability, with a focus on cost efficiency and resource optimization, is deemed most critical, with off-site construction emerging as the top sub-criterion. Social sustainability follows, highlighting automation and job creation as vital for balancing technological advancements with workforce opportunities. Environmental sustainability, though ranked lowest, emphasizes sustainable construction practices to minimize ecological impacts. A sensitivity analysis reveals that decision-makers prioritize economic factors over environmental and social considerations, particularly under cost constraints. These findings underline the need for balanced strategies to align economic gains with long-term environmental and social objectives in the construction sector.

The literature review in Section 2.3 focuses on identifying the impacts of Industry 4.0 technologies on the three pillars of sustainability—**social, economic, and environmental**—to promote sustainable development in the construction industry. These sustainability dimensions play a crucial role in evaluating how the integration of Industry 4.0 can contribute to achieving long-term sustainability goals, particularly in the construction industry.

To address the complexities and uncertainties associated with human judgment during the evaluation process, the "**Fuzzy Analytic Hierarchy Process (Fuzzy AHP)** method is employed. This method allows for a structured and systematic assessment of sustainability impacts by incorporating expert opinions while addressing ambiguity. The study evaluates the main sustainability criteria—**economic, environmental, and social**—and further breaks them down into sub-criteria that reflect specific sustainability aspects. This approach ensures a comprehensive and prioritized understanding of how Industry 4.0 technologies influence sustainability in the construction industry.

### 6.1 Sustainability Criterias Identification

A case study of a construction company in the Delhi-NCR region is considered for assessment purposes and; the company's identity is suppressed for privacy concerns. The business is well known for its broad experience with large-scale construction projects utilizing cutting-edge technology. With the help of the literature review, a survey was created and distributed to decision-makers and specialists. Their knowledge was put to use investigating typical obstacles to I4.0 technology adoption in the construction industry. In order to reduce potential biases towards their particular organizations, the study takes decision makers from both business and academia into consideration. To further reduce identified restrictions and create a pairwise choice matrix, eight individuals with more than 20 years of experience in the building business were selected. Based on the conclusions of literature study as well as the opinions of experts, 12 variables/sub-criteria were ultimately divided into 3 major criterias, as shown in table 30.

#### i. Major Criteria

The three major criteria that guide sustainability assessments in the construction industry are:

- **Economic Sustainability (EC)**: This focuses on cost efficiency, resource optimization, and long-term financial viability. In the construction industry, economic sustainability is tied to reducing project costs, improving resource use, and achieving financial savings through the use of advanced technologies.
- **Environmental Sustainability (EV)**: This criterion evaluates the impact of construction activities on the environment. It aims to minimize the ecological footprint of projects by reducing waste, improving energy efficiency, and promoting sustainable construction practices.
- **Social Sustainability (SO)**: Social sustainability is centered around improving worker safety, health, well-being, and ensuring fair labor practices. This also involves enhancing collaboration among stakeholders and ensuring that the workforce is upskilled to meet the challenges of new technologies.

**ii. Sub-Criteria**

Each major criterion is broken down into sub-criteria, reflecting specific sustainability objectives.

**Economic Sustainability Sub-Criteria (EC)**

- **EC1 - Building Information Modeling (BIM)**: This technology reduces errors and rework, leading to significant cost savings by improving planning and resource allocation during construction.
- **EC2 - IoT and RFID Technologies**: These enable real-time tracking of materials and equipment, which enhances inventory management, reduces material wastage, and improves operational efficiency.
- **EC3 - Big Data Analytics**: Predictive maintenance through big data analytics reduces downtime and maintenance costs by forecasting equipment failures.
- **EC4 - Off-site Construction**: Utilizing Industry 4.0 technologies for off-site construction reduce overall project costs and increases efficiency by enabling pre-fabrication and optimized resource use.

**Environmental Sustainability Sub-Criteria (EV)**

- **EV1 - IoT Sensors**: These sensors monitor energy usage in real time, which helps optimize energy consumption and reduces the environmental impact of construction activities.
- **EV2 - BIM and Digital Tools**: These technologies facilitate the design of energy-efficient buildings and support the integration of renewable energy sources, promoting greener building practices.
- **EV3 - Smart Construction**: Advanced Industry 4.0 technologies contribute to environmentally sustainable construction by enabling smart resource management and reducing waste.
- **EV4 - Sustainable Construction Practices**: Green building techniques and sustainable material use are promoted to minimize the ecological footprint of construction projects.

**Social Sustainability Sub-Criteria (SO)**

- **SO1 - Wearable Devices and IoT-enabled Machinery**: These technologies provide real-time data on workers' health and safety, reducing risks and improving workplace conditions.
- **SO2 - Digital Platforms**: Digital communication tools enhance collaboration among stakeholders, allowing for more inclusive and transparent decision-making processes.
- **SO3 - Digital Skills Training and Education**: The upskilling of the construction workforce ensures that employees are prepared to operate advanced digital technologies, which improves job satisfaction and career development opportunities.
- **SO4 - Automation and Job Creation**: Automation not only improves operational efficiency but also creates new job opportunities in technology-driven roles while enhancing working conditions.

Table 30 Final Criterias and Sub-criterias of Sustainability

| Label | Major Criteria | Sub-criteria | Label |
|---|---|---|---|
| **EC** | **Economic** | Building Information Modeling (BIM) | EC1 |
| | | IoT and RFID Technologies | EC2 |
| | | Big Data Analytics | EC3 |
| | | Off-site Construction | EC4 |
| **EV** | **Environmental** | IoT Sensors | EV1 |
| | | BIM and Digital Tools | EV2 |
| | | Smart Construction | EV3 |
| | | Sustainable Construction Practices | EV4 |
| **SO** | **Social** | Wearable Devices and IoT-enabled Machinery | SO1 |
| | | Digital Platforms | SO2 |
| | | Digital Skills Training and Education | SO3 |
| | | Automation and Job Creation | SO4 |

### 6.2 Pairwise Assessment of Major and Sub Criterias

**Table 31** shows the pairwise comparison of the three major criteria: **Economic (EC), Environmental (EV), and Social (SO)**. The numbers in parentheses represent the fuzzy triangular values used to compare the importance of each criterion. The table captures the following key points:

- **Economic (EC)** is compared against Environmental (EV) and Social (SO), where EC is more important than both, as reflected by the fuzzy values: EC to EV (2,3,4) and EC to SO (3,4,5). This indicates a strong preference for economic considerations in the construction industry.
- **Environmental (EV)** is given lower importance when compared to EC, with a fuzzy value of (0.25, 0.33, 0.50), indicating that environmental sustainability is seen as less critical in relation to economic factors.
- **Social (SO)** is compared with EV, showing that SO is considered more important, but still secondary to economic factors.

The pairwise comparisons are essential for calculating the relative weights of each criterion, which reflects how decision-makers prioritize these sustainability dimensions. This analysis shows a strong preference for economic factors over social and environmental aspects, aligning with previous research highlighting cost-efficiency as a key driver in construction (Azhar, 2011; Li et al., 2022).

Table 31. Pairwise Assessment of Major criteria

| | EC | EV | SO |
|---|---|---|---|
| EC | (1, 1, 1) | (2, 3, 4) | (3, 4, 5) |
| EV | (0.25, 0.33, 0.50) | (1, 1, 1) | (1, 2, 3) |
| SO | (0.20, 0.25, 0.33) | (0.33, 0.50, 1) | (1, 1, 1) |

**Table 32** presents the **relative weights and ranks** of the three major sustainability criteria:

- **Economic (EC)** has the highest relative weight of **0.333** and is ranked **1st**, indicating its dominance in decision-making.
- **Social (SO)** has a relative weight of **0.264** and is ranked **2nd**, reflecting its moderate importance.
- **Environmental (EV)**, with the lowest relative weight of **0.189**, is ranked **3rd**, showing it is less prioritized in construction sustainability assessments.

The results indicate that economic concerns, such as cost savings and resource efficiency, remain the primary focus in the construction industry. This is consistent with studies that highlight the cost-driven nature of construction projects and the tendency to prioritize economic benefits over environmental and social factors (Perera et al., 2020; Wang et al., 2021).

Table 32. Summary of Relative Weights and Ranks

| Major Criteria | Relative Weights | Rank |
|---|---|---|
| EC (Economic) | 0.333 | 1 |
| SO (Social) | 0.264 | 2 |
| EV (Environmental) | 0.189 | 3 |

**Table 33** breaks down the **economic (EC)** dimension into four sub-criteria: **Building Information Modeling (BIM)**, **IoT and RFID Technologies**, **Big Data Analytics**, and **Off-site Construction**.

- **Off-site Construction (EC4)** is rated the highest, with values like (3,4,5) against other sub-criteria, reflecting its significant impact on cost reduction and efficiency gains.
- **Building Information Modeling (BIM) (EC1)** is considered important but less critical than off-site construction, with values like (1,1,1) when compared with other sub-criteria.
- **Big Data Analytics (EC3)** and **IoT and RFID Technologies (EC2)** are given moderate importance in comparison to BIM and Off-site Construction.

The table highlights that decision-makers in the construction industry prioritize technologies like **Off-site Construction** and **BIM**, which directly reduce costs and optimize resources, as found in previous studies (Azhar, 2011; Perera et al., 2020).

Table 33. Pairwise Assessment of Economic Sub-criteria

| | **EC1 (BIM)** | **EC2 (IoT and RFID)** | **EC3 (Big Data Analytics)** | **EC4 (Off-site Construction)** |
|---|---|---|---|---|
| EC1 | (1, 1, 1) | (2, 3, 4) | (0.33, 0.5, 1) | (3, 4, 5) |
| EC2 | (0.25, 0.33, 0.5) | (1, 1, 1) | (0.33, 0.5, 1) | (1, 2, 3) |
| EC3 | (1, 2, 3) | (1, 2, 3) | (1, 1, 1) | (0.25, 0.33, 0.5) |
| EC4 | (0.2, 0.25, 0.33) | (0.33, 0.5, 1) | (2, 3, 4) | (1, 1, 1) |

**Table 34** evaluates the **environmental (EV)** dimension by comparing the sub-criteria: **IoT Sensors**, **BIM and Digital Tools**, **Smart Construction**, and **Sustainable Construction Practices**.

- **Sustainable Construction Practices (EV4)** is rated the highest, with values (3,4,5) when compared to other environmental sub-criteria, underscoring the importance of reducing the environmental footprint.

- **IoT Sensors (EV1)** are also important but considered slightly less impactful than Sustainable Practices, as reflected by lower values in pairwise comparisons.
- **BIM and Digital Tools (EV2)** and **Smart Construction (EV3)** are seen as contributing to environmental sustainability but rank lower.

The emphasis on **Sustainable Construction Practices** aligns with current trends in green building design and sustainable practices aimed at minimizing environmental impacts (Zuo & Zhao, 2014).

Table 34. Pairwise Assessment of Environmental Sub-criteria

| | **EV1 (IoT Sensors)** | **EV2 (BIM and Digital Tools)** | **EV3 (Smart Construction)** | **EV4 (Sustainable Construction Practices)** |
|---|---|---|---|---|
| EV1 | (1, 1, 1) | (2, 3, 4) | (0.33, 0.5, 1) | (3, 4, 5) |
| EV2 | (0.25, 0.33, 0.5) | (1, 1, 1) | (0.33, 0.5, 1) | (1, 2, 3) |
| EV3 | (1, 2, 3) | (1, 2, 3) | (1, 1, 1) | (0.25, 0.33, 0.5) |
| EV4 | (0.2, 0.25, 0.33) | (0.33, 0.5, 1) | (2, 3, 4) | (1, 1, 1) |

**Table 35** assesses the **social (SO)** dimension, comparing sub-criteria such as **Wearable Devices and IoT-enabled Machinery**, **Digital Platforms**, **Digital Skills Training**, and **Automation and Job Creation**.

- **Automation and Job Creation (SO4)** is ranked the highest with strong comparisons (3,4,5) against other sub-criteria. This reflects the critical role that automation plays in both enhancing operational efficiency and creating new job opportunities.
- **Wearable Devices and IoT (SO1)** follow closely behind, due to their impact on worker safety and well-being.
- **Digital Skills Training (SO3)** and **Digital Platforms (SO2)** are recognized for their importance but are ranked lower in comparison to SO4.

This ranking highlights the construction industry's focus on the social benefits of technological advancements, particularly the job creation potential of automation, which is consistent with recent literature on digital transformation (Lu, 2022).

Table 35. Pairwise Assessment of Social Sub-criteria

| | SO1 (Wearable Devices and IoT) | SO2 (Digital Platforms) | SO3 (Digital Skills) | SO4 (Automation and Job Creation) |
|---|---|---|---|---|
| SO1 | (1, 1, 1) | (2, 3, 4) | (0.33, 0.5, 1) | (3, 4, 5) |
| SO2 | (0.25, 0.33, 0.5) | (1, 1, 1) | (0.33, 0.5, 1) | (1, 2, 3) |
| SO3 | (1, 2, 3) | (1, 2, 3) | (1, 1, 1) | (0.25, 0.33, 0.5) |
| SO4 | (0.2, 0.25, 0.33) | (0.33, 0.5, 1) | (2, 3, 4) | (1, 1, 1) |

### 6.3 Final results and ranking using Fuzzy AHP

**Table 36** ranks the global weights of various sub-criteria under the major criteria of **economic, environmental, and social sustainability**. These sub-criteria were evaluated using a **Fuzzy Analytic Hierarchy Process (Fuzzy AHP)** to assess their relative importance within the construction industry.

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## Economic Sustainability (EC)

Economic sustainability received the highest relative weight (0.333), emphasizing its critical importance within the construction industry. The four sub-criteria ranked under this criterion are:

- **EC4 - Off-site Construction (Global Weight: 0.122, Rank: 1)**: Off-site construction ranks the highest due to its potential to significantly reduce costs and improve efficiency. This approach minimizes on-site labor and material waste, contributing to greater productivity and resource optimization (Li et al., 2022).
- **EC1 - Building Information Modeling (BIM) (Global Weight: 0.088, Rank: 3)**: BIM plays a vital role in enhancing project management, collaboration, and visualization, resulting in cost savings and fewer project delays. Its ability to streamline project design and reduce rework makes it an essential tool in modern construction (Azhar, 2011).

- **EC3 - Big Data Analytics (Global Weight: 0.073, Rank: 4)**: Big data analytics improves operational efficiency through predictive maintenance and enhanced resource management. The ability to leverage vast amounts of data to optimize decision-making processes underscores its growing importance (Zhong et al., 2016).
- **EC2 - IoT and RFID (Global Weight: 0.051, Rank: 8)**: IoT and RFID technologies, though ranked lower in importance, are crucial for tracking materials and enhancing inventory management. Their capacity to enable real-time monitoring of resources contributes to improved efficiency in construction operations (Gbadamosi et al., 2020).

## Environmental Sustainability (EV)

Environmental sustainability was assigned a relative weight of 0.189, indicating moderate importance relative to the economic and social dimensions. The four sub-criteria under this criterion are:

- **EV4 - Sustainable Construction Practices (Global Weight: 0.069, Rank: 6)**: Sustainable construction practices, such as energy-efficient designs and green building techniques, ranked the highest in this category. These practices are critical in reducing the environmental impact of construction projects and promoting long-term sustainability (Zuo & Zhao, 2014).
- **EV1 - IoT Sensors (Global Weight: 0.050, Rank: 9)**: IoT sensors play an essential role in environmental sustainability by facilitating real-time monitoring of energy consumption and resource use, which contributes to optimizing the environmental performance of construction projects (Kamilaris et al., 2019).
- **EV3 - Smart Construction (Global Weight: 0.041, Rank: 10)**: Smart construction technologies, while beneficial for resource efficiency, rank lower in this analysis, likely due to their indirect impact on environmental outcomes compared to more direct interventions like sustainable construction practices (Zhou et al., 2015).
- **EV2 - BIM and Digital Tools (Global Weight: 0.029, Rank: 12)**: BIM and digital tools, though important for planning energy-efficient buildings, are ranked lower

in environmental sustainability because their effects are more indirect compared to hands-on practices like sustainable construction (Oesterreich & Teuteberg, 2016).

## Social Sustainability (SO)

Social sustainability, with a relative weight of 0.264, reflects its significant role in advancing digital transformation in the construction industry. The four sub-criteria within this category are:

- **SO4 - Automation and Job Creation (Global Weight: 0.097, Rank: 2)**: Automation not only improves operational efficiency but also creates opportunities for job growth, making it the second-highest ranked factor overall. This reflects the industry's interest in technologies that balance technological advancement with job creation (Lu, 2022).
- **SO1 - Wearable Devices and IoT (Global Weight: 0.069, Rank: 5)**: Wearable devices that enhance worker safety and monitor health are essential to improving workplace conditions. This technology supports social sustainability by reducing risks and improving the well-being of workers (Guo et al., 2017).
- **SO3 - Digital Skills Training (Global Weight: 0.057, Rank: 7)**: The development of digital skills is crucial for workforce adaptability in the face of new technologies. Upskilling initiatives improve job satisfaction and ensure that workers are prepared to handle the technological demands of the industry (Perera et al., 2020).
- **SO2 - Digital Platforms (Global Weight: 0.040, Rank: 11)**: Digital platforms, while valuable for enhancing communication and collaboration among stakeholders, are ranked lower in terms of overall impact on social sustainability. Their benefits, though important, are viewed as less direct compared to technologies that drive safety and job creation (Oesterreich & Teuteberg, 2016).

Table 36. Global Weights and Ranks of Sub-criterias

| Criteria | Relative Weights | Sub-Criteria | Relative Weights | Global Weights | Rank |
|---|---|---|---|---|---|
| **Economic** | 0.333 | EC1 (BIM) | 0.263 | 0.088 | 3 |
| | | EC2 (IoT and RFID) | 0.153 | 0.051 | 8 |
| | | EC3 (Big Data Analytics) | 0.218 | 0.073 | 4 |
| | | EC4 (Off-site Construction) | 0.366 | 0.122 | 1 |
| **Environmental** | 0.189 | EV1 (IoT Sensors) | 0.263 | 0.05 | 9 |
| | | EV2 (BIM and Digital Tools) | 0.153 | 0.029 | 12 |
| | | EV3 (Smart Construction) | 0.218 | 0.041 | 10 |
| | | EV4 (Sustainable Construction Practices) | 0.366 | 0.069 | 6 |
| **Social** | 0.264 | SO1 (Wearable Devices and IoT) | 0.263 | 0.069 | 5 |
| | | SO2 (Digital Platforms) | 0.153 | 0.04 | 11 |
| | | SO3 (Digital Skills) | 0.218 | 0.057 | 7 |
| | | SO4 (Automation and Job Creation) | 0.366 | 0.097 | 2 |

### 6.4 Sensitivity Analysis

Sensitivity analysis in this study evaluates the robustness of the prioritization of sustainability criteria under different weighting scenarios. The analysis primarily focuses on how changing the weight of the **Economic (EC)** criterion affects the relative importance of the **Environmental (EV)** and **Social (SO)** criteria. The purpose of this analysis is to observe the shifts in rankings of sub-criteria across the economic, environmental, and social dimensions when the economic criterion's weight is incrementally increased.

➢ **Key Steps in Sensitivity Analysis:**

1. **Varying the Economic Criterion Weight**:
   - The sensitivity analysis is conducted by increasing the weight of the **Economic** criterion from **0.1 to 0.9** in steps of 0.1.
   - This allows the study to assess how the importance of the Environmental and Social criteria diminishes as economic considerations become more prioritized.
2. **Impact on Major Criteria**:
   - As the weight of **Economic (EC)** increases, the relative importance of the **Environmental (EV)** and **Social (SO)** criteria decreases significantly.

- This effect is illustrated in **Table 37**, where the normalized weights of EV and SO reduce as the EC weight increases. For example:
  - At an EC weight of 0.1, the normalized weight of EV is **0.375**, and SO is **0.525**.
  - At an EC weight of 0.9, the normalized weight of EV drops to **0.042**, and SO reduces to **0.058**.

Table 37 Major criteria weight variations after increasing Economic weight value

| Criteria | Normalized Weight | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6 | Run 7 | Run 8 | Run 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Economic | 0.333 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
| Environmental | 0.189 | 0.375 | 0.334 | 0.292 | 0.25 | 0.209 | 0.167 | 0.125 | 0.083 | 0.042 |
| Social | 0.264 | 0.525 | 0.466 | 0.408 | 0.35 | 0.291 | 0.233 | 0.175 | 0.117 | 0.058 |

➢ **Sub-Criteria Rank Changes:**

- **Table 38 and figure 4** shows how the rankings of sub-criteria change across different economic weight runs.
- **Off-site Construction (EC4)** consistently ranks first across all runs, emphasizing its critical importance in enhancing efficiency and reducing costs. This stable ranking highlights its significant value in the construction industry, regardless of economic weight shifts.
- **Building Information Modeling (BIM) (EC1)** remains consistently ranked third throughout most runs, except for a slight improvement in Run 8 where it rises to second position. This stability underscores the importance of BIM in improving project design, reducing rework, and enhancing collaboration within the construction industry.
- **Big Data Analytics (EC3)** maintains a stable fourth position across all runs, reflecting its consistent role in improving operational efficiency and resource management through predictive analytics.
- **IoT and RFID (EC2)**, while essential for material tracking and inventory management, consistently ranks lower at eighth place, with only a minor shift to

seventh in Run 7. This suggests that its significance, while recognized, is seen as secondary compared to other economic sub-criteria.

- **Sustainable Construction Practices (EV4)** holds a middle-ranking position, fluctuating slightly between fifth and sixth positions across the runs. This suggests that while sustainability is a concern, it may be deprioritized in favor of more immediate economic benefits, especially when economic weight is emphasized.
- **IoT Sensors (EV1)** consistently occupy the ninth and tenth positions throughout all runs, indicating a lesser focus on environmental optimization through real-time monitoring as economic priorities take precedence.
- **Wearable Devices and IoT (SO1)** demonstrate stable rankings in fifth place across most runs, showcasing a consistent focus on worker safety and well-being in social sustainability.
- **Automation and Job Creation (SO4)** maintains a strong second position for the majority of the runs, dropping only to third in Run 8. This demonstrates the construction industry's recognition of the balance between automation and workforce expansion, further emphasizing the digital transformation of the industry.
- **BIM and Digital Tools (EV2)**, **Smart Construction (EV3)**, and **Digital Platforms (SO2)** rank consistently lower across the runs, suggesting that their impact is less direct or prioritized compared to the economic and social sub-criteria.

