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The Factors for Success in Implementing Industry 5.0 in the Sheet Metal Manufacturing Industry

Chien-Hua Chen

Department of Management Sciences, Tamkang University, Taiwan, China

Tel: 886-937-994-670 E-mail: ahua67@gmail.com

Wen-Tsung Wu

Dep. of International Business, National Dong Hwa University, Taiwan, China

Tel: 886-911-088-889 E-mail: 810232011@gms.ndhu.edu.tw

Chu-Hung Liu

Dep. of International Business, National Dong Hwa University, Taiwan, China

Tel: 886-927-712-502 E-mail: 610433509@gms.ndhu.edu.tw

Hsu-Hua Lee

Department of Management Sciences, Tamkang University, Taiwan, China

Tel: 886-917-214-368 E-mail: 132576@o365.tku.edu.tw

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Abstract

Industry 5.0, as a continuation of Industry 4.0, emphasizes the integration of human-centric thinking and intelligent technologies, achieving synergetic development among humans, machines, and the environment through Artificial Intelligence (AI) and Human-Robot Collaboration (HRC). Against this backdrop, the sheet metal manufacturing industry faces challenges such as technological upgrades, green production goals, and labor shortages. The market urgently requires exploration of the Critical Success Factors (CSFs) for implementing Industry 5.0 to achieve smart and sustainable development. The purpose of this study is to identify the success factors for implementing Industry 5.0 in the sheet metal manufacturing industry, providing feasible pathways for companies to enhance operational efficiency and adopt smart manufacturing. Initially, the study applies relevant literature and the Fuzzy Delphi Method to screen key criteria and sub-criteria, constructing a hierarchical framework of five primary criteria and 25 sub-criteria for success. Subsequently, the Analytic Hierarchy Process (AHP) is employed to analyze the weights and rankings of these criteria and sub-criteria. The five primary criteria include "Sustainability," "Industry 4.0 Technology," "Organizational Resilience," "Supply Chain Resilience," and "Human-Centric Technology," alongside their respective 25 sub-criteria. The analysis reveals that the top two critical success factors for successfully adopting smart manufacturing in the sheet metal industry are "Artificial Intelligence" and "Human-Robot Collaboration," highlighting their pivotal influence on the implementation of Industry 5.0. The findings provide strategic recommendations for resource-constrained companies, proposing actionable plans to achieve green and intelligent manufacturing. The study not only offers a theoretical basis for the sheet metal manufacturing industry's adoption of Industry 5.0 but also helps companies gain a competitive advantage through the coordinated development of technological innovation and environmental sustainability.

Keywords: Industry 5.0, Sheet Metal Manufacturing, Artificial Intelligence, Human-Robot Collaboration, Sustainable Development

1. Introduction

1.1 Research Background and Significance

Since the concept of smart manufacturing was first introduced during the Industry 4.0 era, the economic development philosophy aimed at improving production efficiency has aligned with the optimization standards of traditional business models (Lu, 2021) As a result, smart manufacturing technologies have been significantly developed (Jagatheesaperumal *et al*., 2021). With the rapid evolution of global manufacturing technologies, Industry 5.0 has gradually become the core direction of modern industrial development. Industry 5.0 promotes advancements in smart manufacturing technologies, achieving intelligent and automated production while exerting a profound impact on the sustainable development of the manufacturing sector (Lee *et al*., 2025). However, within the context of sustainability, the transformation of smart manufacturing technologies still faces challenges and uncertainties regarding driving factors. Although Industry 4.0 emphasizes productivity and efficiency, its objectives often diverge from the principles of sustainable development, particularly in terms of social and environmental sustainability. Furthermore, the intensification of global issues such as climate change, resource scarcity, and the COVID-19 pandemic has highlighted the limitations of Industry 4.0. To facilitate industrial transformation and build more resilient economic systems, Industry 5.0 has emerged as a new paradigm (Johri *et al*., 2021). (Maddikunta *et al*., 2022) Industry 5.0 is expected to bring technological disruption, superior performance, and sustainable development to the manufacturing industry. (Iqbal *et al*., 2022) Smart manufacturing, as a core technology for the transformation and upgrading of the manufacturing industry, integrates information technology, advanced manufacturing, automation, and artificial intelligence. In Industry 5.0, it emphasizes human-machine collaboration and sustainability.

Amid the rapid development of information technology and the guidance of sustainability principles, achieving sustainable development and transformation in the manufacturing sector has become a key focus for nations and enterprises alike. Against this backdrop, the flat metal manufacturing industry, as a cornerstone of global manufacturing, faces three major challenges: increasing demands for technological upgrades, the urgency of meeting green production goals, and the pressure of global labor shortages. Against this backdrop, the flat metal manufacturing industry, as the cornerstone of global manufacturing, faces three major challenges: the increasing demand for technological upgrades, the urgency of achieving green production goals, and the pressure of global labor shortages.

The sustainable development trend of achieving net-zero carbon emissions by 2050 further drives the flat metal manufacturing industry toward intelligent and sustainable transformation. Vijaya *et al*. (2025) For example, the United Nations' Sustainable Development Goals (SDGs) emphasize reducing carbon footprints while enhancing production efficiency, aiming to balance economic benefits with social responsibility. The principles of Industry 5.0 present new opportunities for the flat metal manufacturing industry. Through innovative applications such as human-machine collaboration technologies and Intelligent Energy Management Systems (IEMS), businesses can achieve enhanced production efficiency and green transformation (Chen & Ren, 2024).

1.2 Research Questions and Motivation

In the process of adopting Industry 5.0, the flat metal manufacturing industry, while helping to overcome existing technological bottlenecks, also faces complex challenges: Technological and Infrastructure Limitations: The demand for intelligent upgrades of traditional equipment and the inadequacy of infrastructure may affect the progress of implementing Industry 5.0.

1. Multi-Criteria Decision-Making Challenges: Identifying key success factors among numerous influencing elements and clarifying the causal relationships between these factors are significant hurdles for enterprises in formulating adoption strategies for Industry 5.0.

2. Resource Allocation and Sustainability Needs: Balancing efficiency improvements with achieving green objectives under limited resources presents a critical challenge for sustainable development.

This study primarily investigates the key success factors for adopting Industry 5.0 in the flat metal manufacturing industry and aims to construct a multi-level decision-making model. The core research questions include:

1. What are the key success factors for the adoption of Industry 5.0?

2. How can the influence relationships among these factors be quantified to provide a reference for enterprise strategy formulation?

3. What are the practical benefits of adopting Industry 5.0 for green smart manufacturing?

The motivation for this study stems from the urgent need for intelligence and sustainable development in the flat metal manufacturing industry. The aim is to propose specific strategic guidelines to promote coordinated development in technological innovation and environmental friendliness within the industry. Accordingly, this study employs relevant literature and the Fuzzy Delphi Method (FDM) to identify related criteria and sub-criteria. Subsequently, the Analytic Hierarchy Process (AHP) is applied to determine the success factors for implementing Industry 5.0 in the flat metal manufacturing industry, serving as the research methodology for this study.

The innovations and contributions of this study include: proposing a comprehensive multi-level analysis framework, combining the Fuzzy Delphi Method with RDWGA to address inconsistencies in expert opinions, and establishing a hierarchical structure through expert questionnaires using the Analytic Hierarchy Process (AHP). Furthermore, the study provides a novel process for identifying key success factors, enhancing the scientific rigor and practicality of Industry 5.0 strategies.

In terms of practical contributions, this study successfully identifies five criteria and 25 sub-criteria as key success factors for the adoption of Industry 5.0 in the flat metal manufacturing industry. These include factors such as Artificial Intelligence (C_{21}), Industry, Innovation, and Infrastructure (C_{11}), and Human-Machine Collaboration (C_{51}). The findings provide clear prioritization and resource allocation recommendations for resource-constrained enterprises implementing Industry 5.0.

Application Value: Based on the research findings, this study proposes strategic recommendations for the flat metal manufacturing industry in the field of green smart manufacturing. These include specific action plans to enhance the application of artificial intelligence, improve human-machine collaboration efficiency, and promote investment in green technologies. The motivation for this research stems from the identified relationships among the key success factors for implementing Industry 5.0 in the flat metal manufacturing industry, driven by the industry's strong demand for intelligence and sustainable development. Through scientific analysis, the study provides clear strategic guidance for the industry, emphasizing the integration of AI and sustainability.

The implementation of Industry 5.0 requires AI technology as the core driver to achieve optimized production processes that align with sustainability goals, reducing environmental burdens. This approach supports the industry's coordinated development in technological innovation and environmental friendliness.

1.3 Research Objectives

The research objectives are outlined as follows:

1. Identify the key success factors for the adoption of Industry 5.0 in the flat metal manufacturing industry, with a human-centric approach at its core.
2. Construct a multi-level decision-making model to reveal the relationships and

hierarchical structure among factors, emphasizing the coordination between human-machine collaboration and sustainable development.

3. Propose specific human-centric strategic recommendations to help enterprises achieve the dual goals of smart manufacturing and sustainable development.