Table 38 Ranks after variations (post sensitivity analysis)

| **Sub-Criteria** | **Run 1** | **Run 2** | **Run 3** | **Run 4** | **Run 5** | **Run 6** | **Run 7** | **Run 8** | **Run 9** |
|---|---|---|---|---|---|---|---|---|---|
| EC1 (BIM) | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 |
| EC2 (IoT and RFID) | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 8 | 8 |
| EC3 (Big Data Analytics) | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| EC4 (Off-site Construction) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| EV1 (IoT Sensors) | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 10 |
| EV2 (BIM and Digital Tools) | 12 | 12 | 12 | 11 | 12 | 12 | 12 | 12 | 11 |
| EV3 (Smart Construction) | 10 | 9 | 10 | 10 | 10 | 10 | 10 | 10 | 11 |
| EV4 (Sustainable Construction Practices) | 6 | 6 | 6 | 6 | 5 | 6 | 6 | 6 | 6 |
| SO1 (Wearable Devices and IoT) | 5 | 5 | 5 | 5 | 6 | 5 | 5 | 5 | 5 |
| SO2 (Digital Platforms) | 11 | 11 | 11 | 12 | 11 | 11 | 11 | 11 | 12 |
| SO3 (Digital Skills) | 7 | 7 | 7 | 7 | 7 | 7 | 8 | 7 | 7 |
| SO4 (Automation and Job Creation) | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 |

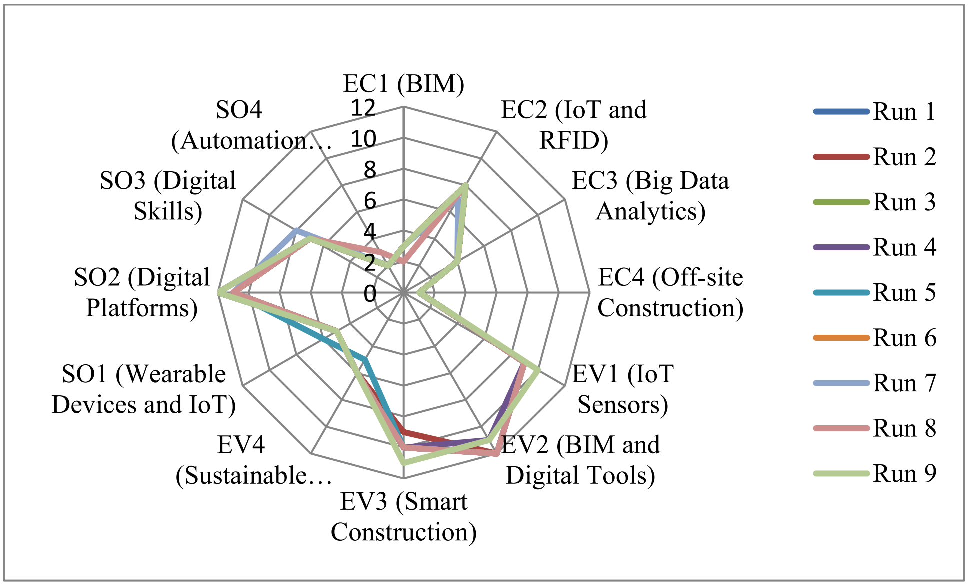


Fig 4. Rank variations after sensitivity analysis

### 6.5 Discussions

This chapter delves into the integration of Industry 4.0 (I4.0) technologies into the construction industry, with a specific focus on the economic, environmental, and social sustainability dimensions." The study employs a Fuzzy Analytic Hierarchy Process (Fuzzy AHP) to identify and rank the relative importance of sub-criteria within each sustainability dimension. Below is a detailed discussion of the key findings:

## a) Economic Sustainability

**Results**: Economic sustainability emerges as the most critical dimension in the construction industry, with a relative weight of 0.333. Among the sub-criteria, *Off-site Construction (EC4)* ranks the highest, with a global weight of 0.122. This is followed by *Building Information Modeling (BIM) (EC1)*, *Big Data Analytics (EC3)*, and *IoT and RFID (EC2)*. Off-site construction, which focuses on prefabrication and minimizing on-site labor, offers significant economic advantages by enabling faster project delivery and cost reduction, underscoring the industry's emphasis on cost efficiency and resource optimization.

**Discussion**: The prioritization of economic sustainability aligns with prior studies, which highlight the cost-driven nature of construction projects (Azhar, 2011). BIM's role in reducing rework and enhancing project management also contributes to cost savings (Perera et al., 2020). However, the lower ranking of IoT and RFID technologies, despite their ability to improve material tracking and inventory management, points to their underutilization in the industry.

## b) Environmental Sustainability

**Results**: Environmental sustainability is ranked lower than economic and social criteria, with a relative weight of 0.189. The highest-ranked sub-criterion in this category is *Sustainable Construction Practices (EV4)*, with a global weight of 0.069, followed by *IoT Sensors (EV1)*, *Smart Construction (EV3)*, and *BIM and Digital Tools (EV2)*. This reflects a focus on reducing the environmental footprint through sustainable practices and optimizing energy use.

**Discussion**: While environmental sustainability is acknowledged, it often takes a back seat to economic priorities. Prior research has shown that sustainable practices are crucial for mitigating the industry's environmental impact, yet immediate cost savings tend to be prioritized (Zuo & Zhao, 2014). The relatively low ranking of technologies such as BIM and Smart Construction suggests that their environmental potential remains underutilized in current construction projects.

## c) Social Sustainability

**Results**: Social sustainability is assigned a relative weight of 0.264, underscoring the importance of job creation and worker well-being. *Automation and Job Creation (SO4)* ranks the highest among the social sub-criteria, with a global weight of 0.097. This demonstrates the industry's dual focus on improving efficiency through automation while addressing the need to create new job opportunities in an increasingly digitalized industry. *Wearable Devices and IoT (SO1)*, which enhance worker safety, rank second.

**Discussion**: The emphasis on automation and job creation reflects the industry's commitment to maintaining workforce relevance amid technological advancements (Lu, 2022). Wearable devices also play a vital role in improving worker safety, a critical concern in an accident-prone industry. These findings are consistent with broader discussions on how Industry 4.0 introduces both challenges and opportunities for workers, necessitating digital skills training and workforce development (Perera et al., 2020).

## d) Sensitivity Analysis

**Results**: The sensitivity analysis highlights the dynamic nature of sustainability prioritization. When the weight assigned to the economic criterion increases, the importance of environmental and social criteria diminishes significantly. For instance, when the weight of economic criteria rises to 0.9, the normalized weights of environmental and social criteria drop to 0.042 and 0.058, respectively.

**Discussion**: This result demonstrates that decision-makers in the construction industry tend to prioritize economic efficiency over environmental and social concerns when resources are constrained, or when cost-saving measures are critical. However, as economic pressures ease, environmental and social sustainability gain more importance. This variability suggests that a balanced approach is necessary to ensure environmental and social goals are not neglected (Wang et al., 2021).

# 7 Strategic Assessment of Industry 4.0 Perceived Risks

This chapter identifies and evaluates perceived risks hindering the adoption of Industry 4.0 (I4.0) technologies in the construction industry using the Analytic Hierarchy Process

(AHP) and Fuzzy AHP methodologies. The study categorizes risks into four major areas: technological, organizational, regulatory, and financial. Technological risks, particularly cybersecurity and data privacy issues, rank as the most critical, followed by interoperability challenges and technological complexity. Organizational risks, including resistance to change and workforce skill gaps, are significant but rank lower. Regulatory risks, such as compliance with evolving standards and data privacy regulations, are substantial concerns, while financial risks, notably high initial costs and ROI uncertainty, also pose challenges. Sensitivity analysis validates the findings, highlighting the dominance of cybersecurity and privacy concerns across all scenarios. The chapter emphasizes the need for secure, privacy-compliant, and integrated approaches to Industry 4.0 implementation in the construction sector.

## 7.1 **Perceived Risks Identification**

With the help of the literature review, a survey was created and distributed to decision-makers and specialists. Their knowledge was put to use investigating typical obstacles to I4.0 technology adoption in the construction industry. In order to reduce potential biases towards their particular organizations, the study takes decision makers from both business and academia into consideration. To further reduce identified restrictions and create a pairwise choice matrix, Twenty three individuals with more than 15 years of experience in the building business were selected for achieving more reliable and consistent results. Table 39 illustrates finalized perceived risks considered from case analysis.

### a) Technological Risks

These are the most significant perceived risks associated with adopting I4.0 technologies in construction:

- **Cybersecurity Risks**: This includes concerns about data breaches, hacking, and unauthorized access to sensitive project information. Cybersecurity is the top perceived risk, as construction projects increasingly rely on digital tools and data exchanges (Patel et al., 2023).
- **Data Privacy Issues**: As construction processes become more digitized, managing personal and sensitive data securely becomes critical (Liu et al., 2019). Inadequate data privacy safeguards lead to significant risk.
- **Interoperability Challenges**: The challenge of integrating new I4.0 technologies with existing systems is a prominent risk, potentially leading to operational disruptions (Khosrowshahi & Arayici, 2012).
- **Technological Complexity**: The complexity of using new technologies can result in steep learning curves and high training costs (Sharma & Sharma, 2022).

### b) Organizational Risks

Organizational risks arise from the internal challenges construction firms face in adopting I4.0 technologies:

- **Resistance to Change**: Employees and stakeholders may be reluctant to adopt new technologies due to uncertainty and the disruption of existing workflows (Kumar et al., 2020).
- **Lack of Skilled Workforce**: The shortage of skilled workers capable of managing and operating advanced I4.0 technologies is a significant barrier to adoption (Gupta & Jain, 2021).
- **Infrastructure Limitations**: Inadequate technological infrastructure within firms hinders the effective implementation of I4.0 solutions (Sharma & Sharma, 2022).

**c) Regulatory Risks**

Regulatory risks stem from the evolving and unclear regulatory environment:

- **Compliance with Evolving Standards**: New and evolving regulations around I4.0 technologies can create uncertainties and challenges regarding compliance (Khosrowshahi & Arayici, 2012).
- **Data Privacy Regulations**: Compliance with stringent data privacy laws adds complexity to the adoption of technologies that handle sensitive data (Liu et al., 2019).
- **Safety and Liability Issues**: Ensuring that new technologies meet safety standards and addressing liability concerns pose significant risks (Kumar et al., 2020).

**d) Financial Risks**

Financial risks are associated with the cost and economic implications of adopting I4.0 technologies:

- **High Initial Costs**: The significant capital investment required for implementing I4.0 solutions is a major financial barrier (Patel et al., 2023).
- **Cost Overruns**: There is a risk of exceeding budgets due to unforeseen expenses during the implementation of new technologies (Gupta & Jain, 2021).
- **ROI Uncertainty**: Uncertainty about the return on investment and the long-term benefits of adopting I4.0 technologies adds to the financial risk (Kumar et al., 2020).

Table 39 Finalized perceived risks considered for case analysis

| Category | Alternatives | Description |
|---|---|---|
| Technological Risks | Cybersecurity Risks | Threats related to data breaches, hacking, and unauthorized access to sensitive project information. |
| | Data Privacy Issues | Risks associated with the collection, storage, and management of sensitive and personal data. |
| | Interoperability Challenges | Difficulties in integrating new technologies with existing systems and processes. |
| | Technological Complexity | Complexity of new technologies leading to a steep learning curve and increased training requirements. |
| Organizational Risks | Resistance to Change | Employee and stakeholder resistance to adopting new technologies due to fear of disruption or uncertainty. |
| | Lack of Skilled Workforce | Shortage of skilled professionals capable of operating and managing advanced Industry 4.0 technologies. |
| | Infrastructure Limitations | Inadequate technological infrastructure to support the deployment and integration of Industry 4.0 solutions. |
| Regulatory Risks | Compliance with Evolving Standards | Uncertainty and challenges in adhering to new and evolving regulations and standards for Industry 4.0 technologies. |
| | Data Privacy Regulations | Challenges related to compliance with data privacy laws and regulations. |
| | Safety and Liability Issues | Risks related to ensuring compliance with safety standards and handling liability issues. |
| Financial Risks | High Initial Costs | Significant capital investment required for the adoption of Industry 4.0 technologies. |
| | Cost Overruns | Risk of exceeding budget due to unforeseen expenses related to technology implementation. |
| | ROI Uncertainty | Uncertainty regarding the return on investment and long-term benefits of adopting new technologies. |

**7.2 Pairwise Assessment of Major Category and Alternatives**

Table 40 displays the pairwise comparison of the major risk categories in Industry 4.0 adoption within the construction industry. The four major categories assessed are Technological Risks, Organizational Risks, Regulatory Risks, and Financial Risks.

- Technological Risks are deemed the most critical, consistently outranking the others, with values like (3,4,5) when compared to Organizational and Regulatory Risks.

- Organizational Risks rank the lowest, as seen in their lower comparison values (0.33, 0.25, 0.20) against the other categories.
- Regulatory Risks fall between technological and organizational risks, primarily due to the uncertainty surrounding new and evolving regulations.
- Financial Risks are also significant, reflecting concerns over the initial costs and uncertainty in return on investment associated with new technologies.

Table 40. Major criteria matrix pairwise assessment

| Categories | Technological Risks | Organizational Risks | Regulatory Risks | Financial Risks |
|---|---|---|---|---|
| Technological Risks | (1, 1, 1) | (3, 4, 5) | (2, 3, 4) | (4, 5, 6) |
| Organizational Risks | (0.33, 0.25, 0.20) | (1, 1, 1) | (2, 3, 4) | (3, 4, 5) |
| Regulatory Risks | (0.50, 0.33, 0.25) | (0.50, 0.33, 0.25) | (1, 1, 1) | (2, 3, 4) |
| Financial Risks | (0.25, 0.20, 0.16) | (0.33, 0.25, 0.20) | (0.50, 0.33, 0.25) | (1, 1, 1) |

Table 41 provides the relative weights and rankings of the four major criteria determined from the pairwise comparisons:

- Technological Risks receive the highest weight (0.5041), signifying their dominance in the risk perception for Industry 4.0 adoption in construction.
- Regulatory Risks follow with a weight of 0.2686, reflecting concerns over evolving standards and compliance.
- Financial Risks rank third with a weight of 0.2093, showing that cost and return on investment uncertainties are also substantial considerations.
- Organizational Risks are ranked lowest with a weight of 0.1943, indicating that while internal factors such as resistance to change are important, they are not perceived as the most significant threat compared to external and technological risks.

Table 41. Relative weights and ranks of major criteria

| Criteria | Relative Weight (RW) | Rank |
|---|---|---|
| Technological Risks | 0.5041 | 1 |
| Organizational Risks | 0.1943 | 4 |
| Regulatory Risks | 0.2686 | 2 |
| Financial Risks | 0.2093 | 3 |

Table 42 breaks down technological risks into four sub-categories: Cybersecurity Risks, Data Privacy Issues, Interoperability Challenges, and Technological Complexity.

- Cybersecurity Risks are rated the highest, with values such as (5,6,7) and (6,7,8) when compared with other risks. This reflects the growing concern over data breaches and unauthorized access as more data becomes digitalized in construction projects.
- Data Privacy Issues are also important, but rank slightly lower than cybersecurity, reflecting concerns about the secure handling of sensitive data.
- Interoperability Challenges are viewed as significant but less critical than cybersecurity risks, given the difficulties in integrating new technologies with existing systems.
- Technological Complexity is rated the lowest, showing that while learning new technologies poses a challenge, it is seen as less severe than security-related risks.

Table 42. Technological alternatives matrix pairwise assessment

| Categories | Cyber security Risks | Data Privacy Issues | Interoperability Challenges | Technological Complexity |
|---|---|---|---|---|
| Cyber security Risks | (1, 1, 1) | (4, 5, 6) | (5, 6, 7) | (6, 7, 8) |
| Data Privacy Issues | (0.16, 0.20, 1/4) | (1, 1, 1) | (3, 4, 5) | (4, 5, 6) |
| Interoperability Challenges | (0.14, 0.16, 0.20) | (0.20, 0.25, 0.33) | (1, 1, 1) | (3, 4, 5) |
| Technological Complexity | (0.12, 0.14, 0.16) | (0.16, 0.20, 0.25) | (0.20, 0.25, 0.33) | (1, 1, 1) |

Table 43 assesses organizational risks, which include Resistance to Change, Lack of Skilled Workforce, and Infrastructure Limitations:

- Resistance to Change is the top-ranked organizational risk, reflecting the common challenge in getting employees and stakeholders to adapt to new technologies.
- Lack of Skilled Workforce follows, emphasizing the shortage of professionals who can operate Industry 4.0 technologies.
- Infrastructure Limitations are ranked the lowest, suggesting that while important, technological infrastructure is seen as less critical compared to workforce readiness and organizational change resistance.

Table 43. Organizational alternatives matrix pairwise assessment

| Categories | Resistance to Change | Lack of Skilled Workforce | Infrastructure Limitations |
|---|---|---|---|
| Resistance to Change | (1, 1, 1) | (3, 4, 5) | (4, 5, 6) |
| Lack of Skilled Workforce | (0.20, 0.25, 0.33) | (1, 1, 1) | (2, 3, 4) |
| Infrastructure Limitations | (0.16, 0.20, 0.25) | (0.25, 0.33, 0.50) | (1, 1, 1) |

Table 44 presents the regulatory risks, which consist of Compliance with Evolving Standards, Data Privacy Regulations, and Safety and Liability Issues:

- Compliance with Evolving Standards is ranked the highest, as organizations often struggle to keep up with changes in regulations and standards, especially concerning new technologies.
- Data Privacy Regulations are also a significant concern, though secondary to compliance with standards.
- Safety and Liability Issues are rated the lowest, suggesting that while important, they are not perceived as major barriers compared to regulatory compliance and data privacy concerns.

Table 44. Regulatory alternatives matrix pairwise assessment

| Categories | Compliance with Evolving Standards | Data Privacy Regulations | Safety and Liability Issues |
|---|---|---|---|
| Compliance with Evolving Standards | (1, 1, 1) | (3, 4, 5) | (4, 5, 6) |
| Data Privacy Regulations | (0.20, 0.25, 0.33) | (1, 1, 1) | (2, 3, 4) |
| Safety and Liability Issues | (0.16, 0.20, 0.25) | (0.25, 0.33, 0.50) | (1, 1, 1) |

Table 45 evaluates financial risks, including High Initial Costs, Cost Overruns, and ROI Uncertainty:

- High Initial Costs are rated the highest, reflecting the substantial investment required to adopt Industry 4.0 technologies in construction projects.
- Cost Overruns are also a significant risk, as unexpected expenses during technology implementation can strain project budgets.
- ROI Uncertainty ranks the lowest, showing that while there are concerns over the returns from these technologies, the upfront costs and potential for budget overruns are perceived as more immediate financial risks.

Table 45. Financial alternatives matrix pairwise assessment

| Categories | High Initial Costs | Cost Overruns | ROI Uncertainty |
|---|---|---|---|
| High Initial Costs | (1, 1, 1) | (3, 4, 5) | (4, 5, 6) |
| Cost Overruns | (0.20, 0.25, 0.33) | (1, 1, 1) | (2, 3, 4) |
| ROI Uncertainty | (0.16, 0.20, 0.25) | (0.25, 0.33, 0.50) | (1, 1, 1) |

### 7.3 Final results and ranking using Fuzzy AHP

**Table 46** ranks the alternative risks associated with Industry 4.0 adoption in the construction industry, providing the **global weights** of each risk calculated through the **Fuzzy AHP** process. The table ranks the alternative risks across four major categories: **Technological, Organizational, Regulatory, and Financial Risks**.

Table 46. Global weights and Rank of alternatives

| Major-Criteria | Sub-Criteria | Relative Weight (RW) | Global Weight (GW) | Rank |
|---|---|---|---|---|
| **Technological Risks** | Cyber security Risks | 0.3571 | 0.1799 | 1 |
| | Data Privacy Issues | 0.2857 | 0.1439 | 2 |
| | Interoperability Challenges | 0.2143 | 0.1081 | 4 |
| | Technological Complexity | 0.1429 | 0.0721 | 8 |
| **Organizational Risks** | Resistance to Change | 0.4444 | 0.0863 | 7 |
| | Lack of Skilled Workforce | 0.3333 | 0.0648 | 10 |
| | Infrastructure Limitations | 0.2222 | 0.0432 | 13 |
| **Regulatory Risks** | Compliance with Evolving Standards | 0.4444 | 0.1194 | 3 |
| | Data Privacy Regulations | 0.3333 | 0.0895 | 6 |
| | Safety and Liability Issues | 0.2222 | 0.0597 | 11 |
| **Financial Risks** | High Initial Costs | 0.4444 | 0.093 | 5 |
| | Cost Overruns | 0.3333 | 0.0698 | 9 |
| | ROI Uncertainty | 0.2222 | 0.0464 | 12 |

➢ **Technological Risks**

The most significant risk category in Industry 4.0 adoption for construction is technological, as shown by the high global weights of the following sub-criteria:

- **Cybersecurity Risks (Global Weight: 0.1799, Rank: 1):** Cybersecurity risks, including data breaches and cyberattacks, are the top-ranked risk, highlighting the importance of securing sensitive project data. The need to protect information as digital solutions increase is a critical concern that impacts the adoption of Industry 4.0 technologies.
- **Data Privacy Issues (Global Weight: 0.1439, Rank: 2):** Closely related to cybersecurity, data privacy risks address concerns about the management of sensitive information collected through IoT and AI systems in construction projects. With stringent regulations and ethical considerations, data privacy is a crucial area to address in technology implementation.

- **Interoperability Challenges (Global Weight: 0.1081, Rank: 4):** Interoperability issues, which involve the integration of new technologies with existing systems, are a notable concern. The ability to ensure seamless interaction among diverse systems and tools is essential for Industry 4.0 adoption but can be challenging.
- **Technological Complexity (Global Weight: 0.0721, Rank: 8):** Technological complexity, while a recognized risk, ranks lower than security and privacy concerns. This reflects that while complex technology might pose challenges, stakeholders prioritize addressing immediate cybersecurity and privacy issues over the learning curve.

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- **Organizational Risks**

The second major risk category encompasses organizational challenges, which highlight internal issues in adopting new technologies:

- **Resistance to Change (Global Weight: 0.0863, Rank: 7):** The highest-ranked organizational risk, resistance to change, indicates that a reluctance within firms to adopt new technologies is a key barrier. Addressing this requires change management strategies to foster acceptance of Industry 4.0 advancements.
- **Lack of Skilled Workforce (Global Weight: 0.0648, Rank: 10):** The shortage of skilled personnel proficient in advanced technologies presents a substantial barrier. With the demand for technical expertise increasing, this risk underscores the need for training programs to prepare the workforce.
- **Infrastructure Limitations (Global Weight: 0.0432, Rank: 13):** Infrastructure constraints rank as the least significant organizational risk. While they can impact technology adoption, other issues such as workforce readiness and adaptability are more critical in this context.

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- **Regulatory Risks**

The regulatory risk category reflects challenges related to evolving policies and standards, which affect the integration of new technologies:

- **Compliance with Evolving Standards (Global Weight: 0.1194, Rank: 3):** Compliance with evolving standards is the top-ranked regulatory risk. As regulations continuously change, organizations face uncertainties in adhering to new policies that impact technology adoption and operations.
- **Data Privacy Regulations (Global Weight: 0.0895, Rank: 6):** Ensuring compliance with data privacy regulations is a prominent concern. The increase in data collection through digital technologies demands vigilance in upholding privacy laws, which can significantly affect project operations.
- **Safety and Liability Issues (Global Weight: 0.0597, Rank: 11):** Safety and liability issues are ranked lower among regulatory risks. While essential, stakeholders consider compliance with privacy and evolving standards to have a more immediate impact on the adoption of Industry 4.0.

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- **Financial Risks**

Financial risks are also significant, as they directly influence an organization’s ability to invest in and sustain new technologies:

- **High Initial Costs (Global Weight: 0.093, Rank: 5):** High upfront investment costs are the leading financial risk, making it challenging for organizations to allocate resources for new technologies. This factor highlights the need for careful financial planning.
- **Cost Overruns (Global Weight: 0.0698, Rank: 9):** Cost overruns, due to unforeseen expenses during implementation, are a noteworthy financial risk. Organizations need effective budgeting and management to prevent unexpected costs from derailing projects.

- **ROI Uncertainty (Global Weight: 0.0464, Rank: 12):** Uncertainty in the return on investment (ROI) ranks lower but remains a concern. While not as pressing as initial costs, ensuring a positive ROI is crucial for justifying the adoption of Industry 4.0 technologies.
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### 7.4 Sensitivity Analysis

The sensitivity analysis of various risks within technological, organizational, regulatory, and financial domains highlights the prioritization of risks based on their relative and global weights, which ultimately dictate their rank in the analysis. **Table 47 and figure 5** shows how the rankings of alternatives change across different weight runs.

➢ **Cyber Security Risks**

- Consistently ranked **1st** across all runs (0.1 to 0.9).
- This stable ranking highlights Cyber Security as the most critical risk factor, irrespective of the weight variations. Organizations prioritize securing their digital infrastructure, reflecting the significance of protecting against cyber threats as Industry 4.0 technologies are adopted.

➢ **Data Privacy Issues**

- Primarily holds the **2nd rank** across most runs (Run 1, Run 2, Run 5, and Runs 6–9).
- Briefly shifts to **3rd** position in Run 4.
- The slight variation in ranks indicates that Data Privacy Issues are a significant concern, though slightly less critical than Cyber Security Risks. This stability in high ranking suggests a strong focus on protecting sensitive information within digital systems.

➢ **Interoperability Challenges**

- Maintains a stable **4th rank** from Run 1 to Run 8.
- Moves to **5th** place in Run 9.

- This near-constant ranking indicates that interoperability is an important, yet somewhat manageable challenge. It implies that while the ability of systems to work seamlessly is valued, it is slightly less urgent than Cyber Security and Data Privacy.

➢ **Technological Complexity**

- Mostly ranked **8th** across Runs 1–3, Runs 5, 7, and Runs 8–9.
- Moves up to **9th** position in Run 4 and Run 6.
- The minor rank variations suggest that while Technological Complexity is a relevant issue, it is not perceived as a top-priority risk, likely because organizations expect to manage this challenge with suitable resources and expertise.

➢ **Resistance to Change**

- Consistently ranks **7th** across all runs.
- This unchanging rank highlights that Resistance to Change is perceived as a moderate challenge that organizations need to address for successful implementation. It suggests that internal organizational resistance is a predictable barrier, but it is not as urgent as Cyber Security or Data Privacy.

➢ **Lack of Skilled Workforce**

- Ranked **10th** across most runs (Runs 1–4 and Runs 6–9).
- Moves to **9th** in Run 5.
- The slight shift indicates that while the availability of skilled personnel is a concern, organizations may have strategies in place to develop or hire skilled talent, making this risk relatively less immediate.

➢ **Infrastructure Limitations**

- Generally ranked **13th** in most runs (Runs 1–5, Run 8, and Run 9).
- Moves up slightly to **12th** in Runs 6 and 7.

- The low ranking signifies that Infrastructure Limitations are not seen as a major risk factor, suggesting that organizations feel confident in their existing infrastructure or are able to address these limitations effectively.

➢ **Compliance with Evolving Standards**

- Holds the **3rd rank** in most runs, with the exception of Run 4, where it rises to **2nd**.
- This high ranking highlights the importance of adhering to regulatory standards, which are constantly evolving with technological advancements. Organizations view compliance as a critical factor in the adoption of Industry 4.0, making it a priority.

➢ **Data Privacy Regulations**

- Consistently ranked **6th** across all runs.
- The stable rank reflects that while Data Privacy Regulations are important, they are somewhat less immediate than general Data Privacy Issues. The distinction may be due to the specific legal requirements around privacy, which are viewed as part of broader data management efforts.

➢ **Safety and Liability Issues**

- Remains in the **11th** rank across all runs.
- This consistency indicates that while safety and liability are concerns, they are not seen as urgent compared to other risks. Organizations may already have established protocols in place to manage these issues effectively.

➢ **High Initial Costs**

- Consistently ranked **5th** across most runs (Runs 1–8), moving up to **4th** in Run 9.
- This stable position emphasizes that financial investment is a significant consideration for Industry 4.0 adoption. Although not the highest priority, it is a consistent factor in decision-making, highlighting the financial burden that organizations need to account for.

➢ **Cost Overruns**

- Primarily holds the **9th rank** across most runs, except in Run 4, where it rises to **8th**.
- The slight fluctuation suggests that while organizations recognize the risk of exceeding budgets, it is not seen as one of the most critical challenges. Financial planning strategies may help to keep this risk manageable.

➢ **ROI Uncertainty**

- Generally ranked **12th** across most runs, moving down to **13th** in Run 7.
- This consistent low ranking suggests that organizations are less concerned about immediate financial returns on Industry 4.0 investments, focusing instead on addressing more immediate technological, privacy, and regulatory risks.

Table 47 Perceived risks after variations (post sensitivity analysis)

| Sub-Criteria | Run 1 (0.1) | Run 2 (0.2) | Run 3 (0.3) | Run 4 (0.4) | Run 5 (0.5) | Run 6 (0.6) | Run 7 (0.7) | Run 8 (0.8) | Run 9 (0.9) |
|---|---|---|---|---|---|---|---|---|---|
| Cyber Security Risks | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Data Privacy Issues | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 |
| Interoperability Challenges | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| Technological Complexity | 8 | 8 | 8 | 9 | 8 | 9 | 8 | 8 | 8 |
| Resistance to Change | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Lack of Skilled Workforce | 10 | 10 | 10 | 10 | 9 | 10 | 10 | 10 | 10 |
| Infrastructure | 13 | 13 | 13 | 13 | 13 | 12 | 12 | 13 | 13 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Limitations | | | | | | | | | |
| Compliance with Evolving Standards | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 |
| Data Privacy Regulations | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| Safety and Liability Issues | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| High Initial Costs | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 |
| Cost Overruns | 9 | 9 | 9 | 8 | 10 | 8 | 9 | 9 | 9 |
| ROI Uncertainty | 12 | 12 | 12 | 12 | 12 | 12 | 13 | 12 | 12 |

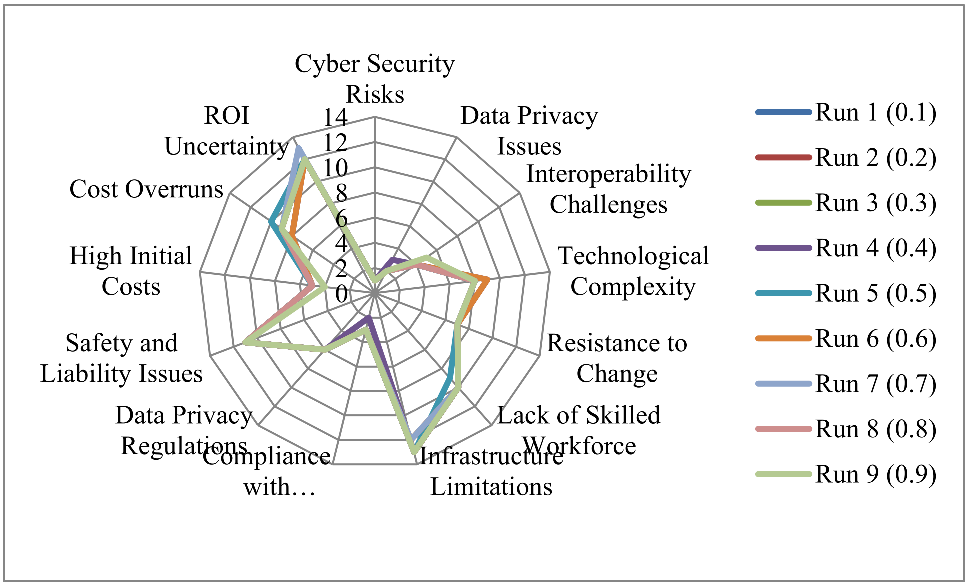


Figure 5. Rank variations after sensitivity analysis

### 7.5 Discussions

This chapter provide valuable insights into the perceived risks hindering the adoption of Industry 4.0 (I4.0) technologies in the construction industry, specifically from the perspective of Indian decision-makers. Using the Analytic Hierarchy Process (AHP) and

Fuzzy AHP methodologies, the study has ranked various risks across four main categories: Technological, Organizational, Regulatory, and Financial risks.

**Technological Risks**

Technological risks were found to be the most significant category, confirming that digital threats are a primary concern for decision-makers. **Cybersecurity Risks**, with a high global weight (0.1799), emerged as the top risk, highlighting issues like data breaches and unauthorized access that intensify as construction projects digitize. **Data Privacy Issues** (global weight: 0.1439) follow, showing the need for stringent data protection practices, particularly in an era of growing data reliance in I4.0. **Interoperability Challenges** (0.1081) reflect challenges firms face in integrating I4.0 technologies with existing systems, and **Technological Complexity** (0.0721) ranks lower, indicating it is perceived as manageable compared to security and privacy risks.

**Organizational Risks**

Organizational risks rank lower than technological risks but still represent significant barriers to I4.0 adoption. **Resistance to Change** (0.0863) is the most pressing issue in this category, as employees and stakeholders often resist new digital methods due to workflow disruptions or uncertainty. **Lack of Skilled Workforce** (0.0648) indicates a shortage of personnel skilled in I4.0 technology, underlining the need for training and workforce development. **Infrastructure Limitations** (0.0432) are perceived as less pressing, implying that firms may already be equipped with adequate technology or have plans to address these gaps.

**Regulatory Risks**

Among regulatory risks, **Compliance with Evolving Standards** (0.1194) is the highest-ranked issue, showing that firms struggle to keep pace with regulatory changes. **Data Privacy Regulations** (0.0895) also rank high, emphasizing the importance of adhering to legal requirements surrounding data handling and protection. **Safety and Liability Issues** (0.0597), while essential, are rated lower, likely due to established safety protocols that mitigate these concerns in I4.0 applications.

**Financial Risks**

Financial risks are significant but rank below technological and regulatory risks. **High Initial Costs** (0.0930) are the foremost financial concern, as substantial investment is necessary to adopt I4.0 technologies. **Cost Overruns** (0.0698) and **ROI Uncertainty** (0.0464) follow, highlighting financial uncertainties around implementation expenses and the long-term benefits of these technologies.

**Sensitivity Analysis**

Sensitivity analysis confirms the robustness of these rankings, with **Cybersecurity Risks** maintaining the highest priority across varied weight settings. **Data Privacy Issues** and **Interoperability Challenges** are consistently important, reinforcing the need for secure, privacy-focused, and integrated digital frameworks. Lower-ranked risks like **Technological Complexity** and **ROI Uncertainty** maintain lesser influence in decision-making.

In summary, your analysis underscores that Technological risks, especially related to cybersecurity and data privacy, are the most critical barriers to I4.0 adoption in construction. Firms aiming to integrate these technologies must prioritize secure, privacy-compliant, and cost-effective implementations to overcome these hurdles effectively.

# 8 Conclusions

This chapter concludes the study by emphasizing the transformative potential of Industry 4.0 technologies in the Indian construction industry, focusing on efficiency, sustainability, and innovation. The findings highlight key enablers such as profitability, stakeholder investments, and advanced technologies like BIM and IoT, alongside organizational factors like strategic planning and supportive regulations. Financial barriers, particularly high initial investments and uncertain ROI, emerge as the most significant obstacles, followed by technological challenges like data security and skill gaps. Sustainability is framed across economic, environmental, and social dimensions, with economic considerations, such as cost efficiency and off-site construction, taking precedence. The chapter discusses practical implications, including enhanced project management, waste reduction, and the need for leadership and workforce upskilling to overcome organizational resistance. Regulatory barriers, especially related to data privacy and compliance, are noted as critical concerns, requiring robust legal frameworks. The chapter concludes with recommendations for future research and a proposed framework integrating enablers, barriers, and perceived risks to guide Industry 4.0 adoption in the sector.

## 8.1 Findings

The adoption of Industry 4.0 technologies in the construction industry offers substantial opportunities for transformation, efficiency, and sustainability, especially in developing nations like India. However, the path to full-scale integration is impeded by several technological, organizational, regulatory, and financial barriers. The thesis comprehensively evaluates these factors through advanced analytical methods and offers insightful conclusions that are grounded in empirical research. This section provides a detailed analysis of the key conclusions drawn from the study, supported by the relevant data, tables, and figures referenced in the thesis.

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Chapter 4, titled "Assessment of Industry 4.0 Enablers, delves into identifying, categorizing, and analyzing the significance of various enablers crucial for adopting Industry 4.0 in the construction industry, with a focus on India. This assessment considers factors from organizational, economic, and technological perspectives, emphasizing the ranking and prioritization of each enabler through expert evaluations and multi-criteria decision-making (MCDM) techniques.

In Section 4.1, the study categorizes the enablers into three main criteria: organizational, economic, and technological. Each enabler is evaluated to understand its contribution toward facilitating Industry 4.0 technologies in construction.

- **Organizational Enablers** : Organizational enablers set the stage for adopting Industry 4.0 by creating a supportive and strategically focused environment within the organization. Among these, *Organization Strategic Planning* (E2) and *Governmental Regulations* (E4) emerge as particularly impactful. Strategic planning ensures that Industry 4.0 integration aligns with long-term business goals, while regulatory policies enforce compliance and drive innovation (Devi et al., 2021; Olsson et al., 2021). The study emphasizes that fostering a risk-taking culture and providing ethical training to employees are essential to support technological adoption in construction (Shayganmehr et al., 2021).

- **Economic Enablers** : Economic factors play a decisive role, as they address financial incentives and profitability associated with adopting new technologies. *Profitability* (E6) is ranked as the most influential enabler across all criteria, underscoring the importance of financial returns in motivating Industry 4.0 adoption. The chapter also highlights the role of *Stakeholders' Investment* (E7) and *Market Demand* (E8) as key drivers, as these elements facilitate funding and support for digital transformation (Famakin et al., 2023; Bamgbade et al., 2017).
- **Technological Enablers** : Technological enablers, such as *Artificial Intelligence (AI)* (E9), *Building Information Modeling (BIM) and Digital Twin* (E11), and *Internet of Things (IoT)* (E12), provide the necessary tools and innovations for implementing Industry 4.0 in construction. Notably, *BIM* and *Digital Twin* technologies (E11) stand out for their ability to streamline project planning, execution, and monitoring, fostering real-time data accessibility and accuracy in construction processes (Hossain & Nadeem, 2019).

In Section 4.2 presents the weighting of the three primary criteria—organizational, economic, and technological—using the **Fuzzy Stepwise Weight Assessment Ratio Analysis (SWARA)** method, based on expert input.

- **Economic Criteria**: This category holds the highest weight, reflecting the critical role of financial enablers in the adoption of Industry 4.0. Within economic enablers, *Profitability* (E6) is paramount, as it represents financial viability and improved project efficiency (Aghimien et al., 2021).
- **Organizational Criteria**: Organizational aspects like *Organization Strategic Planning* (E2) and *Risk-Taking Behavior* (E3) are moderately weighted, signifying that effective planning and openness to risk are vital for successful implementation.
- **Technological Criteria**: Although crucial, technological enablers receive the lowest weight among the three criteria, indicating that, while technology facilitates adoption, economic and organizational considerations often precede it.

The **Fuzzy COmplex PRoportional ASsessment (COPRAS)** method ranks each enabler's importance based on their contributions to Industry 4.0 adoption, consolidating their performance across different criteria.

- **Top-Ranked Enablers**:
  - *Profitability (E6)* emerges as the most influential enabler, with an overall score of 100%. This enabler highlights that the financial gains from Industry 4.0 technologies, such as cost reductions and improved productivity, are decisive for adoption (Bamgbade et al., 2017).
  - *Stakeholders' Investment (E7)* ranks second, indicating the importance of financial backing from stakeholders, such as contractors and investors, to drive digital transformation (Aghimien et al., 2021).
  - *Governmental Regulations (E4)* ranks third, illustrating that regulatory policies and incentives play a significant role in facilitating technological adoption, particularly in heavily regulated sectors like construction (Olsson et al., 2021).
- **Mid-Ranked Enablers**:
  - *Market Demand (E8)* ranks fourth, showing that client and consumer demand for technology-enabled construction solutions is a powerful motivator.
  - *Building Information Modeling (BIM) and Digital Twin (E11)* ranks fifth, underscoring the transformative potential of BIM and Digital Twin technology in enhancing design accuracy and project management (Hossain & Nadeem, 2019).
  - *Organization Strategic Planning (E2)* is sixth, reinforcing the importance of strategic foresight in adapting to new technologies (Devi et al., 2021).
- **Lower-Ranked Enablers**:
  - *Artificial Intelligence (AI) (E9)* ranks lower, likely due to its novelty and the associated challenges in adapting it specifically for construction purposes.
  - *Internet of Things (IoT) (E12)* ranks lowest, suggesting that challenges such as integration issues and data security concerns may hinder its full utilization in construction.

Section 4.4 explains the sensitivity analysis conducted to test the robustness of the ranking results. By modifying the weight distribution across the criteria in 19 different configurations, the analysis confirms that financial enablers, particularly *Profitability (E6)*, consistently maintain their top position. This consistency reaffirms the significance of profitability as a core driver for adopting Industry 4.0.

- The analysis also shows that *Stakeholders' Investments (E7)* and *Governmental Regulations (E4)* maintain high rankings in most scenarios, supporting the importance of financial backing and regulatory frameworks.
- Technological enablers like *3D Printing (E10)* and *IoT (E12)* exhibit variability in their rankings, suggesting that their influence may depend on specific project needs or organizational priorities.

In Section 4.5, the study emphasize on economic enablers, particularly *Profitability*, highlights that financial viability is the foremost consideration for stakeholders. This focus suggests that companies must demonstrate cost savings, productivity enhancements, and potential profitability to encourage widespread adoption (Bamgbade et al., 2017). The high ranking of *Stakeholders' Investment* and *Governmental Regulations* underscores the importance of securing both stakeholder commitment and government support. In India, where regulatory compliance is essential, policymakers can facilitate Industry 4.0 by providing incentives and establishing supportive legal frameworks. Although BIM and Digital Twin technologies are highly ranked, other technological enablers like AI and IoT are comparatively lower in priority. This ranking suggests that, while innovative, these technologies require further development and adaptation to suit construction industry needs.

Chapter 5 provides a comprehensive analysis of barriers to Industry 4.0 (I4.0) adoption in the construction industry, particularly in India, using a structured approach involving the Fuzzy Analytical Hierarchy Process (FAHP). It categorizes these barriers into five major groups—financial, technological, regulatory, organizational, and market-related—and evaluates their impact on the construction industry's integration of I4.0 technologies.

In Section 5.1 initially identification of 20 barriers grouped into five main categories. A survey was developed based on literature review and expert insights to refine these barriers.

- **Financial Barriers**: Financial constraints emerge as the most significant barrier group. Key barriers include:
    - *High Initial Investment* (FI1): The upfront costs of adopting I4.0 technologies, such as IoT, BIM, and automation tools, are prohibitive, especially for small to medium enterprises (SMEs) (Shayganmehr et al., 2021).
    - *Uncertain Return on Investment (ROI)* (FI2): Due to the industry's long project cycles and market variability, estimating ROI remains challenging, making investments harder to justify (Famakin et al., 2023).
    - *Lack of Funding* (FI3): Limited access to financial resources further impedes technology acquisition, while investor confidence remains low (Bamgbade et al., 2017).
- **Technological Barriers**: This category addresses the complexity and challenges of integrating advanced technologies.
    - *Data Management and Security* (TE3): Managing and securing the large volumes of data generated by I4.0 is challenging, raising concerns over data privacy and compliance (Ghosh et al., 2021).
    - *Skill Gaps and Training Needs* (TE4): The lack of trained personnel to operate advanced I4.0 technologies, compounded by limited training opportunities, hinders effective adoption.
- **Regulatory Barriers**: This category includes barriers imposed by legal frameworks.
    - *Privacy Regulations* (RE1): Strict data privacy laws like GDPR complicate data collection and sharing (Olsson et al., 2021).
    - *Poor Tax Rebates* (RE4): Limited governmental financial support for I4.0 adoption discourages firms from investing in new technologies.
- **Organizational Barriers**: These barriers relate to internal company factors.
    - *Lack of Leadership and Vision* (OR1): The absence of strong leadership and strategic goals hinders digital transformation.

- *Resistance to Change* (OR2): Employees and managers may resist adopting new technologies due to concerns over job displacement and a preference for traditional methods.

- **Market-Related Barriers**: These barriers arise from market conditions.
  - *Market Fragmentation* (MR1): The fragmented nature of the construction industry limits widespread adoption of I4.0 technologies.
  - *Limited Customer Awareness* (MR2): Low awareness of I4.0 benefits among clients affects demand and, subsequently, firm investment in these technologies.

In Section 5.2, the FAHP method assesses the relative importance of each major and sub-barrier by comparing them in pairs. Financial barriers are rated as the most critical, followed by technological and regulatory barriers.