2. Literature Review

2.1 Theoretical Background of Industry 5.0

Industry 4.0 is primarily driven by technology, leveraging machine learning to achieve interconnectivity among devices and improve production efficiency. However, its focus on economic benefits and scalability often overlooks the role of workers. Certain production strategies aimed at reducing labor costs have raised concerns among workers, society, and governments (Ghobakhloo *et al*., 2022). While Industry 4.0 introduces a significant number of industrial robots that enhance production efficiency, it has objectively led to job reductions, sparking opposition from workers and unions, and exacerbating interpersonal tensions (Moraru & Popa, 2021). The challenges of Industry 4.0 can be analyzed from three perspectives: human factors, sustainability, and systems. Although Industry 4.0 improves efficiency, it neglects human needs, resulting in employee fatigue and stress (Briken & Taylor, 2018). Technical demands and excessive oversight contribute to employee dissatisfaction, fear, and resistance (Grosse *et al*., 2023). From a sustainability perspective, Industry 4.0's economic and environmental impacts are largely positive at the micro and meso levels, but controversial at the macro level. Its impact on social sustainability is generally negative Grabowska *et al*., 2022) With the rapid advancement of technology, the global manufacturing industry is undergoing profound transformation and upgrading. Industry 5.0, as a continuation of Industry 4.0, is gradually becoming the focal point of modern manufacturing development. The theory of Industry 5.0 is still in its early stages, with its definition yet to be clearly established. The European Commission (EC) envisions it as a future concept of a human-centric, sustainable, and systemic manufacturing system (Breque *et al*., 2021).

Pranav (2024) Industry 5.0 emphasizes a human-centric approach, highlighting collaboration between humans and collaborative robots (cobots). Cobots perform repetitive tasks by detecting human presence, allowing humans to focus on customization and critical thinking. These robots adapt to users' skills and preferences rather than requiring humans to conform to the machines (Kaasinen *et al*., 2020). Unlike Industry 4.0, which centers on automation, digitalization, and Internet of Things (IoT)-driven production, Industry 5.0 stresses the deep integration of human-centric thinking and smart technologies. Through artificial intelligence (AI) and human-robot collaboration (HRC), Industry 5.0 enables seamless cooperation between machines and humans. This development not only enhances production efficiency but also redefines the role of humans in the production process, emphasizing a balance between technology and humanization (Leng *et al*., 2024).

The implementation framework of Industry 5.0 defines the foundational support and application constraints. The European Commission has proposed three core principles: sustainability, resilience, and human-centricity. Sustainability aims to minimize harm to the natural environment and ensure long-term development; resilience emphasizes the adaptability and shock-resistance of industries to external changes; human-centricity focuses on placing human well-being at the core of production, ensuring health and safety while realizing human value (Xu *et al*., 2021).

Li & Duan (2025) The core concept of Industry 5.0 lies in applying intelligent technologies to personalized production, meeting diverse market demands. It goes beyond the technical scope of Industry 4.0 and further focuses on:

1. Emphasizing Human Value: Combining human creativity, judgment, and emotions with machine precision.
2. Innovative Collaboration Models: Achieving more efficient and flexible production processes through human-robot collaboration and advanced technologies.
3. Promoting Sustainable Development: Reducing resource waste, lowering carbon emissions, and supporting environmentally friendly manufacturing models in the production process.

Furthermore, Industry 5.0 not only focuses on technological development but also rapidly advances with the progress of cyber-physical systems and the Industrial Internet of Things (IIoT). This progress significantly enhances productivity while supporting Corporate Social Responsibility (CSR) and the Sustainable Development Goals (SDGs) (Basavaraju *et al*., 2025). This implies that businesses must not only improve competitiveness but also achieve a balance between economic benefits and social impacts (Bai *et al*., 2020). Under the guidance of Industry 5.0 and sustainability principles, there is growing recognition that human creativity and intelligence can effectively enhance the efficiency of smart manufacturing (Leng *et al*., 2022). The concept of Industry 5.0 is based on the integration of multiple disciplines, primarily involving the following three key areas:

1. Artificial Intelligence and Smart Manufacturing: The application of AI technology serves as the foundation of Industry 5.0, enabling businesses to achieve intelligent decision-making, automated control, and precise resource management.
2. Human-Robot Collaboration Technologies: By facilitating interaction between robots and humans, Industry 5.0 enhances production flexibility and safety, enabling more efficient collaboration within production processes.
3. Sustainability and Green Technologies: Combining intelligent energy management systems with green manufacturing technologies, Industry 5.0 promotes environmentally friendly manufacturing models.

As the manufacturing sector faces challenges such as labor shortages, limited resources, and environmental pressures, Industry 5.0 offers businesses a new development pathway. Through the integration of human-centric and intelligent systems, Industry 5.0 is not merely a symbol of technological advancement but also a critical milestone for the comprehensive transformation and upgrading of the manufacturing industry.

2.2 Literature on the Characteristics of Industry 5.0 Adoption in the Flat Metal Manufacturing Industry

2.2.1 Sustainability-Related Characteristics

Sustainable Development is a development model that balances economic growth, social well-being, and environmental protection. Its core principle is to meet the needs of the present generation without compromising the ability of future generations to meet their own needs. Against the backdrop of global challenges such as climate change, resource scarcity, and social inequality, sustainable development has become a shared goal and action framework for the international community (Lee *et al*., 2025).