- **Financial Barriers** (Highest Priority): These barriers have the highest relative weight of 0.655, emphasizing that financial constraints are the primary concern. *High Initial Investment* (FI1) ranks first within this group, highlighting that financial hurdles are particularly prohibitive for technology adoption.
- **Technological and Regulatory Barriers** (Moderate Priority): Technological barriers (0.520 weight) and regulatory barriers (0.399 weight) underscore the challenges related to technology integration and regulatory compliance.
- **Market Barriers** (Lowest Priority): Market barriers, though impactful, are the least critical, with the lowest relative weight of 0.021. This suggests that financial and technological factors take precedence.

Using FAHP, the chapter ranks individual sub-barriers within each category, identifying the most significant obstacles to I4.0 adoption.

- **Top-Ranked Barriers**:
  - *High Initial Investment (FI1)* ranks first, with a global weight of 0.489, confirming that cost is the most critical barrier to I4.0 integration.
  - *Lack of Funding (FI3)* ranks second, reflecting the need for external financial support and government subsidies.

- **Technological Challenges**: Within technological barriers, *Data Management and Security (TE3)* ranks third overall due to concerns over managing and securing large amounts of sensitive data. *Complexity of Technologies (TE1)* ranks fourth, underlining the challenges posed by the fragmented nature of the construction industry and the technical expertise required to integrate advanced technologies.
- **Organizational and Regulatory Issues**: *Lack of Leadership and Vision (OR1)* ranks fifth, indicating that strong leadership is necessary to guide companies through digital transformation. *Poor Tax Rebates (RE4)* ranks sixth, underscoring the importance of governmental support for I4.0 adoption.

Section 5.4 describes the sensitivity analysis conducted to test the robustness of the rankings by altering the weights of each major barrier.

- **Financial Barriers' Dominance**: As the weight of financial barriers increases, other barriers, particularly technological and organizational ones, decrease in rank. This suggests that financial concerns overshadow other factors, and addressing these could shift priorities towards organizational and technological improvements.
- **Ranking Variability**: Technological barriers, such as *Data Management and Security (TE3)*, show significant ranking fluctuations, confirming their sensitivity to changes in financial conditions. Meanwhile, market-related barriers maintain stable, low rankings, indicating that they have a minimal impact compared to financial, technological, and organizational concerns.

In Section 5.5, the discussion emphasizes the need for targeted strategies to overcome the Financial barriers, especially *High Initial Investment* and *Lack of Funding*, require immediate attention to enable I4.0 adoption. Financial support, such as tax incentives and access to capital, could alleviate these concerns (Aghimien et al., 2021). The ranking of technological barriers like *Data Management and Security* and *Complexity of Technologies* suggests a need for industry standards and enhanced data security measures. Training initiatives could also address skill gaps, ensuring that construction firms are prepared to handle advanced technologies (Hossain & Nadeem, 2019). The high rank of organizational barriers highlights that visionary leadership and performance metrics are critical to guide digital transformation. Companies should invest in leadership development and establish clear objectives for integrating I4.0 technologies (Devi et al., 2021). The importance of regulatory barriers, specifically *Poor Tax Rebates*, suggests that policymakers need to offer more substantial financial incentives and tax rebates to encourage I4.0 adoption.

Chapter 6 examines key sustainability criteria in the construction industry, focusing on how Industry 4.0 (I4.0) technologies can contribute to economic, environmental, and social sustainability goals. Using a Fuzzy Analytical Hierarchy Process (Fuzzy AHP), the study prioritizes these sustainability dimensions and ranks specific sub-criteria within each.
In section 6.1 the study assesses the three major criteria for sustainability—economic, environmental, and social—based on insights from industry experts and existing literature (Section 2.3). These criteria encompass 12 sub-criteria, as follows:

- **Economic Sustainability (EC)**: Emphasizes cost efficiency, resource optimization, and long-term financial benefits. Sub-criteria include *Building Information Modeling (BIM)*, *IoT and RFID Technologies*, *Big Data Analytics*, and *Off-site Construction* (Azhar, 2011).

- **Environmental Sustainability (EV)**: Focuses on minimizing the ecological footprint. Key aspects include *IoT Sensors*, *BIM and Digital Tools*, *Smart Construction*, and *Sustainable Construction Practices* (Perera et al., 2020).

- **Social Sustainability (SO)**: Centers on worker safety, collaboration, and upskilling. Sub-criteria involve *Wearable Devices*, *Digital Platforms*, *Digital Skills Training*, and *Automation and Job Creation* (Lu, 2022).

In Section 6.2 describes the pairwise comparisons used to evaluate the relative importance of the three sustainability criteria:

- **Economic Sustainability (EC)** receives the highest weight (0.333), indicating that economic concerns like cost savings and resource efficiency dominate construction decision-making.

- **Social Sustainability (SO)** ranks second, with a weight of 0.264, showing moderate importance. Social factors, such as worker safety and skill development, are prioritized but are secondary to economic concerns.

- **Environmental Sustainability (EV)** is ranked third (0.189), suggesting that while environmental impacts are considered, they are generally deprioritized in construction settings.

This finding aligns with previous studies that highlight the industry's preference for economic goals over environmental and social objectives (Perera et al., 2020; Wang et al., 2021).
Using the Fuzzy AHP, the study ranks sub-criteria within each sustainability category, identifying the most critical factors in each.

- **Economic Sustainability Sub-Criteria**:
    - *Off-site Construction (EC4)* ranks first (0.122), reflecting its potential to significantly reduce costs and enhance efficiency through prefabrication and resource optimization (Li et al., 2022).
    - *Building Information Modeling (BIM) (EC1)* ranks third (0.088), underscoring its value in minimizing errors and streamlining project management (Azhar, 2011).
    - *Big Data Analytics (EC3)* ranks fourth (0.073), highlighting its importance for predictive maintenance and improved resource allocation.
    - *IoT and RFID Technologies (EC2)* rank lower (0.051), indicating their relatively limited role in construction settings despite their efficiency benefits.
- **Environmental Sustainability Sub-Criteria**:
    - *Sustainable Construction Practices (EV4)* ranks highest within this category (0.069), emphasizing the importance of eco-friendly building methods (Zuo & Zhao, 2014).
    - *IoT Sensors (EV1)* are also highly ranked (0.050) for their ability to optimize energy use in real time.

  - *BIM and Digital Tools (EV2)*, though valuable for designing energy-efficient buildings, rank lower in environmental sustainability due to their indirect environmental effects.

- **Social Sustainability Sub-Criteria**:

  - *Automation and Job Creation (SO4)* ranks second overall (0.097), reflecting the balance between technological advancement and job creation in digital construction (Lu, 2022).

  - *Wearable Devices (SO1)* rank fifth (0.069), emphasizing their role in improving worker safety.

  - *Digital Skills Training (SO3)* ranks seventh (0.057), underscoring the need to prepare the workforce for digital transformation.

In Section 6.4 describes the sensitivity analysis conducted to examine how varying the weight of economic criteria affects the relative importance of environmental and social criteria.

- **Increasing Economic Priority**: As the weight of economic criteria is increased, environmental and social criteria weights decrease significantly. For instance, when the economic weight rises to 0.9, environmental and social criteria weights drop to 0.042 and 0.058, respectively, indicating that economic goals overshadow other sustainability concerns under constrained resources.
- **Stable Rankings for Key Sub-Criteria**: Despite variations in weight, *Off-site Construction (EC4)* and *Automation and Job Creation (SO4)* consistently rank among the highest, demonstrating their robust importance in the construction industry.

The findings prioritization of economic sustainability aligns with the construction industry's cost-driven approach. Off-site construction, in particular, enhances productivity and reduces on-site labor and material waste, making it a favored approach for cost-conscious construction firms (Azhar, 2011). Although environmental concerns rank lower, sustainable construction practices like green building and energy-efficient designs are still acknowledged. This suggests a need for a balanced approach that incorporates long-term environmental goals alongside immediate economic benefits (Zuo & Zhao, 2014). Social sustainability is underscored by a focus on automation's role in job creation and worker safety. The consistent ranking of wearable technologies for safety reflects the construction industry's prioritization of well-being in an industry prone to workplace hazards (Lu, 2022).

Chapter 7 examines perceived risks that hinder the adoption of Industry 4.0 (I4.0) technologies in the construction industry, focusing on technological, organizational, regulatory, and financial barriers. Through the Analytic Hierarchy Process (AHP), the chapter ranks these risk categories based on their impact as assessed by industry experts and previous studies.

In Section 7.1, the study identifies four primary risk categories based on expert surveys and literature:

- **Technological Risks**: The most significant category, covering issues like Cybersecurity Risks, Data Privacy, Interoperability Challenges, and Technological Complexity. **Cybersecurity Risks** rank highest, indicating that concerns over data breaches and hacking are top barriers to I4.0 adoption in construction (Patel et al., 2023). **Data Privacy Issues** are next, underscoring the importance of securely managing sensitive data in digitalized workflows (Liu et al., 2019). **Interoperability Challenges** and **Technological Complexity** highlight the difficulties of integrating new technologies with existing systems (Khosrowshahi & Arayici, 2012).
- **Organizational Risks**: These risks arise from internal challenges within firms. **Resistance to Change** ranks highest, showing that employees and stakeholders often resist new technologies due to workflow disruptions (Kumar et al., 2020). **Lack of Skilled Workforce** reflects the shortage of personnel trained in advanced I4.0 technologies, while **Infrastructure Limitations** indicate technological gaps that inhibit digital adoption (Sharma & Sharma, 2022).
- **Regulatory Risks**: Compliance with new standards is a critical concern. **Compliance with Evolving Standards** ranks highest, reflecting the industry's

struggle to adapt to regulatory changes (Section 7.2). **Data Privacy Regulations** emphasize the need to meet stringent data protection laws, while **Safety and Liability Issues** indicate that while important, safety concerns are less immediate barriers to I4.0 integration (Liu et al., 2019).

- **Financial Risks**: Significant financial concerns arise from the high costs of implementing I4.0 technologies. **High Initial Costs** are the primary financial risk, suggesting that cost constraints are a major hurdle to adoption. **Cost Overruns** and **ROI Uncertainty** further highlight financial hesitations regarding the long-term benefits of I4.0 (Section 7.3).

In Section 7.2, pairwise comparisons among the risk categories reveal the relative importance of each:

- **Technological Risks** (highest weight: 0.5041) demonstrate the dominant concern over cybersecurity and privacy issues.
- **Regulatory Risks** rank second (weight: 0.2686), underscoring the need for compliance with evolving standards.
- **Financial Risks** rank third (weight: 0.2093), showing that while costs are significant, they are secondary to security and compliance.
- **Organizational Risks** rank lowest (weight: 0.1943), suggesting internal resistance is less immediate but still impactful.

Section 7.3 further details the rankings of technological sub-criteria, identifying **Cybersecurity Risks** as the most critical, given the urgency of securing sensitive data in digital construction. **Data Privacy Issues** follow closely, highlighting the need for secure data handling in compliance with privacy laws.

The sensitivity analysis in Section 7.4 examines the stability of these rankings across different weight adjustments:

- **Stable Technological Priority**: Cybersecurity Risks maintain their highest rank across all weight adjustments, emphasizing the universal importance of secure digital infrastructure in I4.0 adoption.

- **Data Privacy and Interoperability Consistency**: Despite weight changes, data privacy and interoperability consistently rank high, indicating these are stable priorities for firms.

In conclusion, the prioritization of **Technological Risks**, especially cybersecurity and data privacy, aligns with the construction industry's emphasis on secure and integrated digital solutions. While regulatory and financial risks are substantial, technological and organizational challenges represent the most immediate barriers to I4.0 adoption. A balanced approach addressing these risks can support successful integration and operational efficiency in the construction sector (Patel et al., 2023; Khosrowshahi & Arayici, 2012).

## 8.2 IMPLICATIONS

The adoption of Industry 4.0 technologies has profound implications for the Indian construction industry, particularly concerning sustainability, economic performance, and regulatory compliance. This section analyzes the **practical** and **managerial** implications derived from the thesis, with references to specific results, tables, and figures obtained from the research.

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### I. Practical Implications for the Construction Industry

The integration of Industry 4.0 technologies, such as **BIM**, **AI**, and **IoT**, is transforming traditional construction practices by enhancing project management, reducing operational costs, and improving sustainability. However, the adoption of these technologies comes with significant challenges that require addressing at both practical and managerial levels.

**a. Enhanced Project Management and Real-Time Monitoring**
As noted in **Table 4** of the thesis, technologies like **BIM** and **digital twins** enable real-time monitoring and predictive analysis of construction projects, leading to improved **project scheduling** and **resource optimization** (Saini et al., 2020; Yang et al., 2022). The practical implications are substantial, as construction firms can now manage projects more

efficiently by predicting potential delays, minimizing cost overruns, and optimizing resource allocation.

For instance, **digital twins** allow for continuous real-time simulation and feedback, helping project managers detect bottlenecks before they escalate (Honghong et al., 2023). This reduces the risk of project failure, enhances productivity, and enables firms to respond promptly to unforeseen challenges, as evidenced in **Table 3**.

### b. Waste Reduction and Sustainability Goals

Industry 4.0 technologies, particularly **IoT** and **AI**, have shown significant potential in improving **resource efficiency** and minimizing waste, a critical requirement for achieving environmental sustainability in construction. According to **Table 4**, IoT-enabled systems allow for real-time tracking of material usage, reducing unnecessary consumption and improving inventory management (Sharma et al., 2020). This has direct implications for sustainable construction practices, as firms can now lower their carbon footprint by reducing waste and optimizing resource use.

Furthermore, the use of **AI** in project design and management enables predictive analysis that can forecast material needs accurately, contributing to more sustainable resource utilization (Lakhouit et al., 2023). This is critical in India, where rapid urbanization demands efficient use of resources to minimize environmental degradation.

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## II. Economic Implications

The adoption of Industry 4.0 technologies has significant economic implications, particularly in terms of **cost efficiency**, **return on investment (ROI)**, and the creation of new job opportunities. However, financial barriers such as **high initial costs** and **uncertain ROI** remain significant challenges for many firms, especially small and medium-sized enterprises (SMEs).

### a. Cost Efficiency and Reduced Operational Costs

One of the primary economic benefits of adopting Industry 4.0 technologies is the potential for significant **cost savings** through **automated processes** and **real-time data analysis**. Technologies like **3D printing** and **robotics** can reduce labor costs, minimize construction time, and lower material wastage (Salazar et al., 2023). According to **Table 5**, the cost savings from automation can help firms remain competitive in the market, even as they navigate the high initial investments required for technology adoption.

For example, **3D printing** reduces construction waste by using only the required materials, leading to more efficient designs and minimizing the overall environmental impact (Kazemian et al., 2022). Similarly, **robotics** can handle repetitive or dangerous tasks, reducing the reliance on human labor and improving safety, thereby cutting down long-term operational costs (Wang et al., 2023).

**b. Financial Barriers and Investment in Technology**

Despite the clear cost benefits, the thesis identifies significant financial barriers to the adoption of Industry 4.0 technologies. **Table 5** ranks **high initial investment** and **uncertain ROI** as some of the top challenges for firms considering these technologies (Patel et al., 2023; Liu et al., 2019). This creates a risk-averse environment, particularly among SMEs that may struggle to justify such investments without a clear, short-term return on investment.

However, the thesis recommends **public-private partnerships** and **government incentives** as potential solutions to mitigate financial barriers. By providing subsidies or tax incentives for the adoption of Industry 4.0 technologies, the government can encourage more firms to adopt these innovations, leading to broader industry-wide benefits.

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**III. Managerial Implications**

The successful adoption of Industry 4.0 technologies requires significant shifts in **organizational culture**, **leadership**, and **training strategies**. These technologies are not just tools but require firms to rethink how they operate and manage both their projects and workforce.

**a. Leadership and Change Management**

The thesis highlights **resistance to change** as a key organizational barrier (see Table 5), particularly among employees and stakeholders who are hesitant to adopt new technologies due to fear of disruption (Kumar et al., 2020). This resistance can be mitigated through effective leadership and **change management strategies** that focus on building trust and demonstrating the tangible benefits of technology adoption.

Managers must foster a **culture of innovation** and support employees as they navigate the challenges of adopting new tools like **BIM** and **AI**. This involves offering **incentives** for learning and innovation, as well as creating clear communication channels to address concerns regarding the implementation of Industry 4.0 technologies (Gupta & Jain, 2021).

**b. Workforce Training and Skill Development**

Another critical managerial implication involves the **upskilling of the workforce**. The thesis emphasizes that many firms face a **lack of skilled professionals** capable of managing and operating advanced Industry 4.0 technologies (Kumar et al., 2020). As outlined in **Table 5**, the shortage of skilled workers is a major barrier to technology adoption, which could limit the industry's growth potential.

To overcome this, firms need to invest in **employee training programs** that equip workers with the necessary technical skills. Collaboration with academic institutions and vocational training centers is essential to ensure that the workforce is prepared to handle the complexities of Industry 4.0 technologies. Moreover, offering **on-the-job training** and **certification programs** will help mitigate skill gaps and foster a more adaptable workforce.

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**IV. Regulatory and Compliance Implications**

The thesis identifies several **regulatory challenges** associated with the adoption of Industry 4.0 technologies in the construction industry, particularly around **data privacy**,

**cybersecurity**, and **compliance with evolving standards**. These regulatory concerns must be addressed to ensure the safe and efficient implementation of these technologies.

**a. Data Privacy and Cybersecurity**

With the increased reliance on digital tools and IoT-enabled devices, **cybersecurity risks** and **data privacy issues** have emerged as major concerns (see Table 5). Firms must adopt robust **cybersecurity measures** to protect sensitive project data from breaches and unauthorized access (Patel et al., 2023). Furthermore, complying with **data privacy regulations**, especially in relation to personal and project-related information, is critical for building trust among stakeholders (Liu et al., 2019).

The managerial implication here is the need for firms to invest in **secure digital infrastructure** and **data protection protocols** to mitigate these risks. This includes adopting **data encryption**, establishing **firewalls**, and ensuring that all digital tools comply with international data privacy standards.

**b. Evolving Standards and Legal Frameworks**

As noted in **Table 5**, the lack of clear **regulatory frameworks** for Industry 4.0 technologies presents a significant barrier to adoption (Khosrowshahi & Arayici, 2012). The rapid pace of technological advancement often outpaces regulatory changes, creating uncertainty for firms about how to comply with safety standards and liability issues.

The thesis recommends the establishment of **industry-specific guidelines** and **government policies** to streamline the adoption of Industry 4.0 technologies. Firms must stay updated on evolving regulations and engage with policymakers to ensure that their projects comply with legal requirements while also advocating for more supportive regulatory frameworks.

## 8.3 LIMITATIONS

While the thesis makes substantial contributions to the understanding of Industry 4.0 technologies in the Indian construction industry, several limitations must be acknowledged. These limitations span across methodological constraints, data collection challenges, and scope limitations. Identifying and discussing these limitations is critical for contextualizing the findings and offering directions for future research.

- Methodological Constraints

One of the key limitations of the study lies in the methodological framework employed. While the use of advanced decision-making techniques such as Fuzzy AHP, Fuzzy SWARA, and Fuzzy DEMATEL (as discussed in Section 1.8) provides robust insights, these methods have inherent limitations, particularly in their application to dynamic and fast-evolving industries like construction.

- Dependence on Expert Judgment

The thesis heavily relies on expert judgment for data collection, particularly in the use of pairwise comparisons in Fuzzy AHP to assess the perceived risks and barriers of Industry 4.0 technologies (see Table 5). Although the selection of experts with over 15 years of experience ensures the credibility of the input (Section 7.1), the study is limited by the subjectivity of expert opinions. Expert judgments can vary based on personal experiences and organizational biases, which may impact the reliability of the results. Furthermore, the relatively small sample size (23 experts) may limit the generalizability of the findings.

- Limitations of Fuzzy Logic Models

While fuzzy logic models are excellent for handling uncertainty, they have limitations in accurately quantifying subjective judgments. The Fuzzy AHP and Fuzzy DEMATEL methods used to rank barriers and enablers introduce subjectivity in the formulation of pairwise comparisons. This subjectivity can lead to inconsistencies in the final rankings, as noted in the sensitivity analysis (Section 7.4). Additionally, these models may oversimplify the complexity of technological and organizational interactions, thus limiting the precision of the study's conclusions.

- Data Collection and Representation Issues

The study also faces challenges related to data collection and representation, which affect the comprehensiveness of the findings. The reliance on qualitative data and expert surveys introduces certain limitations regarding the scope and depth of the results.

- Limited Sample Size and Representation

As mentioned, the study surveyed a relatively small group of 23 industry experts to identify and rank the perceived risks of Industry 4.0 technologies (Section 7.1). While these experts were chosen based on their extensive experience, the limited sample size restricts the statistical power of the analysis. This small sample may not capture the diversity of perspectives across different regions or company sizes, especially in a country as large and diverse as India.

Moreover, the findings are heavily reliant on the input from decision-makers in the construction industry, which may overlook the perspectives of other stakeholders, such as contractors, on-site workers, and suppliers. This limited representation can affect the study's ability to comprehensively assess the practical challenges of Industry 4.0 adoption across different levels of the industry.

- Lack of Quantitative Data for Validation

Although the study uses qualitative data and expert input to rank the risks, barriers, and enablers, it does not integrate a quantitative validation process to cross-verify these findings. Incorporating quantitative performance data from construction projects that have implemented Industry 4.0 technologies could provide a more objective foundation for validating the rankings and weightings of risks and barriers (as shown in Tables 5 and 6).
The absence of such quantitative data limits the study's ability to provide a holistic view of the success factors and challenges associated with Industry 4.0 technologies in the Indian construction industry.

➢ Scope Limitations

The scope of the study is also constrained in several areas, limiting its generalizability and application to the broader construction industry, both within

India and globally.

- Focus on Large-Scale Firms

The study predominantly focuses on large-scale construction firms in India, which may have more resources to invest in Industry 4.0 technologies (Section 2.1). These firms are more likely to adopt advanced technologies like BIM, AI, and IoT, which skews the findings toward organizations with substantial capital and technological infrastructure (Saini et al., 2020). This focus limits the study's relevance for small and medium-sized enterprises (SMEs), which constitute a significant portion of the Indian construction industry but face greater barriers in terms of costs and technical expertise (Patel et al., 2023).

Future research could address this limitation by specifically studying the challenges and enablers for SMEs and offering customized recommendations for their adoption of Industry 4.0 technologies.

- Lack of Longitudinal Analysis

Another limitation in the scope is the absence of longitudinal data. The study provides a snapshot of the current state of Industry 4.0 adoption in the Indian construction industry but does not examine how the adoption of these technologies evolves over time. Longitudinal studies could offer valuable insights into how firms gradually overcome barriers like cost and technological complexity and how the perceived risks shift as firms become more familiar with these technologies.

Moreover, a longitudinal approach would allow for tracking the long-term impacts of Industry 4.0 technologies on sustainability and operational efficiency, providing more robust data on ROI and cost-effectiveness over time.

➢ Contextual and Geographical Limitations

The study also faces contextual limitations in terms of its focus on the Indian construction industry, which may not fully generalize to other regions or countries.

- Specific Focus on Indian Market

The thesis primarily examines the Indian construction industry and its unique challenges in adopting Industry 4.0 technologies. While this provides deep insights into the specific barriers and enablers within this context, the findings may not be fully applicable to other developing economies or global markets where regulatory frameworks, technological infrastructure, and workforce readiness may differ.

For example, certain technological barriers identified in the Indian context, such as inadequate infrastructure and lack of skilled workforce (Table 5), may not be as pronounced in countries with more developed digital infrastructure or better access to training programs. Therefore, the study's conclusions, particularly regarding the barriers to adoption, should be interpreted with caution when applied to different geographic contexts.

- Regulatory Differences Across Regions

As noted in Section 2.2.3, regulatory risks play a significant role in hindering the adoption of Industry 4.0 technologies, particularly due to data privacy laws and evolving standards (Khosrowshahi & Arayici, 2012). These risks are heavily influenced by national regulatory environments, which vary significantly across countries. The regulatory challenges faced by Indian construction firms may differ considerably from those in more digitally mature markets like the United States or Europe, where standards for data privacy and cybersecurity are more established.

Future research should explore how different regulatory frameworks impact the adoption of Industry 4.0 technologies across various regions to provide a more global perspective on these challenges.

## 8.4 FUTURE SCOPE OF THE STUDY

The adoption of Industry 4.0 technologies in the Indian construction industry is still in its nascent stages, and several areas warrant further investigation to enhance understanding, implementation, and long-term benefits. This section explores the **future scope** of the study based on the findings, data, and results from the thesis. Future research could explore more nuanced aspects of Industry 4.0 adoption, such as technological advancements, training requirements, economic viability, and sustainability.

- **Expansion of Technological Research and Innovations**

While the thesis provides an in-depth examination of current Industry 4.0 technologies like **BIM**, **IoT**, and **AI** (as discussed in **Section 1.2**), the rapidly evolving nature of digital innovations suggests that future research should continue exploring **emerging technologies**.

- **Integration of Advanced Technologies like Blockchain and Quantum Computing**

Although the thesis discusses the potential of **blockchain** for secure data management (Section 2.3.2), further exploration is needed regarding its integration with existing construction management systems. Blockchain's role in improving **supply chain transparency**, **contract management**, and **data security** offers promising future avenues for research. Studies could assess the implementation of blockchain technologies in improving **data privacy** and minimizing risks associated with **cybersecurity breaches** (Patel et al., 2023; Table 5).

Furthermore, the potential of **quantum computing** to handle large-scale data processing in construction, especially in tasks like **project simulation** and **AI-driven predictions**, remains an unexplored area. Future research could investigate how quantum computing can accelerate the analysis and execution of **complex construction models** and improve **real-time decision-making**.

- **Integration of Augmented Reality (AR) and Virtual Reality (VR) in Construction Projects**

While **AR** and **VR** have been recognized for their roles in **design visualization** and **training simulations** (Section 2.3.9), their potential for improving **on-site decision-making** and **project collaboration** has not been fully explored. Future studies could investigate how AR/VR technologies could be integrated with **BIM** and **digital twins** to create **immersive construction environments**, enabling project managers to visualize project outcomes before actual implementation (Senanayake et al., 2023).

- **Economic Viability and Cost-Benefit Analysis**

The economic challenges, particularly the **high initial costs** and **uncertainty in ROI**, are significant barriers to Industry 4.0 adoption, as discussed in **Table 5** and **Section 2.2**. While the thesis highlights the financial hurdles, more research is required to provide **comprehensive cost-benefit analyses** that will encourage more firms, especially SMEs, to adopt these technologies.

- **Longitudinal Studies on Return on Investment (ROI)**

Future research could focus on **longitudinal studies** that track the long-term financial impacts of Industry 4.0 technologies. These studies could assess how firms that have implemented these technologies manage **cost efficiencies** over time and how their **return on investment** (ROI) evolves. By identifying patterns of **cost recovery**, researchers could offer more precise financial models that construction firms can use to assess the viability of investing in **BIM**, **AI**, and **robotics** (Gupta & Jain, 2021).

- **Economic Models for SMEs**

Given the focus of the thesis on large-scale firms (Section 2.1), future studies should investigate how **small and medium-sized enterprises (SMEs)** can economically integrate Industry 4.0 technologies. Developing tailored **financial models** and **government-backed subsidies** could help SMEs overcome barriers related to **high initial costs** and **cost overruns** (Patel et al., 2023). Research could also explore the economic benefits of **shared digital platforms**, where multiple SMEs can pool resources to adopt digital tools like **BIM** and **IoT** collaboratively.

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- **Sustainability and Environmental Impacts**

The thesis strongly emphasizes the sustainability benefits of Industry 4.0 technologies, particularly in reducing **material waste**, improving **energy efficiency**, and lowering **carbon emissions** (Section 2.4). However, future research could delve deeper into the **long-term environmental impacts** of these technologies and assess their role in achieving **sustainable construction goals**.

- **Quantitative Analysis of Environmental Gains**

Future studies should focus on **quantifying** the environmental benefits derived from using

**BIM**, **AI**, and **IoT** technologies in construction. Specifically, researchers could track **energy consumption**, **material usage**, and **waste reduction** across various projects and compare them to traditional construction methods. This quantitative analysis would provide clearer data on how Industry 4.0 can drive **sustainability initiatives**, especially in rapidly urbanizing regions like India (Saini et al., 2020).

- **Industry 4.0 and Circular Economy**

Future research could explore how Industry 4.0 technologies contribute to the **circular economy**, particularly by promoting the **reuse** and **recycling** of construction materials. As highlighted in **Table 4**, technologies like **3D printing** and **AI** can help optimize material usage and create more sustainable construction processes. Investigating how these technologies can be scaled to support **sustainable resource management** would further strengthen their role in reducing the environmental impact of construction (Kazemian et al., 2022).

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- **Workforce Development and Training**

A significant barrier to Industry 4.0 adoption identified in the thesis is the **lack of skilled workforce**, which prevents firms from fully leveraging these advanced technologies (Section 2.2.2). Future research should focus on developing comprehensive **workforce training programs** that can bridge the skills gap and prepare construction professionals to handle new technologies.

- **Development of Training Frameworks**

Future research could focus on designing **industry-specific training modules** for workers to master digital tools like **AI**, **IoT**, and **BIM**. Collaborating with **vocational institutions** and **universities** to create **certification programs** could offer a structured approach to training, ensuring that workers gain the necessary competencies to operate these technologies (Gupta & Jain, 2021).

- **Impact of Automation on Workforce Dynamics**

Another area that warrants further exploration is the impact of automation on **workforce dynamics**. While automation reduces labor costs and improves efficiency, it also raises concerns about **job displacement**. Future studies could explore the **social implications** of automation in construction, identifying strategies for **job transition** and **upskilling**, particularly for on-site workers displaced by robotic systems and **AI-driven processes** (Kumar et al., 2020).

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➢ **Regulatory Frameworks and Data Privacy**

The regulatory environment surrounding Industry 4.0 technologies, particularly concerning **data privacy** and **cybersecurity**, is still evolving (Section 2.2.3). The thesis highlights the challenges posed by **regulatory uncertainty**, but more research is needed to develop **clear legal frameworks** that can facilitate the safe and compliant use of these technologies.

- **Development of Comprehensive Data Privacy Laws**

Future research could focus on the formulation of **data privacy regulations** that are tailored to the needs of the construction industry. As noted in **Table 5**, the increasing use of **IoT** and **AI** in construction raises concerns about **data security** and **cyber-attacks** (Patel et al., 2023). Research should explore how firms can adopt **cybersecurity best practices** and comply with **global data privacy standards** while leveraging these technologies.

- **Establishing Global Regulatory Standards**

To ensure that Industry 4.0 technologies can be implemented across borders, there is a need for **global regulatory standards**. Future research could assess how existing frameworks like **ISO standards** can be adapted to include provisions for **digital construction technologies**. By developing global guidelines, researchers can ensure that firms in different countries can adopt Industry 4.0 technologies without facing regulatory hurdles (Khosrowshahi & Arayici, 2012).

➢ **Cross-Industry Collaboration**

The adoption of Industry 4.0 technologies in construction is not an isolated process; it requires collaboration with other industries such as **manufacturing**, **logistics**, and **information technology**. Future studies could explore the potential for **cross-industry collaboration** to enhance the implementation of these technologies.

- **Interoperability with Other Industry 4.0 Sectors**

Future research could examine how the construction industry can benefit from the experiences of other sectors, particularly **manufacturing** and **automotive**, which are further along in their Industry 4.0 journeys. For example, integrating technologies like **additive manufacturing** (used in the automotive industry) with **construction techniques** could accelerate the use of **3D printing** for large-scale construction projects (Kazemian et al., 2022).

- **Partnerships with Technology Providers**

Another important area of future research is the development of **partnerships** between construction firms and **technology providers**. Collaborating with IT firms specializing in **AI**, **IoT**, and **cloud computing** could help construction firms overcome technical challenges and improve the **scalability** of digital solutions (Sharma & Sharma, 2022).

### 8.5 Proposed Framework

The framework for the adoption of **Industry 4.0 (I4.0)** in the Indian construction industry presents a structured and comprehensive approach to modernizing the sector as illustrated in Figure 6. At its core lies the **main frame**, represented by the middle box, which focuses on the adoption process based on the **three pillars of sustainability**: economic, environmental, and social dimensions. These pillars comprise **12 different criteria** that highlight the technologies and strategies essential for achieving sustainable growth in the construction industry. The economic dimension includes Building Information Modeling (BIM), IoT and RFID technologies, Big Data Analytics, and Off-site Construction, all aimed at enhancing cost-efficiency and productivity. The environmental dimension emphasizes IoT sensors, BIM and digital tools, smart construction methods, and sustainable construction practices to minimize environmental impact. The social dimension focuses on wearable devices, digital platforms, training for digital skills, and automation for workforce empowerment and job creation.

This core adoption framework is **supported by 12 enablers** on the left, which serve as key drivers facilitating the integration of I4.0 technologies. These enablers include employer training with corporate ethics, organizational strategic planning, governmental regulations, rewards and incentives, profitability, stakeholder investment, and advanced technologies like artificial intelligence, 3D printing, BIM, and IoT.” Together, these factors create a supportive ecosystem for Industry 4.0 adoption. However, the implementation process is constrained by **20 barriers** on the right, which highlight the challenges the industry faces. These barriers range from high initial investments, uncertain ROI, and lack of funding to technical issues like skill gaps, poor standards, and technological complexity. Regulatory challenges, privacy concerns, market fragmentation, and vendor lock-in further complicate the adoption landscape.

Adding another layer of complexity to the framework are **13 perceived risks**, categorized into four major types: **technological, organizational, financial, and regulatory**. Technological risks include cybersecurity threats, data privacy issues, interoperability challenges, and the inherent complexity of advanced technologies. Organizational risks involve resistance to change, lack of skilled workforce, and infrastructure limitations. Financial risks encompass high initial costs, cost overruns, and ROI uncertainty, while regulatory risks relate to compliance with evolving standards, privacy regulations, and safety and liability concerns. These risks significantly influence decision-making and the overall success of Industry 4.0 implementation.

Overall, the framework provides a holistic view of the ecosystem necessary for adopting Industry 4.0 in the Indian construction industry. By balancing the enabling factors with strategies to overcome barriers and mitigate risks, the framework offers a pathway to sustainable, efficient, and innovative construction practices.

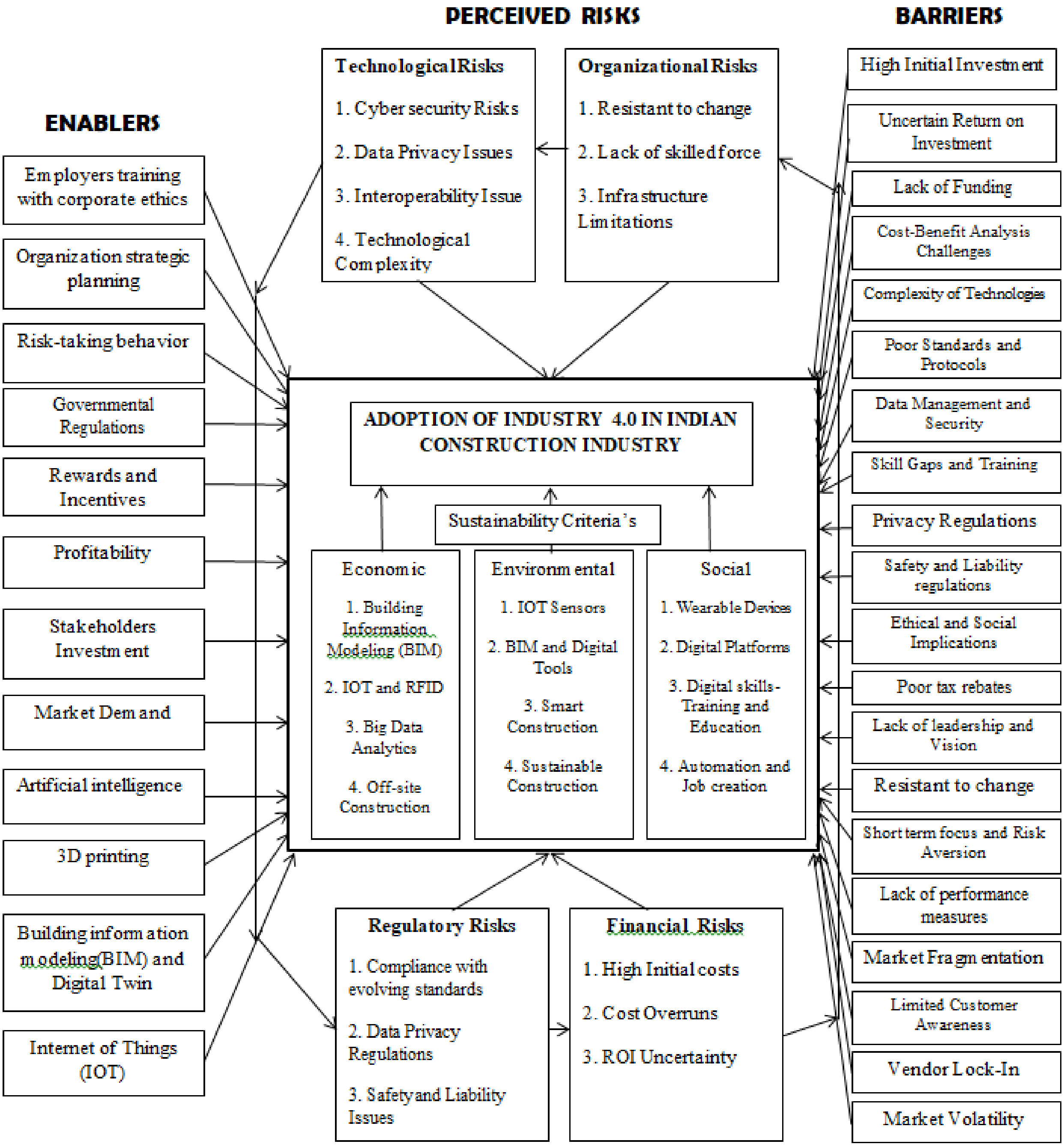


Figure 6. Framework for the adoption of Industry 4.0 (I4.0)

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# Appendix I : Research Questionnaires

## Questionnaire 1: - Questionnaire for Industry 4.0 Enablers in Construction

### Section A: General Information

1. **Your Designation:**
   - ☐ Project Manager
   - ☐ Construction Engineer
   - ☐ Design Architect
   - ☐ Technology Specialist
   - ☐ Other (Please specify): __________
2. **Years of Experience in the Construction Industry:**
   - ☐ Less than 5 years
   - ☐ 5–10 years
   - ☐ 10–15 years
   - ☐ More than 15 years
3. **Type of Projects Handled:**
   - ☐ Residential
   - ☐ Commercial
   - ☐ Infrastructure (Roads, Highways)
   - ☐ Mixed-use
   - ☐ Other (Please specify): __________
4. **Highest Level of Education Completed:**
   - ☐ High School Diploma
   - ☐ Bachelor's Degree
   - ☐ Master's Degree
   - ☐ Doctorate Degree
   - ☐ Other (Please specify): __________
5. **Field of Study:**
   - ☐ Civil Engineering
   - ☐ Mechanical Engineering
   - ☐ Electrical Engineering
   - ☐ Architecture
   - ☐ Management/Project Management
   - ☐ Other (Please specify): __________
6. **Size of Organization:**
   - ☐ Small (1-50 employees)
   - ☐ Medium (51-200 employees)
   - ☐ Large (201-1000 employees)
   - ☐ Very Large (More than 1000 employees)
7. **Geographic Location of Your Organization:**
   - ☐ Urban
   - ☐ Suburban

- ☐ Rural

8. **Industry Sector:**
   - ☐ Public Sector
   - ☐ Private Sector
   - ☐ Non-Profit
   - ☐ Other (Please specify): __________
9. **Familiarity with Industry 4.0:**
   - ☐ Not Familiar
   - ☐ Somewhat Familiar
   - ☐ Familiar
   - ☐ Very Familiar
   - ☐ Expert
10. **Have you or your organization implemented any Industry 4.0 technologies?**
    - ☐ Yes
    - ☐ No
    - If yes, please specify the technologies: _______________
11. **Which Industry 4.0 technologies are you currently using or planning to use? (Select all that apply)**
    - ☐ Building Information Modeling (BIM)
    - ☐ Internet of Things (IoT)
    - ☐ Big Data Analytics
    - ☐ Artificial Intelligence (AI)
    - ☐ Robotics and Automation
    - ☐ Digital Twins
    - ☐ Cloud Computing
    - ☐ Other (Please specify): __________
12. **How would you rate your organization's readiness for Industry 4.0 adoption?**
    - ☐ Not Ready
    - ☐ Somewhat Ready
    - ☐ Ready
    - ☐ Very Ready
    - ☐ Fully Ready
13. **What is the primary driver for adopting Industry 4.0 technologies in your organization? (Select one)**
    - ☐ Cost Efficiency
    - ☐ Sustainability/Environmental Concerns
    - ☐ Productivity Improvement
    - ☐ Government Regulations
    - ☐ Technological Innovation
    - ☐ Other (Please specify): __________
14. **Which of the following enablers would you consider most critical for Industry 4.0 adoption in your organization? (Select up to three)**
    - ☐ Employer Training with Corporate Ethics

- ☐ Organization Strategic Planning
- ☐ Risk-Taking Behavior
- ☐ Governmental Regulations
- ☐ Rewards and Incentives
- ☐ Profitability
- ☐ Stakeholders' Investments
- ☐ Market Demand
- ☐ Artificial Intelligence (AI)
- ☐ 3D Printing
- ☐ BIM & Digital Twin
- ☐ Internet of Things (IoT)
- ☐ Other (Please specify): __________

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**Section B: Fuzzy Evaluation of Criterias for Industry 4.0 Implementation**

**Instructions:**

For each of the following sub-criteria under the major categories, evaluate its importance in implementing Industry 4.0 using the linguistic scale mapped to the triangular fuzzy number (TFN) provided below.

| Major Criteria | Sub-Criteria | Code |
|---|---|---|
| **Organizational** | Employers training with corporate ethics | E1 |
| | Organization strategic planning | E2 |
| | Risk-taking behavior | E3 |
| | Governmental regulations | E4 |
| **Economic** | Rewards and Incentives | E5 |
| | Profitability | E6 |
| | Stakeholders Investment | E7 |
| | Market Demand | E8 |
| **Technological** | Artificial intelligence | E9 |
| | 3D printing | E10 |

| | | |
|---|---|---|
| | Building information modeling(BIM) and Digital Twin | E11 |
| | Internet of Things (IOT) | E12 |

**Linguistic Scale**

- **Very Low (VL):** (0.222, 0.25, 0.286)
- **Low (L):** (0.286, 0.333, 0.4)
- **Medium (M):** (0.4, 0.5, 0.667)
- **High (H):** (0.667, 1, 1.5)
- **Very High (VH):** (1.5, 2, 2.5)

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**Organizational Criteria**

| **Sub-Criteria** | **Code** | **VL** | **L** | **M** | **H** | **VH** |
|---|---|---|---|---|---|---|
| Employers training with corporate ethics | E1 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Organization strategic planning | E2 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Risk-taking behavior | E3 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Governmental regulations | E4 | ☐ | ☐ | ☐ | ☐ | ☐ |

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**Economic Criteria**

| **Sub-Criteria** | **Code** | **VL** | **L** | **M** | **H** | **VH** |
|---|---|---|---|---|---|---|
| Rewards and Incentives | E5 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Profitability | E6 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Stakeholders Investment | E7 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Market Demand | E8 | ☐ | ☐ | ☐ | ☐ | ☐ |

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**Technological Criteria**

| **Sub-Criteria** | **Code** | **VL** | **L** | **M** | **H** | **VH** |
|---|---|---|---|---|---|---|
| Artificial intelligence | E9 | ☐ | ☐ | ☐ | ☐ | ☐ |
| 3D printing | E10 | ☐ | ☐ | ☐ | ☐ | ☐ |
| Building Information Modeling (BIM) and Digital Twin | E11 | ☐ | ☐ | ☐ | ☐ | ☐ |

| Sub-Criteria | Code | VL | L | M | H | VH |
|---|---|---|---|---|---|---|
| Internet of Things (IoT) | E12 | ☐ | ☐ | ☐ | ☐ | ☐ |

**Section C: Pairwise Comparison of Major-Criterias**

**Instructions:**

For each of the following pairs of major criteria, rate the relative importance of one criterion compared to the other using the fuzzy triangular number (TFN) scale provided below.

| Comparison | Equal | VL | L | M | H | VH |
|---|---|---|---|---|---|---|
| Organizational (E1-E4) vs Economic (E5-E8) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Organizational (E1-E4) vs Technological (E9-E12) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Economic (E5-E8) vs Technological (E9-E12) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Section D: Pairwise Comparison of Sub-Criteria**

**Instructions:**

For each of the following pairs of sub-criteria, rate the relative importance of one sub-criterion compared to the other using the fuzzy triangular number (TFN) scale provided below.