In 2015, the United Nations adopted the Agenda 2030 for Sustainable Development, which introduced 17 Sustainable Development Goals (SDGs). These goals encompass a wide range of areas, from poverty eradication, health, and well-being, to climate action and sustainable urban development, aiming to promote comprehensive and balanced development of the economy, society, and environment on a global scale. These goals provide clear action guidelines for governments, businesses, and individuals, facilitating the efficient allocation of resources, the application of technological innovations, and more forward-looking policy-making (UN, 2023).

In recent years, global understanding and actions toward sustainable development have deepened significantly. At the policy level, countries are striving to achieve the 2050 net-zero carbon emissions goal and accelerate the transition to a green economy. At the corporate level, sustainable development has become a cornerstone for business model innovation and enhancing competitiveness (Griggs *et al*., 2013; Bai & Sarkis, 2020; Chen & Cao, 2025). For example, companies are increasingly adopting Environmental, Social, and Governance (ESG) evaluation standards to ensure that business operations pursue economic benefits while actively fulfilling social responsibilities and reducing environmental impact. In fact, the foundation of Industry 5.0 lies in incorporating sustainable development principles (Carayannis *et al*., 2022).

The European Commission emphasizes that Industry 5.0 should support a sustainable, human-centric, and resilient industrial system. Transforming industrial production through Industry 4.0 to meet the demands of social sustainable development has become an inevitable trend (Kamble *et al*., 2018; Kamal *et al*., 2025). Moreover, the practice of sustainable development not only involves global collaboration but also emphasizes the importance of local actions. The integration of Industry 4.0 technologies with sustainable development has emerged as a growing research trend (Beltrami *et al*., 2021; Enyoghasi *et al*., 2021; Ghobakhloo *et al*., 2021; Nara *et al*., 2021). Existing studies have explored the sustainability performance of Industry 4.0 technologies and analyzed how they contribute to achieving the Sustainable Development Goals (SDGs) through circular economy approaches (Bai *et al*., 2020). Industry 4.0 can also mitigate unexpected economic losses during disasters (Bai *et al*., 2020; Ahmed *et al*., 2025). Industry, Innovation, and Infrastructure: Building resilient and sustainable infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation are key to economic growth (Wu *et al*., 2021b; Shaferi *et al*., 2025).Responsible

Consumption and Production: Ensuring sustainable consumption and production patterns helps reduce resource waste and environmental pollution. These patterns are often used to improve efficiency across industries, enhance supply chain transparency, and refine production and consumption practices (Morshed, 2025). Singh *et al*. (2025) Sustainable Cities and Communities: Building inclusive, safe, resilient, and sustainable cities and human settlements is essential for addressing the challenges of rapid urbanization. It supports the development of modern, sustainable, smart cities with public order and security while providing green and culturally inspiring living conditions. Key measures include smart city construction, clean energy promotion, and the application of circular economy models (Bai *et al*., 2023). For instance, Taiwan has made significant progress in advancing smart cities and green technologies, offering a valuable reference case for global sustainable development practices.

Research on sustainable development has gradually expanded from theoretical exploration to empirical applications, encompassing strategies for addressing climate change, resource management models, and impact analysis of sustainable production and consumption. These studies not only provide scientific evidence for policy formulation and implementation but also offer concrete action recommendations for businesses and social organizations. As a global consensus, sustainable development has permeated various dimensions, including politics, economics, technology, and culture. Looking ahead, achieving sustainable prosperity and progress will require strengthening global cooperation and local actions, combined with innovative technologies and management models.

2.2.2 Industry 4.0 Technologies

Industry 4.0 is a global industrial revolution aimed at achieving a comprehensive transformation and upgrading of the manufacturing sector through the deep integration of digitalization and intelligent technologies (Qiu *et al*., 2025). Guo *et al*. (2021) The concept was first introduced by the German government in 2011, with the core goal of establishing a highly interconnected intelligent manufacturing system that enables production processes to be more flexible, efficient, personalized, and sustainable. The core principles of Industry 4.0 include: Connectivity: Leveraging the Internet of Things (IoT) and sensors to enable data sharing between devices, forming a fully connected manufacturing network. Intelligence: Utilizing artificial intelligence (AI) and machine learning to achieve automated decision-making and intelligent operations. Flexibility: Employing modular designs and adaptive production systems to meet diverse and personalized market demands. Sustainability: Promoting efficient resource utilization, reducing waste and carbon emissions, and achieving green manufacturing.