**Organizational Criteria**

| Comparison | Equal | VL | L | M | H | VH |
|---|---|---|---|---|---|---|
| Employers training (E1) vs Organization strategic planning (E2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Employers training (E1) vs Risk-taking behavior (E3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Employers training (E1) vs Governmental regulations (E4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Organization strategic planning (E2) vs Risk-taking behavior (E3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Organization strategic planning (E2) vs Governmental regulations (E4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Risk-taking behavior (E3) vs Governmental regulations (E4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Economic Criteria**

| Comparison | Equal | VL | L | M | H | VH |
|---|---|---|---|---|---|---|
| Rewards and Incentives (E5) vs Profitability (E6) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Rewards and Incentives (E5) vs Stakeholders Investment (E7) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Rewards and Incentives (E5) vs Market Demand (E8) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Profitability (E6) vs Stakeholders Investment (E7) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Profitability (E6) vs Market Demand (E8) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Stakeholders Investment (E7) vs Market Demand (E8) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

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**Technological Criteria**

| Comparison | Equal | VL | L | M | H | VH |
|---|---|---|---|---|---|---|
| AI (E9) vs 3D printing (E10) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| AI (E9) vs BIM & Digital Twin (E11) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| AI (E9) vs IoT (E12) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 3D printing (E10) vs BIM & Digital Twin (E11) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 3D printing (E10) vs IoT (E12) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| BIM & Digital Twin (E11) vs IoT (E12) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

## Section E: Enablers for Industry 4.0 Implementation

This section assesses the significance of various organizational, economic, and technological enablers for Industry 4.0 adoption. Please rate the significance of each enabler using the following scale:

## Organizational Enablers

1. **Employer Training with Corporate Ethics**
   How significant is employer training with corporate ethics in enabling Industry 4.0 in your organization?
   VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
2. **Organizational Strategic Planning**
   How critical is organizational strategic planning for Industry 4.0 implementation?
   VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
3. **Risk-Taking Behavior**
   To what extent does fostering risk-taking behavior support Industry 4.0 adoption?
   VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
4. **Government Regulations**
   How influential are government regulations in enabling Industry 4.0 in your

sector?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐

5. **Leadership Commitment**
How important is strong leadership commitment for Industry 4.0 initiatives?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
6. **Change Management Strategies**
How significant is having effective change management strategies for Industry 4.0 adoption?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐

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## Economic Enablers

7. **Rewards and Incentives**
How important are rewards and incentives in promoting Industry 4.0 technologies in your organization?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
8. **Profitability**
How significant is profitability as a motivator for Industry 4.0 adoption?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
9. **Stakeholders' Investments**
How important are stakeholders' investments in the context of Industry 4.0 development in your organization?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
10. **Market Demand**
How does market demand influence your organization's decision to implement Industry 4.0 technologies?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
11. **Financial Incentives from Government**
How important are financial incentives or subsidies from the government in driving Industry 4.0 adoption?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
12. **Availability of Capital**
How critical is access to capital or funding for the adoption of Industry 4.0 technologies?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐

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## Technological Enablers

13. **Artificial Intelligence (AI)**
How significant is the use of AI as an enabler for Industry 4.0 in your organization?
VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐

14. **3D Printing**
    How important is 3D printing in driving Industry 4.0 advancements?
    VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
15. **Building Information Modeling (BIM) and Digital Twin**
    To what extent are BIM and digital twin technologies essential for Industry 4.0 implementation?
    VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
16. **Internet of Things (IoT)**
    How important is IoT for the development of Industry 4.0 in your organization?
    VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
17. **Cybersecurity Measures**
    How critical are cybersecurity measures in ensuring successful Industry 4.0 adoption?
    VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐
18. **Data Management and Analytics**
    How important is the ability to manage and analyze large amounts of data (Big Data) for Industry 4.0 implementation?
    VL ☐ | L ☐ | M ☐ | H ☐ | VH ☐

**Section F: Enablers Evaluation Under Changing Conditions**

**Instructions:**
For each of the following scenarios, you are asked to rate the importance of several enablers. Additionally, provide detailed reasoning for your answers where applicable.

---

## Scenario 1: Economic Growth

Your organization is experiencing strong economic growth, and there is an increased budget available for innovation and technology implementation. Consider the following enablers:

1. **Employer Training with Corporate Ethics:**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - How important is it to invest in employee training when the company has a surplus budget?
     ☐ Not Important ☐ Slightly Important ☐ Moderately Important ☐ Very Important ☐ Critical
   - Should ethics and corporate responsibility training be prioritized in economic growth scenarios?
     ☐ Yes ☐ No ☐ Not Sure

  - How does training improve the organization's adaptation to new technologies?
2. **Organization Strategic Planning:**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - Does a larger budget significantly affect long-term strategic planning?
     ☐ Yes ☐ No ☐ Somewhat
   - Should your organization allocate more resources to strategic innovation during economic growth?
     ☐ Yes ☐ No ☐ Not Sure
3. **Risk-Taking Behavior:**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - Is it easier to take risks in Industry 4.0 adoption during economic booms?
     ☐ Yes ☐ No
   - Should the organization increase investment in riskier but high-potential technologies during times of growth?

---

## Scenario 2: Economic Recession

Your organization is facing an economic downturn, requiring careful and cost-effective decision-making. Analyze the importance of the following enablers under these circumstances:

1. **Employer Training with Corporate Ethics:**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - Should the organization reduce its budget for training in times of economic crisis?
     ☐ Yes ☐ No
   - How does ethics training improve employee performance in challenging financial situations?
2. **Organization Strategic Planning:**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - Should the organization emphasize short-term or long-term planning during a recession?
     ☐ Short-term ☐ Long-term ☐ Balanced
   - What strategic adjustments would be necessary to survive and innovate during economic downturns?

---

## Scenario 3: High Regulatory Pressure

There is increased regulatory pressure from the government to meet sustainability and data privacy mandates. Consider the following enablers under these conditions:

1. **Governmental Regulations:**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - How would increased regulations impact the organization's Industry 4.0 technology adoption strategy?
     ☐ Positively ☐ Negatively ☐ Neutral
   - Should the organization allocate more resources to compliance and regulatory training?
     ☐ Yes ☐ No ☐ Not Sure
2. **Cybersecurity:**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - How critical is cybersecurity when regulatory requirements focus on data protection?
     ☐ Very Critical ☐ Moderately Critical ☐ Not Critical
   - How much budget should be allocated to improving cybersecurity to meet regulatory standards?

---

## Scenario 4: Rapid Technological Advancements

The industry is experiencing rapid technological changes. Consider the following enablers under these conditions:

1. **Artificial Intelligence (AI):**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - How significant is AI for driving future business growth?
     ☐ Very Significant ☐ Moderately Significant ☐ Slightly Significant ☐ Not Significant
   - Should the organization invest heavily in AI during rapid technological advancements?
2. **3D Printing:**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**

- In what areas would 3D printing provide the most value to your organization?
  ☐ Prototyping ☐ Manufacturing ☐ Supply Chain ☐ Other: ___________

---

## Scenario 5: Limited Technological Infrastructure

Your organization faces technological constraints and lacks access to advanced infrastructure.

1. **Building Information Modeling (BIM) & Digital Twin:**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - Is it feasible to implement BIM and Digital Twin technologies given your current infrastructure?
     ☐ Yes ☐ No
   - What challenges are you likely to face in adopting these technologies without substantial infrastructure upgrades?
2. **Internet of Things (IoT):**
   Rate the importance:
   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
   **Sub-questions:**
   - Would the integration of IoT systems improve operational efficiency in the absence of advanced technological infrastructure?
     ☐ Yes ☐ No ☐ Not Sure
   - What basic infrastructure upgrades would be required to implement IoT technologies effectively?

---

## Section G: Sensitivity Analysis

**Instructions:**
Please indicate how changing the relative importance of the following enablers would impact your overall decision-making process. Use the following scale:

- **No Impact**
- **Slight Impact**
- **Moderate Impact**
- **Significant Impact**
- **Extreme Impact**

1. **Changing the importance of Employer Training with Corporate Ethics**:
☐ No Impact ☐ Slight Impact ☐ Moderate Impact ☐ Significant Impact ☐ Extreme Impact
**Reasoning:**
______________________________________________________________
2. **Changing the importance of Organization Strategic Planning**:
☐ No Impact ☐ Slight Impact ☐ Moderate Impact ☐ Significant Impact ☐ Extreme Impact
**Reasoning:**
______________________________________________________________
3. **Changing the importance of Artificial Intelligence (AI)**:
☐ No Impact ☐ Slight Impact ☐ Moderate Impact ☐ Significant Impact ☐ Extreme Impact
**Reasoning:**
______________________________________________________________
4. **Changing the importance of Internet of Things (IoT)**:
☐ No Impact ☐ Slight Impact ☐ Moderate Impact ☐ Significant Impact ☐ Extreme Impact
**Reasoning:**
______________________________________________________________
5. **Changing the importance of Governmental Regulations**:
☐ No Impact ☐ Slight Impact ☐ Moderate Impact ☐ Significant Impact ☐ Extreme Impact
**Reasoning:**
______________________________________________________________

Thank you for taking the time to complete this detailed questionnaire on the analysis of Industry 4.0 enablers. Your valuable insights will greatly contribute to our understanding prioritization of these enablers. This analysis will help inform strategic decision-making, ensuring that organizations like yours can better navigate the evolving technological landscape.

We appreciate your honest and thoughtful responses. Should you have any additional thoughts or suggestions, feel free to include them. Together, we can drive innovation and transformation in Industry 4.0, ensuring sustainable growth and competitiveness in the future.

**Additional Comments or Suggestions:**

Thank you once again for your participation!

**Questionnaire 2: - Questionnaire for Investigating Barriers to Industry 4.0 (I4.0) Implementation in the Construction Industry**

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## Section A: General Information

15. **Your Designation:**
    - ☐ Project Manager
    - ☐ Construction Engineer
    - ☐ Design Architect
    - ☐ Technology Specialist
    - ☐ Other (Please specify): __________
16. **Years of Experience in the Construction Industry:**
    - ☐ Less than 5 years
    - ☐ 5–10 years
    - ☐ 10–15 years
    - ☐ More than 15 years
17. **Type of Projects Handled:**
    - ☐ Residential
    - ☐ Commercial
    - ☐ Infrastructure (Roads, Highways)
    - ☐ Mixed-use
    - ☐ Other (Please specify): __________
18. **Highest Level of Education Completed:**
    - ☐ High School Diploma
    - ☐ Bachelor's Degree
    - ☐ Master's Degree
    - ☐ Doctorate Degree
    - ☐ Other (Please specify): __________
19. **Field of Study:**
    - ☐ Civil Engineering
    - ☐ Mechanical Engineering
    - ☐ Electrical Engineering
    - ☐ Architecture
    - ☐ Management/Project Management
    - ☐ Other (Please specify): __________
20. **Size of Organization:**
    - ☐ Small (1-50 employees)
    - ☐ Medium (51-200 employees)
    - ☐ Large (201-1000 employees)
    - ☐ Very Large (More than 1000 employees)
21. **Geographic Location of Your Organization:**
    - ☐ Urban

- ☐ Suburban
- ☐ Rural

22. **Industry Sector:**
    - ☐ Public Sector
    - ☐ Private Sector
    - ☐ Non-Profit
    - ☐ Other (Please specify): __________
23. **Familiarity with Industry 4.0:**
    - ☐ Not Familiar
    - ☐ Somewhat Familiar
    - ☐ Familiar
    - ☐ Very Familiar
    - ☐ Expert
24. **Have you or your organization implemented any Industry 4.0 technologies?**
    - ☐ Yes
    - ☐ No
    - If yes, please specify the technologies: _______________
25. **Which Industry 4.0 technologies are you currently using or planning to use? (Select all that apply)**
    - ☐ Building Information Modeling (BIM)
    - ☐ Internet of Things (IoT)
    - ☐ Big Data Analytics
    - ☐ Artificial Intelligence (AI)
    - ☐ Robotics and Automation
    - ☐ Digital Twins
    - ☐ Cloud Computing
    - ☐ Other (Please specify): __________
26. **How would you rate your organization's readiness for Industry 4.0 adoption?**
    - ☐ Not Ready
    - ☐ Somewhat Ready
    - ☐ Ready
    - ☐ Very Ready
    - ☐ Fully Ready
27. **What do you see as the biggest barrier to adopting Industry 4.0 in your organization? (Select one)**
    - ☐ Financial Constraints
    - ☐ Lack of Skilled Workforce
    - ☐ Resistance to Change
    - ☐ Regulatory Challenges
    - ☐ Technological Complexity
    - ☐ Other (Please specify): __________

**Section B: Fuzzy Evaluation of Industry 4.0 Barriers**

*Instructions:*

For each barrier listed below, please evaluate its importance as a barrier to implementing Industry 4.0 (I4.0) in the construction industry. Use the following fuzzy linguistic variables to indicate your assessment.

| Major Barriers/Criteria | Barriers Code | Sub-Criterias |
|---|---|---|
| Financial Barriers | FI1 | High Initial Investment |
| | FI2 | Uncertain Return on Investment |
| | FI3 | Lack of Funding |
| | FI4 | Cost-Benefit Analysis Challenges |
| Technological Barriers | TE1 | Complexity of Technologies |
| | TE2 | Poor Standards and Protocols |
| | TE3 | Data Management and Security |
| | TE4 | Skill Gaps and Training needs |
| Regulatory Barriers | RE1 | Privacy Regulations |
| | RE2 | Safety and Liability regulations |
| | RE3 | Ethical and Social Implications |
| | RE4 | Poor tax rebates |
| Organizational Barriers | OR1 | Lack of leadership and Vision |
| | OR2 | Resistant to change |
| | OR3 | Short term focus and Risk Aversion |
| | OR4 | Lack of performance measures |
| Market Barriers | MR1 | Market Fragmentation |
| | MR2 | Limited Customer Awareness |
| | MR3 | Vendor Lock-In |
| | MR4 | Market Volatility |

**Fuzzy Triangular Numbers (TFN)**

| **Lingual Variables** | |
|---|---|
| **Equal** | (1, 1, 1) |
| **Very Low** | (1, 2, 3) |
| **Low** | (2, 3, 4) |
| **Moderate** | (3, 4, 5) |
| **High** | (4, 5, 6) |
| **Very Strong** | (5, 6, 7) |
| **Extreme** | (7, 8, 9) |

| Barrier | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| High Initial Investment (FI1) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Uncertain Return on Investment (FI2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Lack of Funding (FI3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cost-Benefit Analysis Challenges (FI4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Technological Barriers:**

| Barrier | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Complexity of Technologies (TE1) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Poor Standards and Protocols (TE2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Data Management and Security (TE3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Skill Gaps and Training Needs (TE4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Regulatory Barriers:**

| Barrier | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Privacy Regulations (RE1) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Safety and Liability Regulations (RE2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Ethical and Social Implications (RE3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Poor Tax Rebates (RE4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Organizational Barriers:**

| Barrier | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Lack of Leadership and Vision (OR1) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Resistance to Change (OR2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Short-term Focus and Risk Aversion (OR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Lack of Performance Measures (OR4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Market Barriers:**

| Barrier | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Market Fragmentation (MR1) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Limited Customer Awareness (MR2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Vendor Lock-In (MR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Market Volatility (MR4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

## Section C: Pairwise Comparisons Between Major Barriers

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Financial Barriers (FI) vs Technological Barriers (TE) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Financial Barriers (FI) vs Regulatory Barriers (RE) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Financial Barriers (FI) vs Organizational Barriers (OR) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Financial Barriers (FI) vs Market Barriers (MR) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Technological Barriers (TE) vs Regulatory Barriers (RE) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Technological Barriers (TE) vs Organizational Barriers (OR) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Technological Barriers (TE) vs | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Market Barriers (MR) | | | | | | | |
| Regulatory Barriers (RE) vs Organizational Barriers (OR) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Regulatory Barriers (RE) vs Market Barriers (MR) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Organizational Barriers (OR) vs Market Barriers (MR) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Section D: Pairwise Comparison of Sub-Barriers**

**Instructions:**

For each of the following pairs of sub-barriers, rate the relative importance of one sub-barrier compared to the other within the same major barrier using the fuzzy triangular number (TFN) scale provided.

**Sub-barriers of Financial Barriers**

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| High Initial Investment (FI1) vs Uncertain Return on Investment (FI2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| High Initial Investment (FI1) vs Lack of Funding (FI3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| High Initial Investment (FI1) vs Cost-Benefit Analysis Challenges (FI4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Uncertain Return on Investment (FI2) vs Lack of Funding (FI3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Uncertain Return on Investment (FI2) vs Cost-Benefit Analysis Challenges (FI4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Lack of Funding (FI3) vs Cost-Benefit Analysis Challenges (FI4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Sub-barriers of Technological Barriers**

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Complexity of Technologies (TE1) vs Poor Standards and Protocols (TE2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Complexity of Technologies (TE1) vs Data Management and Security (TE3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Complexity of Technologies (TE1) vs Skill Gaps and Training Needs (TE4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Poor Standards and Protocols (TE2) vs Data Management and Security (TE3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Poor Standards and Protocols (TE2) vs Skill Gaps and Training Needs (TE4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Data Management and Security (TE3) vs Skill Gaps and Training Needs (TE4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Sub-barriers of Regulatory Barriers**

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Privacy Regulations (RE1) vs Safety and Liability Regulations (RE2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Privacy Regulations (RE1) vs Ethical and Social Implications (RE3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Privacy Regulations (RE1) vs Poor Tax Rebates (RE4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Safety and Liability Regulations (RE2) vs Ethical and Social Implications (RE3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Safety and Liability Regulations (RE2) vs Poor Tax Rebates (RE4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Ethical and Social Implications (RE3) vs Poor Tax Rebates (RE4) | ☐ | ☐ | ☐ | ☐ | ☐ | | |

### Sub-barriers of Organizational Barriers

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Lack of Leadership and Vision (OR1) vs Resistance to Change (OR2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Lack of Leadership and Vision (OR1) vs Short-Term Focus and Risk Aversion (OR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Lack of Leadership and Vision (OR1) vs Lack of Performance Measures (OR4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Resistance to Change (OR2) vs Short-Term Focus and Risk Aversion (OR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Resistance to Change (OR2) vs Lack of Performance Measures (OR4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Short-Term Focus and Risk Aversion (OR3) vs Lack of Performance Measures (OR4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

### Sub-barriers of Market Barriers

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Market Fragmentation (MR1) vs Limited Customer Awareness (MR2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Market Fragmentation (MR1) vs Vendor Lock-In (MR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Market Fragmentation (MR1) vs Market Volatility (MR4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Limited Customer Awareness (MR2) vs Vendor Lock-In (MR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Limited Customer Awareness (MR2) vs Market Volatility (MR4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Vendor Lock-In (MR3) vs Market Volatility (MR4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

## Section E: Ranking the Significance of Barriers to Industry 4.0 Implementation

**Instructions:** For each barrier listed below, please rank its significance as a barrier to implementing Industry 4.0 (I4.0) in your organization. Use the Fuzzy Triangular Numbers (TFN) provided to indicate your assessment:

- Equal (1, 1, 1)
- Very Low (1, 2, 3)
- Low (2, 3, 4)
- Moderate (3, 4, 5)
- High (4, 5, 6)
- Very Strong (5, 6, 7)
- Extreme (7, 8, 9)

---

### Financial Barriers

1. **High Initial Investment**
   - ☐ Equal (1, 1, 1)
   - ☐ Very Low (1, 2, 3)
   - ☐ Low (2, 3, 4)
   - ☐ Moderate (3, 4, 5)
   - ☐ High (4, 5, 6)
   - ☐ Very Strong (5, 6, 7)
   - ☐ Extreme (7, 8, 9)

   **Do you believe the high initial investment is a barrier to your organization's adoption of I4.0?**

   - ☐ Yes
   - ☐ No
   - ☐ Unsure
2. **Uncertain Return on Investment**
   - ☐ Equal (1, 1, 1)
   - ☐ Very Low (1, 2, 3)
   - ☐ Low (2, 3, 4)
   - ☐ Moderate (3, 4, 5)
   - ☐ High (4, 5, 6)
   - ☐ Very Strong (5, 6, 7)
   - ☐ Extreme (7, 8, 9)

   **Is the uncertainty of return on investment a concern for your organization**

**regarding I4.0?**

- ☐ Yes
- ☐ No
- ☐ Unsure

3. **Lack of Funding**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Does your organization currently face a lack of funding for I4.0 initiatives?**

    - ☐ Yes
    - ☐ No
    - ☐ Unsure
4. **Cost-Benefit Analysis Challenges**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Do you encounter challenges in conducting cost-benefit analyses for I4.0 projects?**

    - ☐ Yes
    - ☐ No
    - ☐ Unsure

---

## Technological Barriers

5. **Complexity of Technologies**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)

- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

**Is the complexity of new technologies a barrier to adopting I4.0 in your organization?**

- ☐ Yes
- ☐ No
- ☐ Unsure

6. **Poor Standards and Protocols**
   - ☐ Equal (1, 1, 1)
   - ☐ Very Low (1, 2, 3)
   - ☐ Low (2, 3, 4)
   - ☐ Moderate (3, 4, 5)
   - ☐ High (4, 5, 6)
   - ☐ Very Strong (5, 6, 7)
   - ☐ Extreme (7, 8, 9)

   **Are you concerned about the lack of standards and protocols when implementing I4.0?**

   - ☐ Yes
   - ☐ No
   - ☐ Unsure
7. **Data Management and Security**
   - ☐ Equal (1, 1, 1)
   - ☐ Very Low (1, 2, 3)
   - ☐ Low (2, 3, 4)
   - ☐ Moderate (3, 4, 5)
   - ☐ High (4, 5, 6)
   - ☐ Very Strong (5, 6, 7)
   - ☐ Extreme (7, 8, 9)

   **Is data management and security a major concern in your organization regarding I4.0?**

   - ☐ Yes
   - ☐ No
   - ☐ Unsure
8. **Skill Gaps and Training Needs**
   - ☐ Equal (1, 1, 1)
   - ☐ Very Low (1, 2, 3)
   - ☐ Low (2, 3, 4)

- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

**Does your organization face significant skill gaps or training needs for I4.0 implementation?**

- ☐ Yes
- ☐ No
- ☐ Unsure

---

## Regulatory Barriers

9. **Privacy Regulations**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Are privacy regulations a significant barrier to I4.0 in your organization?**

    - ☐ Yes
    - ☐ No
    - ☐ Unsure
10. **Safety and Liability Regulations**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Do safety and liability regulations hinder your organization's ability to adopt I4.0?**

    - ☐ Yes
    - ☐ No

- ☐ Unsure

11. **Ethical and Social Implications**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Are ethical and social implications a concern for your organization in the context of I4.0?**

    - ☐ Yes
    - ☐ No
    - ☐ Unsure
12. **Poor Tax Rebates**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Does your organization feel that poor tax rebates act as a barrier to adopting I4.0?**

    - ☐ Yes
    - ☐ No
    - ☐ Unsure

---

## Organizational Barriers

13. **Lack of Leadership and Vision**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

**Is a lack of leadership and vision a barrier to your organization's adoption of I4.0?**

- ☐ Yes
- ☐ No
- ☐ Unsure

14. **Cultural Resistance to Change**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

**Does cultural resistance to change hinder your organization's efforts to implement I4.0?**

- ☐ Yes
- ☐ No
- ☐ Unsure

15. **Employee Engagement**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

**Is low employee engagement a barrier to adopting I4.0 in your organization?**

- ☐ Yes
- ☐ No
- ☐ Unsure

16. **Inadequate Infrastructure**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

**Is inadequate infrastructure a significant barrier to I4.0 implementation in your organization?**

- ☐ Yes
- ☐ No
- ☐ Unsure

---

## Knowledge Barriers

17. **Lack of Awareness and Understanding**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Does a lack of awareness and understanding of I4.0 hinder your organization's ability to implement it?**

    - ☐ Yes
    - ☐ No
    - ☐ Unsure
18. **Inadequate Research and Development**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Is inadequate research and development a barrier for your organization regarding I4.0?**

    - ☐ Yes
    - ☐ No
    - ☐ Unsure
19. **Competitive Pressure**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)

- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

**Does competitive pressure significantly impact your organization's I4.0 adoption?**

- ☐ Yes
- ☐ No
- ☐ Unsure

20. **Customer Demand Uncertainty**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Is customer demand uncertainty a barrier for your organization in implementing I4.0?**

    - ☐ Yes
    - ☐ No
    - ☐ Unsure
21. **Global Supply Chain Disruptions**
    - ☐ Equal (1, 1, 1)
    - ☐ Very Low (1, 2, 3)
    - ☐ Low (2, 3, 4)
    - ☐ Moderate (3, 4, 5)
    - ☐ High (4, 5, 6)
    - ☐ Very Strong (5, 6, 7)
    - ☐ Extreme (7, 8, 9)

    **Are global supply chain disruptions a significant barrier to your organization's I4.0 implementation?**

    - ☐ Yes
    - ☐ No
    - ☐ Unsure

## Section F: Sensitivity Analysis on Barriers to Industry 4.0 Implementation

**Instructions:** For each of the following statements, indicate your level of agreement using Fuzzy Triangular Numbers (TFN) as follows:

- (1, 1, 1) – Strongly Disagree
- (1, 2, 3) – Disagree
- (2, 3, 4) – Slightly Disagree
- (3, 4, 5) – Neutral
- (4, 5, 6) – Slightly Agree
- (5, 6, 7) – Agree
- (7, 8, 9) – Strongly Agree

---

1. **If the initial investment for I4.0 were significantly lower, it would increase my organization's likelihood of adoption.**
   - ☐ (1, 1, 1)
   - ☐ (1, 2, 3)
   - ☐ (2, 3, 4)
   - ☐ (3, 4, 5)
   - ☐ (4, 5, 6)
   - ☐ (5, 6, 7)
   - ☐ (7, 8, 9)
2. **If there were clear guidelines and standards for I4.0 implementation, my organization would be more inclined to adopt it.**
   - ☐ (1, 1, 1)
   - ☐ (1, 2, 3)
   - ☐ (2, 3, 4)
   - ☐ (3, 4, 5)
   - ☐ (4, 5, 6)
   - ☐ (5, 6, 7)
   - ☐ (7, 8, 9)
3. **If my organization had access to more funding options, it would facilitate our I4.0 implementation efforts.**
   - ☐ (1, 1, 1)
   - ☐ (1, 2, 3)
   - ☐ (2, 3, 4)
   - ☐ (3, 4, 5)
   - ☐ (4, 5, 6)
   - ☐ (5, 6, 7)
   - ☐ (7, 8, 9)
4. **If training programs were readily available to upskill employees, it would alleviate concerns regarding skill gaps for I4.0.**
   - ☐ (1, 1, 1)

- ☐ (1, 2, 3)
- ☐ (2, 3, 4)
- ☐ (3, 4, 5)
- ☐ (4, 5, 6)
- ☐ (5, 6, 7)
- ☐ (7, 8, 9)

5. **If my organization had a clear strategic vision for I4.0, it would reduce resistance to change among employees.**
   - ☐ (1, 1, 1)
   - ☐ (1, 2, 3)
   - ☐ (2, 3, 4)
   - ☐ (3, 4, 5)
   - ☐ (4, 5, 6)
   - ☐ (5, 6, 7)
   - ☐ (7, 8, 9)
6. **If there was better data management and security infrastructure in place, it would improve my organization's confidence in adopting I4.0.**
   - ☐ (1, 1, 1)
   - ☐ (1, 2, 3)
   - ☐ (2, 3, 4)
   - ☐ (3, 4, 5)
   - ☐ (4, 5, 6)
   - ☐ (5, 6, 7)
   - ☐ (7, 8, 9)
7. **If my organization could demonstrate a clear ROI from I4.0 initiatives, it would justify the investment and facilitate adoption.**
   - ☐ (1, 1, 1)
   - ☐ (1, 2, 3)
   - ☐ (2, 3, 4)
   - ☐ (3, 4, 5)
   - ☐ (4, 5, 6)
   - ☐ (5, 6, 7)
   - ☐ (7, 8, 9)
8. **If industry peers shared successful case studies of I4.0 implementation, it would positively influence my organization's perception of its value.**
   - ☐ (1, 1, 1)
   - ☐ (1, 2, 3)
   - ☐ (2, 3, 4)
   - ☐ (3, 4, 5)
   - ☐ (4, 5, 6)
   - ☐ (5, 6, 7)
   - ☐ (7, 8, 9)
9. **If government incentives for I4.0 implementation were enhanced, it would encourage my organization to adopt these technologies.**

- ☐ (1, 1, 1)
- ☐ (1, 2, 3)
- ☐ (2, 3, 4)
- ☐ (3, 4, 5)
- ☐ (4, 5, 6)
- ☐ (5, 6, 7)
- ☐ (7, 8, 9)

10. **If customer demand for I4.0-driven products increased, it would compel my organization to prioritize its adoption.**
    - ☐ (1, 1, 1)
    - ☐ (1, 2, 3)
    - ☐ (2, 3, 4)
    - ☐ (3, 4, 5)
    - ☐ (4, 5, 6)
    - ☐ (5, 6, 7)
    - ☐ (7, 8, 9)

---

## Additional Open-Ended Questions:

1. **What specific changes in input values do you think would most significantly impact your organization's perception of barriers to I4.0 adoption?**
   *Please describe your thoughts:*

   ---

2. **Can you provide any examples from your organization where changes in funding, technology, or strategy have led to different outcomes regarding I4.0 implementation?**
   *Please share any relevant experiences:*

   ---

3. **What further insights or suggestions do you have regarding how your organization could adapt to overcome these barriers?**
   *Your suggestions:*

   ---

Thank you for taking the time to complete this detailed questionnaire on the analysis of Industry 4.0 barriers. Your valuable insights will greatly contribute to our understanding prioritization of these barriers. This analysis will help inform strategic decision-making, ensuring that organizations like yours can better navigate the evolving technological landscape.

We appreciate your honest and thoughtful responses. Should you have any additional thoughts or suggestions, feel free to include them. Together, we can drive innovation and transformation in Industry 4.0, ensuring sustainable growth and competitiveness in the future.

**Additional Comments or Suggestions:**

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Thank you once again for your participation!

## Questionnaire 3: - Questionnaire for Investigating Sustainability Dimensions to Industry 4.0 (I4.0) Implementation in the Construction Industry

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## Section A: General Information

28. **Your Designation:**
    - ☐ Project Manager
    - ☐ Construction Engineer
    - ☐ Design Architect
    - ☐ Technology Specialist
    - ☐ Other (Please specify): ___________
29. **Years of Experience in the Construction Industry:**
    - ☐ Less than 5 years
    - ☐ 5–10 years
    - ☐ 10–15 years
    - ☐ More than 15 years
30. **Type of Projects Handled:**
    - ☐ Residential
    - ☐ Commercial
    - ☐ Infrastructure (Roads, Highways)
    - ☐ Mixed-use
    - ☐ Other (Please specify): ___________
31. **Highest Level of Education Completed:**

- ☐ High School Diploma
  - ☐ Bachelor's Degree
  - ☐ Master's Degree
  - ☐ Doctorate Degree
  - ☐ Other (Please specify): ___________

32. **Field of Study:**
    - ☐ Civil Engineering
    - ☐ Mechanical Engineering
    - ☐ Electrical Engineering
    - ☐ Architecture
    - ☐ Management/Project Management
    - ☐ Other (Please specify): ___________
33. **Size of Organization:**
    - ☐ Small (1-50 employees)
    - ☐ Medium (51-200 employees)
    - ☐ Large (201-1000 employees)
    - ☐ Very Large (More than 1000 employees)
34. **Geographic Location of Your Organization:**
    - ☐ Urban
    - ☐ Suburban
    - ☐ Rural
35. **Industry Sector:**
    - ☐ Public Sector
    - ☐ Private Sector
    - ☐ Non-Profit
    - ☐ Other (Please specify): ___________
36. **Familiarity with Industry 4.0:**
    - ☐ Not Familiar
    - ☐ Somewhat Familiar
    - ☐ Familiar
    - ☐ Very Familiar
    - ☐ Expert

10. **Use of Sustainable Construction Practices:**

- ☐ Not Used
- ☐ Occasionally Used
- ☐ Regularly Used
- ☐ Always Used

11. **Adoption of Sustainability Certifications:**

- ☐ LEED (Leadership in Energy and Environmental Design)

- ☐ BREEAM (Building Research Establishment Environmental Assessment Method)
- ☐ WELL Certification
- ☐ None
- ☐ Other (Please specify): ___________

12. **Main Focus of Your Projects:**

- ☐ Economic Sustainability
- ☐ Environmental Sustainability
- ☐ Social Sustainability
- ☐ Mixed Focus

13. **Level of Digital Skills in Your Organization:**

- ☐ Low (Basic Use of Technology)
- ☐ Moderate (Use of Specialized Tools)
- ☐ High (Advanced Use of Industry 4.0 Technologies)

14. **How Does Your Organization Prioritize Sustainability in Projects?**

- ☐ Not Prioritized
- ☐ Low Priority
- ☐ Moderate Priority
- ☐ High Priority
- ☐ Critical Priority

15. **What is Your Organization's Investment in Industry 4.0 Technologies?**

- ☐ No Investment
- ☐ Minimal Investment
- ☐ Moderate Investment
- ☐ Significant Investment

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**Section B: Fuzzy Evaluation of Industry 4.0 Technologies and Sustainability**

For each Industry 4.0 technology, please evaluate its impact on the economic, environmental, and social dimensions of sustainability in construction projects. Use the following fuzzy linguistic variables to indicate your assessment.

| Label | Major Criteria | Sub-criteria | Label |
|---|---|---|---|
| EC | Economic | Building Information Modeling (BIM) | EC1 |
| | | IoT and RFID Technologies | EC2 |
| | | Big Data Analytics | EC3 |
| | | Off-site Construction | EC4 |
| EV | Environmental | IoT Sensors | EV1 |
| | | BIM and Digital Tools | EV2 |
| | | Smart Construction | EV3 |
| | | Sustainable Construction Practices | EV4 |
| SO | Social | Wearable Devices and IoT-enabled Machinery | SO1 |
| | | Digital Platforms | SO2 |
| | | Digital Skills Training and Education | SO3 |
| | | Automation and Job Creation | SO4 |

- **Fuzzy Triangular Numbers (TFN) Scale:**
  - Equal (1 1 1)
  - Very Low (1 2 3)
  - Low (2 3 4)
  - Moderate (3 4 5)
  - High (4 5 6)
  - Very Strong (5 6 7)
  - Extreme (7 8 9)

**Economic Dimensions:**

| Sub-criteria | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| **Building Information Modeling (BIM) (EC1)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **IoT and RFID Technologies (EC2)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Big Data Analytics (EC3)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Off-site Construction (EC4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Environmental Dimensions:**

| Sub-criteria | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| **IoT Sensors (EV1)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **BIM and Digital Tools (EV2)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Smart Construction (EV3)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Sustainable Construction Practices (EV4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

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**Social Dimensions:**

| Sub-criteria | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| **Wearable Devices and IoT-enabled Machinery (SO1)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Digital Platforms (SO2)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Digital Skills Training and Education (SO3)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Automation and Job Creation (SO4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Section C: Pairwise Comparison of Major Criteria**

**Instructions:** Please rate the importance of one criterion compared to the other using the scale provided.

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| **Economic (EC)** vs **Environmental (EV)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Economic (EC)** vs **Social (SO)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Environmental (EV)** vs **Social (SO)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Section D: Pairwise Comparison of Economic Sub-Criteria**

**Instructions:** Please rate the relative importance of each sub-criterion under the **Economic (EC)** criterion.

| Economic Sub-Criteria | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| **Building Information Modeling (BIM) (EC1)** vs **IoT and RFID (EC2)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Building Information Modeling (BIM) (EC1)** vs **Big Data Analytics (EC3)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Building Information Modeling (BIM) (EC1)** vs **Off-site Construction (EC4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **IoT and RFID (EC2)** vs **Big Data Analytics (EC3)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **IoT and RFID (EC2)** vs **Off-site Construction (EC4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Big Data Analytics (EC3)** vs **Off-site Construction (EC4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

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**Pairwise Comparison of Environmental Sub-Criteria**

**Instructions:** Please rate the relative importance of each sub-criterion under the **Environmental (EV)** criterion.

| Environmental Sub-Criteria | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| **IoT Sensors (EV1)** vs **BIM and Digital Tools (EV2)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **IoT Sensors (EV1)** vs **Smart Construction (EV3)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **IoT Sensors (EV1)** vs **Sustainable Practices (EV4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **BIM and Digital Tools (EV2)** vs **Smart Construction (EV3)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **BIM and Digital Tools (EV2)** vs **Sustainable Practices (EV4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Smart Construction (EV3)** vs **Sustainable Practices (EV4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

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**Pairwise Comparison of Social Sub-Criteria**

**Instructions:** Please rate the relative importance of each sub-criterion under the **Social (SO)** criterion.

| Social Sub-Criteria | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| **Wearable Devices and IoT (SO1)** vs **Digital Platforms (SO2)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Wearable Devices and IoT (SO1)** vs **Digital Skills Training (SO3)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Wearable Devices and IoT (SO1)** vs **Automation and Job Creation (SO4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Digital Platforms (SO2)** vs **Digital Skills Training (SO3)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Digital Platforms (SO2)** vs **Automation and Job Creation (SO4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Digital Skills Training (SO3)** vs **Automation and Job Creation (SO4)** | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Section E: Close-Ended Questions with Rating Scale**

**Rating Scale:**

- **Equal (1 1 1)**
- **Very Low (1 2 3)**
- **Low (2 3 4)**
- **Moderate (3 4 5)**
- **High (4 5 6)**
- **Very Strong (5 6 7)**
- **Extreme (7 8 9)**

---

**1. Adoption of Industry 4.0 Technologies in Your Organization:**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)

- ☐ Extreme (7 8 9)

**2. The Key Benefits Your Organization Has Experienced from Industry 4.0 Technologies:** *(Rate the benefits based on the scale provided for each option)*

- **Increased operational efficiency:**
  - ☐ Equal (1 1 1)
  - ☐ Very Low (1 2 3)
  - ☐ Low (2 3 4)
  - ☐ Moderate (3 4 5)
  - ☐ High (4 5 6)
  - ☐ Very Strong (5 6 7)
  - ☐ Extreme (7 8 9)
- **Cost reduction:**
  - ☐ Equal (1 1 1)
  - ☐ Very Low (1 2 3)
  - ☐ Low (2 3 4)
  - ☐ Moderate (3 4 5)
  - ☐ High (4 5 6)
  - ☐ Very Strong (5 6 7)
  - ☐ Extreme (7 8 9)
- **Improved project quality:**
  - ☐ Equal (1 1 1)
  - ☐ Very Low (1 2 3)
  - ☐ Low (2 3 4)
  - ☐ Moderate (3 4 5)
  - ☐ High (4 5 6)
  - ☐ Very Strong (5 6 7)
  - ☐ Extreme (7 8 9)
- **Better resource management:**
  - ☐ Equal (1 1 1)
  - ☐ Very Low (1 2 3)
  - ☐ Low (2 3 4)
  - ☐ Moderate (3 4 5)
  - ☐ High (4 5 6)
  - ☐ Very Strong (5 6 7)
  - ☐ Extreme (7 8 9)

**3. The Main Barriers Your Organization Faces in Implementing Industry 4.0:** *(Rate each barrier based on its impact)*

- **High initial costs:**
  - ☐ Equal (1 1 1)
  - ☐ Very Low (1 2 3)

    - ☐ Low (2 3 4)
    - ☐ Moderate (3 4 5)
    - ☐ High (4 5 6)
    - ☐ Very Strong (5 6 7)
    - ☐ Extreme (7 8 9)
- **Lack of skilled workforce:**
    - ☐ Equal (1 1 1)
    - ☐ Very Low (1 2 3)
    - ☐ Low (2 3 4)
    - ☐ Moderate (3 4 5)
    - ☐ High (4 5 6)
    - ☐ Very Strong (5 6 7)
    - ☐ Extreme (7 8 9)
- **Technological complexity:**
    - ☐ Equal (1 1 1)
    - ☐ Very Low (1 2 3)
    - ☐ Low (2 3 4)
    - ☐ Moderate (3 4 5)
    - ☐ High (4 5 6)
    - ☐ Very Strong (5 6 7)
    - ☐ Extreme (7 8 9)
- **Resistance to change:**
    - ☐ Equal (1 1 1)
    - ☐ Very Low (1 2 3)
    - ☐ Low (2 3 4)
    - ☐ Moderate (3 4 5)
    - ☐ High (4 5 6)
    - ☐ Very Strong (5 6 7)
    - ☐ Extreme (7 8 9)

**4. Importance of the Following Sustainability Dimensions in Your Organization's Projects:** *(Rate the importance of each dimension)*

- **Economic Sustainability:**
    - ☐ Equal (1 1 1)
    - ☐ Very Low (1 2 3)
    - ☐ Low (2 3 4)
    - ☐ Moderate (3 4 5)
    - ☐ High (4 5 6)
    - ☐ Very Strong (5 6 7)
    - ☐ Extreme (7 8 9)
- **Environmental Sustainability:**
    - ☐ Equal (1 1 1)
    - ☐ Very Low (1 2 3)

    - ☐ Low (2 3 4)
    - ☐ Moderate (3 4 5)
    - ☐ High (4 5 6)
    - ☐ Very Strong (5 6 7)
    - ☐ Extreme (7 8 9)
- **Social Sustainability:**
    - ☐ Equal (1 1 1)
    - ☐ Very Low (1 2 3)
    - ☐ Low (2 3 4)
    - ☐ Moderate (3 4 5)
    - ☐ High (4 5 6)
    - ☐ Very Strong (5 6 7)
    - ☐ Extreme (7 8 9)

**5. How Critical is Sustainability to Your Organization's Strategy?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**6. How Does Your Organization Prioritize Investment in Sustainability Technologies?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**7. Level of Support from Stakeholders for Industry 4.0 Implementation:**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**Section F: Sensitivity Analysis for Industry 4.0 Technologies and Sustainability**

This section focuses on conducting **sensitivity analysis** to evaluate how changes in the input values affect the final rankings of various criteria and sub-criteria. Sensitivity analysis helps in understanding the robustness of the decision-making process by determining how variations in the weights assigned to the criteria influence the rankings.

---

**Instructions for Sensitivity Analysis:**

In this section, you will evaluate the relative importance of each criterion and sub-criteria under varying conditions. The goal is to assess how changes in input values impact the final rankings.

For each major criterion and sub-criterion, please indicate how sensitive you believe the ranking is to changes in the input values using the provided **Fuzzy Triangular Numbers (TFN) scale**.

---

**Sensitivity Analysis for Major Criteria:**

**1. How sensitive is the ranking between Economic and Environmental Criteria to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**2. How sensitive is the ranking between Economic and Social Criteria to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**3. How sensitive is the ranking between Environmental and Social Criteria to**

**changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

---

**Sensitivity Analysis for Economic Sub-Criteria:**

**4. How sensitive is the ranking between Building Information Modeling (BIM) and IoT and RFID Technologies to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**5. How sensitive is the ranking between BIM and Big Data Analytics to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**6. How sensitive is the ranking between BIM and Off-site Construction to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)

- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

---

**Sensitivity Analysis for Environmental Sub-Criteria:**

**7. How sensitive is the ranking between IoT Sensors and BIM and Digital Tools to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**8. How sensitive is the ranking between IoT Sensors and Smart Construction to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**9. How sensitive is the ranking between IoT Sensors and Sustainable Construction Practices to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

---

**Sensitivity Analysis for Social Sub-Criteria:**

**10. How sensitive is the ranking between Wearable Devices and IoT-enabled Machinery and Digital Platforms to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**11. How sensitive is the ranking between Wearable Devices and IoT-enabled Machinery and Digital Skills Training to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

**12. How sensitive is the ranking between Wearable Devices and IoT-enabled Machinery and Automation and Job Creation to changes in input values?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

---

**Final Question:**

**How sensitive do you believe the overall rankings of Industry 4.0 technologies are to changes in input values for sustainability?**

- ☐ Equal (1 1 1)
- ☐ Very Low (1 2 3)
- ☐ Low (2 3 4)
- ☐ Moderate (3 4 5)
- ☐ High (4 5 6)
- ☐ Very Strong (5 6 7)
- ☐ Extreme (7 8 9)

Thank you for taking the time to complete this detailed questionnaire on the analysis of Industry 4.0 sustainability dimensions. Your valuable insights will greatly contribute to our understanding prioritization of these sustainabile dimensions. This analysis will help inform strategic decision-making, ensuring that organizations like yours can better navigate the evolving technological landscape.

We appreciate your honest and thoughtful responses. Should you have any additional thoughts or suggestions, feel free to include them. Together, we can drive innovation and transformation in Industry 4.0, ensuring sustainable growth and competitiveness in the future.

- **Additional Comments or Suggestions:**

Thank you once again for your participation!

## Questionnaire 4: - Questionnaire for Investigating Perceived Risks to Industry 4.0 (I4.0) Implementation in the Construction Industry

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### Section A: Demographic Information

1. **Your Role in Construction Projects:**
   - ☐ Property Owner
   - ☐ Investor
   - ☐ Developer
   - ☐ End-User/Occupant
   - ☐ Contractor
   - ☐ Other (Please specify): ___________
2. **How familiar are you with the concept of Industry 4.0 technologies (e.g., automation, IoT, AI) in construction?**
   - ☐ Not familiar at all
   - ☐ Slightly familiar
   - ☐ Moderately familiar
   - ☐ Very familiar
   - ☐ Expert
3. **Have you personally been involved in any construction projects that use Industry 4.0 technologies?**
   - ☐ Yes
   - ☐ No
4. **If yes, which Industry 4.0 technologies were implemented? (Select all that apply)**
   - ☐ Building Information Modeling (BIM)
   - ☐ Internet of Things (IoT)
   - ☐ Big Data Analytics
   - ☐ Artificial Intelligence (AI)
   - ☐ Robotics and Automation
   - ☐ Digital Twins
   - ☐ Cloud Computing
   - ☐ Other (Please specify): ___________
5. **Your level of satisfaction with the use of technology in construction projects you've been involved in:**
   - ☐ Very Dissatisfied
   - ☐ Dissatisfied
   - ☐ Neutral
   - ☐ Satisfied
   - ☐ Very Satisfied

6. **What type of construction projects are you typically involved in as a customer?**
   - ☐ Residential
   - ☐ Commercial
   - ☐ Infrastructure (e.g., roads, bridges)
   - ☐ Industrial
   - ☐ Mixed-use
   - ☐ Other (Please specify): ___________
7. **Your level of education:**
   - ☐ High School or Below
   - ☐ Bachelor's Degree
   - ☐ Master's Degree
   - ☐ Doctorate Degree
   - ☐ Other (Please specify): ___________
8. **How many construction projects have you been involved in that used Industry 4.0 technologies?**
   - ☐ None
   - ☐ 1–2 projects
   - ☐ 3–5 projects
   - ☐ More than 5 projects
9. **How would you describe your overall experience with the use of Industry 4.0 technologies in construction projects?**
   - ☐ Very Negative
   - ☐ Negative
   - ☐ Neutral
   - ☐ Positive
   - ☐ Very Positive
10. **What specific issues or challenges have you encountered when dealing with Industry 4.0 technologies in construction projects? (Select all that apply)**
    - ☐ Difficulty understanding or using the technology
    - ☐ Increased project costs
    - ☐ Data privacy and security concerns
    - ☐ Lack of skilled professionals to implement the technology
    - ☐ Other (Please specify): ___________
11. **What improvements do you think Industry 4.0 technologies brought to the construction projects you were involved in? (Select all that apply)**
    - ☐ Increased project efficiency
    - ☐ Better project quality
    - ☐ Faster project completion
    - ☐ Improved communication and collaboration
    - ☐ Cost savings
    - ☐ Other (Please specify): ___________
12. **Your level of trust in adopting new technologies in construction projects:**
    - ☐ Very low trust

- ☐ Low trust
- ☐ Moderate trust
- ☐ High trust
- ☐ Very high trust

13. **What do you consider to be the primary concern when using advanced technologies in construction? (Select one)**
    - ☐ Privacy and data security
    - ☐ Cost and affordability
    - ☐ Technology complexity
    - ☐ Lack of awareness or understanding
    - ☐ Other (Please specify): ___________
14. **Do you believe the adoption of Industry 4.0 technologies will significantly improve construction projects?**
    - ☐ Strongly Disagree
    - ☐ Disagree
    - ☐ Neutral
    - ☐ Agree
    - ☐ Strongly Agree

**Section B: Fuzzy Evaluation of Industry 4.0 Perceived Risks**

*Instructions:*

For each perceived risks listed below, please evaluate its importance as a barrier to implementing Industry 4.0 (I4.0) in the construction industry. Use the following fuzzy linguistic variables to indicate your assessment.

| Category | Alternatives |
|---|---|
| Technological Risks | Cybersecurity Risks |
| | Data Privacy Issues |
| | Interoperability Challenges |
| | Technological Complexity |
| Organizational Risks | Resistance to Change |
| | Lack of Skilled Workforce |
| | Infrastructure Limitations |
| Regulatory Risks | Compliance with Evolving Standards |
| | Data Privacy Regulations |
| | Safety and Liability Issues |
| Financial Risks | High Initial Costs |
| | Cost Overruns |
| | ROI Uncertainty |

Fuzzy Linguistic Scale:

| Lingual Variables | Fuzzy Triangular Numbers |
|---|---|
| Equal | (1, 1, 1) |
| Very Low | (1, 2, 3) |
| Low | (2, 3, 4) |
| Moderate | (3, 4, 5) |
| High | (4, 5, 6) |
| Very Strong | (5, 6, 7) |
| Extreme | (7, 8, 9) |

---

**Technological Risks:**

| Risk | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Cybersecurity Threats (TR1) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Data Privacy Issues (TR2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Interoperability Challenges (TR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Technological Complexity (TR4) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

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**Organizational Risks:**

| Risk | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Resistance to Change (OR1) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Lack of Skilled Workforce (OR2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Infrastructure Limitations (OR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

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**Regulatory Risks:**

| Risk | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Compliance with Evolving Standards (RR1) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Data Privacy Regulations (RR2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

| Risk | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Safety and Liability Issues (RR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Financial Risks:**

| Risk | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| High Initial Costs (FR1) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cost Overruns (FR2) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Uncertain Return on Investment (FR3) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

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**Section C: Pairwise Comparisons Between Major Risks**

Instructions: For each of the following pairs of major risks, please rate the relative importance of one risk compared to the other.

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Technological Risks vs Financial Risks | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Technological Risks vs Regulatory Risks | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Technological Risks vs Organizational Risks | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Financial Risks vs Regulatory Risks | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Financial Risks vs Organizational Risks | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Regulatory Risks vs Organizational Risks | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

---

### Section D: Pairwise Comparisons Between Technological Risk Alternatives

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Cybersecurity Risks vs Data Privacy Issues | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cybersecurity Risks vs Interoperability Issues | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cybersecurity Risks vs Technological Complexity | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Data Privacy Issues vs Interoperability Issues | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Data Privacy Issues vs Technological Complexity | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Interoperability Issues vs Technological Complexity | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

---

### Section D: Pairwise Comparisons Between Organizational Risk Alternatives

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Resistance to Change vs Lack of Skilled Workforce | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Resistance to Change vs Infrastructure Limitations | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Lack of Skilled Workforce vs Infrastructure Limitations | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

---

### Section E: Pairwise Comparisons Between Regulatory Risk Alternatives

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| Compliance with Evolving Standards vs Data Privacy Regulations | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Compliance with Evolving Standards vs Safety and Liability Issues | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Data Privacy Regulations vs Safety and Liability Issues | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Section F: Pairwise Comparisons Between Financial Risk Alternatives**

| Comparison | Equal | Very Low | Low | Moderate | High | Very Strong | Extreme |
|---|---|---|---|---|---|---|---|
| High Initial Costs vs Cost Overruns | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| High Initial Costs vs ROI Uncertainty | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Cost Overruns vs ROI Uncertainty | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Section E: Close-Ended Questions with Rating Scale**

This section collects quantitative data on perceived risks associated with the implementation of Industry 4.0 technologies in the construction industry.

---

**1. Overall Perceived Risk Level of Implementing Industry 4.0 Technologies in Construction:**

How would you rate the overall perceived risk level associated with implementing Industry 4.0 technologies (e.g., IoT, AI, automation) in construction projects?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**2. Perceived Impact of Technological Risks on Project Success:**

To what extent do you believe technological risks (such as cybersecurity threats and technological complexity) impact the success of construction projects utilizing Industry 4.0 technologies?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)

- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**3. Perceived Impact of Organizational Risks on Project Success:**

How significant are organizational risks (such as resistance to change and lack of skilled workforce) in affecting the success of construction projects that implement Industry 4.0 technologies?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**4. Perceived Impact of Regulatory Risks on Project Success:**

To what degree do regulatory risks (such as compliance with evolving standards and data privacy regulations) impact the success of construction projects utilizing Industry 4.0 technologies?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**5. Perceived Impact of Financial Risks on Project Success:**

How do financial risks (such as high initial costs, cost overruns, and uncertain ROI) affect the success of construction projects implementing Industry 4.0 technologies?

- ☐ Equal (1, 1, 1)

- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**6. Level of Concern About Cybersecurity Risks:**

How concerned are you about cybersecurity risks associated with the use of Industry 4.0 technologies in construction projects?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**7. Level of Concern About Data Privacy Issues:**

How significant are your concerns regarding data privacy issues related to the implementation of Industry 4.0 technologies in construction?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**8. Level of Concern About Technological Complexity:**

To what extent do you believe that the complexity of Industry 4.0 technologies poses a concern for successful implementation in construction projects?

- ☐ Equal (1, 1, 1)

- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**9. Level of Concern About Resistance to Change:**

How significant is the concern regarding resistance to change within organizations when implementing Industry 4.0 technologies in construction projects?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**10. Level of Concern About Lack of Skilled Workforce:**

To what extent do you perceive the lack of skilled professionals as a concern for the implementation of Industry 4.0 technologies in construction projects?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

**Section F: Sensitivity Analysis of Perceived Risks**

This section focuses on conducting **sensitivity analysis** to evaluate how changes in input values might impact the final rankings of perceived risks associated with the implementation of Industry 4.0 technologies in the construction industry. Sensitivity analysis is critical for understanding how robust the perceived risks are to variations in the assigned values, providing insights into which factors are most influential in decision-making processes.

**1. Sensitivity of Technological Risks:**

To what extent do you believe changes in input values for technological risks (e.g., cybersecurity threats, data privacy issues) would affect their ranking in terms of perceived importance?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**2. Sensitivity of Organizational Risks:**

How sensitive is the ranking of organizational risks (e.g., resistance to change, lack of skilled workforce) to changes in input values?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**3. Sensitivity of Regulatory Risks:**

To what degree do you think changes in input values related to regulatory risks (e.g., compliance with evolving standards, data privacy regulations) would impact their perceived ranking?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)

- ☐ Extreme (7, 8, 9)

---

**4. Sensitivity of Financial Risks:**

How significantly would changes in input values for financial risks (e.g., high initial costs, cost overruns, ROI uncertainty) affect their ranking in terms of perceived importance?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**5. Sensitivity of Cybersecurity Risks:**

To what extent do you believe that variations in input values for cybersecurity risks would influence their ranking in perceived importance?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**6. Sensitivity of Data Privacy Issues:**

How sensitive do you find the ranking of data privacy issues to changes in input values related to their importance in Industry 4.0 implementation?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)

- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**7. Sensitivity of Interoperability Challenges:**

To what degree do you believe that changes in input values for interoperability challenges would impact their perceived ranking among risks?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

---

**8. Sensitivity of Resistance to Change:**

How sensitive is the ranking of resistance to change as an organizational risk to changes in input values?

- ☐ Equal (1, 1, 1)
- ☐ Very Low (1, 2, 3)
- ☐ Low (2, 3, 4)
- ☐ Moderate (3, 4, 5)
- ☐ High (4, 5, 6)
- ☐ Very Strong (5, 6, 7)
- ☐ Extreme (7, 8, 9)

Thank you for taking the time to complete this detailed questionnaire on the analysis of Industry 4.0 Perceived Risks. Your valuable insights will greatly contribute to our understanding prioritization of these Perceived Risks. This analysis will help inform strategic decision-making, ensuring that organizations like yours can better navigate the evolving technological landscape.

We appreciate your honest and thoughtful responses. Should you have any additional thoughts or suggestions, feel free to include them. Together, we can drive innovation and transformation in Industry 4.0, ensuring sustainable growth and competitiveness in the future.

**Additional Comments or Suggestions:**

Thank you once again for your participation!

# Appendix II : Details of Publications and Conferences

## [1] Papers Published / Accepted in International Journals

- Tayal, A., Agrawal, S., & Yadav, R. (2024). ARank-FSC: Assessment and ranking of Industry 4.0 enablers using fuzzy SWARA and fuzzy COPRAS in Indian construction. *Intelligent Decision Technologies*, *18*(1), 663–683,**doi:** 10.3233/IDT-240459 **(ESCI and SCOPUS).**

- Tayal, A., Agrawal, S., & Yadav, R. (2024). Implementation of Industry 4.0 in the construction industry: A review. *International Journal of System Assurance Engineering and Management*, *15*(1), 1–20, https://doi.org/10.1007/s13198-024-02432-6 **(ESCI and SCOPUS).**

- Tayal, A., Agrawal, S., & Yadav, R. (2025). P4. 0B-FAHP: prioritizing industry 4.0 barriers using fuzzy AHP—case of an Indian construction company. *International Journal of System Assurance Engineering and Management*, 1-16. **(ESCI and SCOPUS).**

## [2] Papers Presented/Published in International Conferences

- Ankur Tayal, Saurabh Agrawal & Rajan Yadav, SAR-I4.0R-Selection and ranking of perceived risk of Industry 4.0 in construction sector: An AHP Approach at ICSSR sponsored 1st International conference on business research and innovation, 2024- NSUT Dwarka

- Ankur Tayal, Saurabh Agrawal & Rajan Yadav, SAR-I4.0R- Ranking of Industry 4.0 and sustainability criterias in construction sector: A Fuzzy AHP Approach at ICERT sponsored International Conference- Convergence on Emerging Issues in Management, Information Technology, Sciences, and Social Sciences in the Contemporary Global World, 2024- JIMS Vasant Kunj – (**BEST PAPER AWARD)**

- Ankur Tayal, Saurabh Agrawal & Rajan Yadav, Sustainable Practices in Construction: Industry 4.0 Challenges for Indian SMEs at the International Research Competition, Anusandhan on June 24, 2024

Intelligent Decision Technologies 18 (2024) 663–683
DOI 10.3233/IDT-240459
IOS Press


# ARank-FSC: Assessment and ranking of Industry 4.0 enablers using fuzzy SWARA and fuzzy COPRAS in Indian construction

Ankur Tayal*, Saurabh Agrawal and Rajan Yadav
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Received 7 April 2024
Accepted 15 April 2024

**Abstract.** Adoption of "Industry 4.0" technologies in construction is rising in recent years due to intervention of government and non government bodies for combating environmental challenges. In order to understand various enablers that influence "adoption of Industry 4.0" – technologies, this study is conducted for assessing degree of enablers in Indian construction. A hybrid MCDM approach using – Fuzzy SWARA and Fuzzy COPRAS named as ARank-FSC is proposed. Fuzzy "SWARA" aids in obtaining relative weights of enablers while COPRAS helps in ranking and selecting most efficient amongst them. The proposed approach is applied on a case organization engaged in construction. Results indicate that profitability acts as top ranked enabler that would significantly affect "Industry 4.0" acceptance in Indian construction. Stakeholders coordination, Governmental regulations, strategic planning, building information modeling and risk taking behavior are also critical enablers that significantly affect acceptance of "Industry 4.0" technologies in construction industry of developing countries like India. The present study aims to analyze-the-rank of enablers-in "adoption-of-Industry-4.0". The proposed approach is put through a sensitivity analysis to determine its robustness. This research's conclusions and ramifications-will-be-useful-to-practitioners-and-researchers-in-understanding degree of enablers for implementation-of-Industry 4.0-in-construction-industries of developing countries like India.

Keywords: Multi criteria decision making, SWARA, COPRAS, "Industry 4.0", construction

## 1. Introduction

"Industry 4.0" can generate sustainable environment due to its numerous dimensions and applications [1]. Strategically development using industry 4.0 transformations can help in achieving social, economic and environmental benefits at maximum level [2]. Industry 4.0 benefits related to performance, quality, productivity, maintenance, inventory space, resource usage, machinery stoppage and downtime are presented as pillars of development for Malaysian economy [3]. "Adoption of Industry 4.0" in developed countries are already well established [4] but requires serious attention in developing nations. Construction sector supports Gross Domestic Product (GDP) upto 13% but also have 36% energy, consumption and 39% carbon emission impacts on the environment [5,6,7].

Increasing demand of affordable housing in developing nations like India has pushed the real estate industry to expand. Construction of affordable and sustainable housing for low income groups creates "high risk markets for treal estate investments due to high unemployment, low salaries and environmental

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REVIEW PAPERS

# Implementation of industry 4.0 in construction industry: a review

Ankur Tayal[1] · Saurabh Agrawal[1] · Rajan Yadav[1]

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**Abstract** The article aims to study the literature on Industry-4.0 technologies and "Triple Bottom Line" (social, economical and environmental) parameters in the construction industry. The study focuses on analyzing the gaps in various researches conducted till now and suggests possible information that can be used to improve business processes. Preferred Reporting Items for Systematic Reviews and Meta-Analysis Method is adopted to select the articles. One hundred fifty-six published articles from 2015 to 2023 are examined to understand various theoretical frameworks. Content-based analysis is used for the categorization of five significant categories: (1) Industry 4.0 Enablers; (2) Barriers in Industry 4.0 Adoption; (3) Challenges in Construction Industry; (4) Opportunities for the principle Industry 4.0 Technology; (5) Impact of "Industry 4.0" Technologies. Based on categorization, rewards or incentives, management involvement, employers training, Building Information Modeling, Big Data, Cloud computing, etc., are major enablers of Industry 4.0 in the construction industry. Implementation cost, lack of knowledge, and poor long-term planning are analyzed as common barriers. Numerous challenges and opportunities related to Industry 4.0 technologies have been identified.

Moreover, the Triple Bottom Line impacts of Industry 4.0 technologies, such as waste management, cost reduction, health and security, and resource planning, are also analyzed. The study also revealed that there are numerous research gaps in the integrated application of technology and sustainability because of information inadequacy and unawareness of the stakeholders. The study's findings will help uncover detailed information in a systematical manner for developing an integrated sustainable business environment in the construction industry. The study considering the specific period and inclusion/exclusion criteria can possibly develop limitations of missing a few relevant articles and information in this context.

**Keywords** Industry 4.0 · Triple bottom line · Construction 4.0 · Sustainability · Construction management

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## 1 Introduction

Notable transformations that occurred in different industries and lifestyles prove that the world is accepting Industry 4.0 faster. Irani (2002) mentioned that investment in information systems is a crucial decision, and a compelling investment through logical evaluation provides cutthroat advantages. The fourth revolution has provided better and latest ways of handling the challenges of business. Changes incorporated in the product life cycle, performance rate, production process, and risk management are numerous benefits provided by techniques of "Industry 4.0". Khoumbati et al. (2006) examined the possibilities of "Industry 4.0" in logistics in the context of economy, human resources, and business operations.

Modern technologies such as "Big Data, Artificial Intelligence, 3D printing, Internet of Things, Augmented reality, sensors, and intelligent objects" have provided the most efficient business solutions to complex problems and challenges in different industries (Rahimian et al. 2021; Chauhan et al.

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https://doi.org/10.1007/s13198-025-02778-5

ORIGINAL ARTICLE

# P4.0B-FAHP: prioritizing industry 4.0 barriers using fuzzy AHP—case of an Indian construction company

**Ankur Tayal**[1] · **Saurabh Agrawal**[1] · **Rajan Yadav**[1]

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© The Author(s) under exclusive licence to The Society for Reliability Engineering, Quality and Operations Management (SREQOM), India and The Division of Operation and Maintenance, Lulea University of Technology, Sweden 2025

**Abstract** Industry 4.0 is revolutionizing the construction industry by integrating advanced technologies to enhance efficiency and productivity. This article offers insights into implementing Industry 4.0 in the construction industry of developing nations like India. However, its implementation faces significant challenges due to diverse barriers. Hence, this research explores and prioritizes these barriers for the effective implementation of Industry 4.0 within the construction industry. This study delved into 20 barriers across five primary criteria, utilizing an extensive literature review and expert input. A Fuzzy Analytical Hierarchy Process is applied to prioritize the barriers. The utilized Fuzzy framework significantly deals with unreliability and ambiguity. A case study of the Indian Construction Company illustrates the suggested model. A sensitivity study was conducted to verify the model's resilience. The findings reveal that high initial investment, lack of funding, data management, and security are notable barriers to the implementation of Industry 4.0 within the construction industry of developing nations. The insights of this study serve as valuable resources for managers and policymakers in strategizing effective implementation of Industry 4.0.

**Keywords** Barriers · Industry 4.0 · Fuzzy analytical hierarchy process (FAHP) · Construction industry

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## 1 Introduction

The construction industry is undergoing a profound transformation with the advent of Industry 4.0, integrating digital technologies into physical processes and reshaping traditional practices. Newman et al. (2021) argued that I4.0 technologies such as "Building Information Modeling (BIM), Internet of Things (IoT), and robotics," etc., are modernizing construction projects, increasing productivity, and improving safety standards. BIM, specifically, has emerged as a cornerstone of digital transformation in construction, facilitating collaborations among stakeholders for effective decision-making (Liu et al. 2021). According to Omrany et al. (2023), the application of IoT sensors and devices on construction sites allows for live tracking of equipment, environmental conditions, and materials, leading to proactive maintenance and optimal resource utilization. Moreover, robots and automated technologies have simplified construction operations by automating repetitive jobs and boosting precision (Javaid et al. 2021).

Despite the potential benefits, implementation of I4.0 in the construction industry faces distinct barriers such as implementation cost, poor standards, legal issues, cyber security, and workforce skills gaps "(Singh et al. 2023; Yap et al. 2022; Oesterreich and Teuteberg 2016)." Analysis of these barriers is crucial for effectively implementing I4.0 in the construction industry.

This study examined 20 specific barriers categorized into five major groups, incorporating insights from literature reviews and expert opinions. "The aim was to offer a comprehensive understanding of these barriers, primarily focusing on the Indian construction industry." "Fuzzy Analytical Hierarchy Process (FAHP) is utilized to assign weights to the identified barriers and prioritize them. Moreover, the proposed model is examined for sensitivity

**Appendix III :** Plagiarism Verification Certificate

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