Under the framework of Industry 4.0, the manufacturing sector is undergoing a transformation from traditional automation to digitalization and intelligence. This transition relies on the support of various cutting-edge technologies, including the following (Liao *et al*., 2017): Al-Raeei (2025) Artificial Intelligence (AI): This encompasses machine learning, deep learning, and natural language processing, which enable automated decision-making through algorithmic analysis and self-learning. As a field within computer science, AI focuses on creating intelligent machines that work and react like humans. AI enhances production efficiency and reduces operational costs through quality inspection, process optimization, demand forecasting, and intelligent maintenance.

Autonomous Robots: These robots are capable of efficiently executing tasks, self-adjusting, and collaborating. They improve production flexibility and accuracy in areas such as logistics distribution, assembly line operations, and warehouse management. Autonomous robots replicate human behavior in manufacturing to optimize operational processes (Olsen and Tomlin, 2020; Dalenogare *et al*.,2018; Zia & Haleem, 2025).

The advancement of Industry 4.0 has reshaped the operational models of traditional manufacturing. In the future, with the widespread adoption of 5G communication technology and the integration of more cutting-edge technologies, Industry 4.0 will play an increasingly significant role in the global manufacturing sector (Vadruccioe *et al*., 2025). The application of Industry 4.0 technologies represents a major milestone in the transition of manufacturing into the digital era, fundamentally altering production models and profoundly influencing socio-economic development, paving the way for infinite possibilities in the future of global industry (Suganthi *et al*., 2025). Key technologies include: Robotics: Robots, particularly collaborative robots, are designed to physically interact with humans in shared workspaces. These advancements enable robots to replace humans in various tasks, improving efficiency and precision (Perotti *et al*., 2025). Achuthan *et al*. (2025) Cybersecurity: As manufacturing systems become digitalized, cybersecurity technologies ensure the safety of data transmission and system stability. Techniques such as data encryption, access control, and threat detection are employed to protect information from being stolen, damaged, or attacked. Radio-Frequency Identification (RFID): RFID technology uses wireless radio frequencies to identify and track items, enhancing logistics and production management efficiency. It enables automatic tracking and identification of objects via wireless communication between tags and readers (Choudhary *et al*., 2025). Sensors and Actuators: Sensors monitor physical conditions, while actuators convert digital signals into physical actions. These devices respond to physical stimuli such as heat, light, sound, pressure, or motion, transmitting impulses for measurement or operational control. Their application improves transparency and reliability in production processes through equipment status monitoring and automated production control (Dwivedi *et al*., 2025). Simulation Technology: Simulation allows for virtual modeling to test the efficiency and feasibility of manufacturing processes. This technology plays a critical role in optimizing production systems and decision-making (Bai & Sarkis, 2023; Perotti *et al*., 2025).

2.2.3 Organizational Resilience

With the influence of globalization, digitalization, and climate change, organizations face increasingly diverse risks, ranging from supply chain disruptions and cyberattacks to reputational risks and market fluctuations. These challenges demand the ability to adapt quickly and respond effectively (Khair *et al*., 2025). Organizations with strong resilience can maintain operational stability during crises and seize opportunities for further development amidst change. Organizational Resilience has become a critical capability for maintaining competitiveness and achieving long-term sustainable development. It is defined as an organization's ability to adapt, recover, and grow in the face of unforeseen events, crises, or rapidly changing environments (Li & Lin, 2025). Organizational resilience encompasses not only crisis management capabilities but also the ability to sustain operations and drive innovation in dynamic conditions. Governance refers to the extent to which policies are clearly defined, and accountability denotes the degree to which senior business leaders are responsible to all stakeholders. Effective governance structures and accountability mechanisms promote transparency and ensure that organizational behavior aligns with ethical and legal standards. A well-designed governance framework reduces risks, increases public trust, and strengthens internal controls and audits (Miao & Nduneseokwu, 2025). It also involves establishing clear responsibility allocation and feedback mechanisms. Business continuity refers to the organization's ability to maintain critical operations during unexpected circumstances. The quality of business continuity frameworks, policies, and procedures is essential to ensure operational resilience in crises. Innovation is the ability to enhance products, services, and operational models through new technologies or methods. It allows organizations to stand out in a competitive environment and increases their flexibility in responding to changes (Khan *et al*., 2025). Sustained innovation capability enables organizations to adapt to market and technological shifts. Building an innovation culture, investing in research and development, and encouraging cross-departmental collaboration are critical strategies to foster innovation. Adaptability is the organization's ability to adjust strategies and action plans in response to a rapidly changing external environment. It involves identifying changes and uncertainties and taking swift and effective actions. High adaptability helps organizations respond quickly to market changes and seize new opportunities. Implementing agile management frameworks, conducting regular market and environmental analyses, and improving rapid response capabilities are key approaches to enhancing adaptability (BSI,2021). Organizational resilience, as a critical capability for businesses to navigate uncertainty, is not only about responding to current crises but also serves as a foundational cornerstone for future growth and sustainable development. By strengthening governance, fostering innovation, and enhancing employee awareness and skills, organizations can achieve long-term success and stable development in challenging environments (Sun *et al*., 2022).

2.2.4 Supply Chain Resilience

Holloway (2025) Supply chain resilience is defined as the ability of a supply chain to quickly adapt, recover, and maintain operations in the face of external disruptions. It encompasses not only the capacity to recover during crises but also the ability to anticipate risks and achieve long-term stability. Strong supply chain resilience enables businesses to maintain operational efficiency amid uncertainty while seizing opportunities arising from change, thereby enhancing competitiveness (Nhu-Mai *et al*., 2025). In today's globalized and digitally driven economic environment, the stability and continuity of supply chains have become critical factors for businesses to achieve a competitive advantage. However, with the increasing challenges posed by fluctuating market demands, frequent natural disasters, geopolitical uncertainties, and global pandemics, the risks and pressures on supply chains are intensifying.

To address these challenges, the concept of Supply Chain Resilience has gained increasing attention (Kazancoglu *et al*., 2022). The importance of supply chain resilience has been fully demonstrated in recent globalevents. For instance, during the COVID-19 pandemic, global supply chains faced severe challenges such as logistics disruptions and raw material shortages, leading many companies without resilience to suffer significant losses. Meanwhile, supply chains with strong resilience quickly adjusted their operating models, mitigating impacts and achieving stable growth (Hsu *et al*., 2022).

Key factors contributing to supply chain resilience the agility is the ability to quickly understand and respond to market demand changes and unexpected events. This involves rapidly adjusting to surges in product demand or supply disruptions, shortening response times, and improving supply chain flexibility and competitiveness (Adomako & Nguyen, 2025). Gera *et al*. (2025) The efficiency is to achieving maximum supply chain benefits with minimal resources. This includes optimizing production processes and enhancing logistics efficiency to reduce operational costs and improve resource utilization. The visibility: is to ensure data transparency and real-time monitoring across the entire supply chain (Holloway, 2025).

This includes agility, efficiency and visibility instant access to inventory status, logistics locations, and supplier conditions, enabling end-to-end supply chain oversight to identify disruptive events. Improved visibility enhances forecasting accuracy and reduces the risk of delays (Singh et al., 2019; Göçer *et al*., 2025).

Goel (2025) Decentralization: Diversifying and decentralizing supply chain resources to reduce risks associated with single-region dependencies. Establishing production and storage facilities in different regions increases supply chain resilience and mitigates the impact of localized risks. Collaborative distribution enhances flexibility and cooperation. Coordination and Collaboration: Joint planning and execution of supply chain operations by two or more autonomous entities(Wesche *et al*., 2025). Effective collaboration with suppliers and logistics partners improves operational efficiency and reduces risks caused by information asymmetry (Rendon *et al*., 2021). (Human *et al*., 2025) Information Sharing: Sharing critical data among supply chain members to enable efficient collaboration. Accurate information flow across all partners ensures effective decision-making and operational synergy. Li *et al*., (2022) Risk Awareness: The ability to proactively identify, analyze, and predict supply chain risks. Early warning systems for natural disasters, geopolitical conflicts, or market fluctuations strengthen resilience and reduce potential losses. (Giraldo *et al*., 2025) Human Resource Management: Enhancing the skills, adaptability, and collaboration efficiency of supply chain personnel through education and training. Trained employees can effectively handle disruptions or process changes, improving overall supply chain performance and response speed. Trust: Building trust with reliable exchange partners fosters long-term cooperative relationships (Schilke *et al*., 2023). Trust ensures suppliers commit to delivering quality and timely goods, reduces transaction costs, and promotes collaborative innovation (Choung *et al*., 2023). Ahmadi & Bello (2022) Sustainability: Meeting market demands while minimizing environmental impact and supporting long-term development. This includes adopting low-carbon logistics, reducing wasteful production methods, and enhancing brand value by aligning with social responsibility expectations. Nicolescu & Tudorache (2022) Customer Service Excellence: Providing customers with fast, accurate, and reliable services, including on-time deliveries and clear post-sales support. Measuring and managing customer satisfaction performance, especially during disruptions, enhances customer satisfaction and fosters brand loyalty (Singh *et al*., 2019; Jain *et al.*, 2017).

Supply chain resilience has become a critical capability for businesses to navigate uncertainty. In the future, as market environments continue to evolve, building supply chain resilience will not only support crisis management but also serve as a vital cornerstone for achieving competitive advantage and sustainable development. By enhancing agility, strengthening collaboration, and improving information sharing, businesses can establish more robust supply chain systems to address various challenges and seize growth opportunities.

2.2.5 Human-Centric Technology

With the rapid advancement of technology and the advent of the digital age, the focus of design and development is gradually shifting from a technology-driven approach to a human-centric philosophy. Human-Centered Design (HCD) emphasizes placing human needs, capabilities, and well-being at the core of technology and system design. This philosophy goes beyond merely optimizing user experience; it represents a profound commitment to safety, sustainability, and human values (Kamal *et al*., 2025).

Brückner *et al*. (2025) Against the backdrop of the rapid development of Industry 4.0 and artificial intelligence, intelligent systems and automation technologies are increasingly integrated into production and daily life. While these technologies enhance efficiency, they also present new challenges regarding the roles, working conditions, and well-being of humans. Therefore, human-centered design (HCD) applies physical, cognitive, and social factors to the design of tools, tasks, machines, systems, and environments to improve effectiveness, efficiency, and safety for human use. This approach is particularly crucial in enhancing human-machine collaboration efficiency, optimizing user experience, and ensuring safety and working conditions (Müller *et al*., 2024). Lu *et al*. (2022) Collaboration Systems Research on collaboration systems focuses on how humans and robots work together to achieve common goals, emphasizing knowledge sharing and social negotiation. User-focused design methods prioritize usability, simplicity, and satisfaction, aiming to enhance user satisfaction and acceptance through improvements in product design, software interfaces, and workplace optimization. Human-Machine Interface (HMI) (Lee *et al*., 2025). An HMI defines the interface that enables humans to understand and operate systems. Following the "5C Path" (Coexistence, Cooperation, Collaboration, Care, and Co-evolution), with care and co-evolution at its core, the goal is to achieve human-centered manufacturing that ensures excellence in manufacturing and human well-being (Mourtzis *et al*., 2023). HMI integrates interdisciplinary knowledge, including human factors, industrial design, information processing, and cognitive psychology, to provide users with intuitive operations and real-time feedback (Wang *et al*., 2022). Examples include simplified control panels for machinery and monitoring screens for automated systems, improving operational efficiency and decision-making accuracy (Pettit *et al*., 2010; Lu *et al*., 2016; Wu *et al*., 2016; Kymäläinen *et* *al*., 2017). User-centered design focuses on an iterative process that revolves around user needs and behavior. Beyond usability, it examines emotional and psychological responses to interactive designs, emphasizing the overall user experience (Barbieri *et al*., 2025). Enhancements such as interface design for smart devices, optimization of user manuals for industrial products, and improved market appeal increase system acceptance and user loyalty (Lin, 2018). Safety and Working Conditions Intelligent technologies monitor potential risks in the workplace. For instance, collaborative robots automatically halt when operators are too close, ensuring safety (Montanaro *et al*., 2023). Speed-distance monitoring of machinery or equipment enhances workplace safety, particularly in industrial robot work zones and logistics paths. Ergonomically designed workplaces reduce accidents, improve employee satisfaction, and boost productivity (Sariyar, 2025). Measures to lower repetitive labor burdens and optimize workstation designs further promote employee well-being (Mazali, 2018; Boschetti *et al*., 2022; Breque *et al*., 2021). Organizational Collaboration and Employee Well-being Efficient collaboration between employees and systems fosters teamwork, particularly in cross-departmental project management and human-machine collaboration in smart manufacturing. This strengthens team cohesion, optimizes resource allocation, and enhances efficiency. Employee well-being focuses on mental and physical health and job satisfaction, creating a human-centered workplace. Health management plans, psychological support, and stress management strategies increase retention, loyalty, and productivity while reinforcing organizational culture (Yasue *et al*., 2025).

The human-centered design philosophy permeates all aspects of industrial and technological applications, emphasizing the prioritization of human needs while ensuring safety, controllability, and workplace well-being. By integrating human-machine collaboration, intelligent monitoring, and user-friendly design, businesses can achieve more efficient and safer operations while enhancing employee satisfaction and organizational cohesion, ultimately achieving long-term stability and sustainable development.

2.3 Challenges and Relevant Decision-Making Methods in the Flat Metal Manufacturing Industry

2.3.1 Fuzzy Delphi Method (FDM)

Murray *et al*. (1985) The Fuzzy Delphi Method (FDM) combines fuzzy mathematics with the traditional Delphi method and is primarily used to integrate expert opinions and identify key factors. Unlike classical set theory, fuzzy theory allows for intermediate states between "belonging" and "not belonging," representing fuzzy sets through the establishment of a membership function. The process of consolidating expert opinions into fuzzy numbers is known as the Fuzzy Delphi Method (Nahavandi, 2019; Jahanvand *et al*., 2023). By incorporating fuzzy theory into the traditional Delphi method, FDM expresses expert opinions using linguistic variables corresponding to varying degrees of human semantics. This approach helps establish consistent opinions or consensus, which can be used for evaluating and planning future policies.

The Fuzzy Delphi Method (FDM) is effective in addressing uncertainties in expert opinions and quickly reaching consensus. It is particularly suitable for strategic planning, indicator design, and risk assessment, as well as for handling multivariable and cross-disciplinary problems with speed and precision (Jahanvand *et al*., 2023).

Its main features include:

1. Handling Uncertainty: Quantifies the uncertainty in expert judgments.
2. Factor Selection: Efficiently identifies critical success factors (CSFs).
3. Wide Applicability: Applicable to various fields such as supply chain management and policy formulation.

For example, the logistics industry is seeking to promote sustainable development through the implementation of Industry 5.0. However, the transformation towards smart logistics in the sector remains at an early stage. By employing the Fuzzy Delphi Method (FDM), key driving factors related to the development of smart logistics in the logistics industry of emerging economies under Industry 5.0 have been identified (Nayeri *et al*., 2023). A separate study on photovoltaic systems in rural island communities of developing economies used the FDM to reduce 85 factors derived from relevant literature to 35 significant ones. To gain a comprehensive understanding of the problem, the Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) method was applied to identify important factor relationships. Based on the screening analysis of the FDM method, this study provides a clearer understanding of the influential relationships among the success factors for implementing Industry 5.0 in the flat metal manufacturing industry. This not only helps identify the core elements driving Industry 5.0 in the metal industry but also aids stakeholders in understanding the causal relationships between different factors, offering a more scientific basis for formulating strategies to implement Industry 5.0 in manufacturing.

2.3.2 Analytic Hierarchy Process (AHP)

Hsu *et al*. (2024) proposed an evaluation model based on the Analytic Hierarchy Process (AHP), which has been further refined in subsequent studies (Di Mario *et al*., 2024; Saaty, 1970; Saaty, 1990). AHP is particularly suitable for multi-criteria group evaluations based on subjective judgments (Saaty, 1996a; Saaty, 2001). Compared to traditional multi-criteria evaluation methods, AHP is simpler and more user-friendly. The hierarchical structure of AHP helps evaluators gain a deeper understanding of the problem. When selecting plans or alternatives, it enables a comprehensive assessment of various options based on different criteria, providing useful information for decision-making and identifying the most advantageous alternative, thereby reducing the risk of evaluation errors. Today, AHP has been widely accepted and applied across various academic fields, including resource allocation, alternative selection, planning, conflict resolution, forecasting, risk assessment, and performance measurement.

Forman & Peniwati (1998) pointed out that the primary function of the Analytic Hierarchy Process (AHP) is to systematize complex and unstructured problems by gradually breaking them down from higher to lower levels. Through quantitative judgments, AHP simplifies and improves traditional intuition-based decision-making processes by calculating the priority weight of each alternative, providing evaluators with sufficient information to select the most suitable option. Alternatives with higher priority weights are more advantageous for adoption, thereby reducing risks in the evaluation process.In recent years, the application scope of AHP has been increasingly expanding.

3. Methodology

As the flat metal manufacturing industry faces the dual challenges of intelligent transformation and sustainable development in global industrial progress, the adoption of Industry 5.0 has become a key direction for enhancing competitiveness. This study aims to construct a "hierarchical framework of factors for implementing Industry 5.0 in the flat metal manufacturing industry." First, using relevant literature and the Fuzzy Delphi Method, the study establishes five criteria and their 25 sub-criteria, the details of which are explained in the preceding literature review chapters. Subsequently, an analytic hierarchy questionnaire is employed to evaluate and rank the success factors, criteria, and sub-criteria, assigning weight values and determining their relative importance for the successful implementation of Industry 5.0 in the flat metal manufacturing industry.

The application of this research methodology not only effectively and systematically reveals the key factors for adopting Industry 5.0 and their intrinsic relationships but also provides clear strategic priorities and resource allocation recommendations for the flat metal manufacturing industry in resource-constrained scenarios. By employing the Fuzzy Delphi Method and Analytic Hierarchy Process (AHP) in the research design, this study offers a scientific basis and practical guidance for enterprises to implement Industry 5.0, driving the realization of their smart manufacturing and sustainable development goals.

3.1 Fuzzy Delphi Method (FDM)

The Fuzzy Delphi Method (FDM) is commonly used to identify the key success factors for implementing Industry 5.0 in the flat metal manufacturing industry. Since Industry 5.0 encompasses diverse technologies (such as artificial intelligence, human-machine collaboration, and intelligent energy management) and sustainable development goals, its successful implementation depends on multiple interrelated factors. FDM effectively aggregates expert evaluations of the importance of these factors, ensuring the scientific rigor and consistency of the screening results. Subsequently, the Analytic Hierarchy Process (AHP) is applied to further analyze the relationships among these factors, providing a solid foundation for decision-making. The relevant steps are as follows:

Step 1: Calculate the minimum value, geometric mean m, of the "most conservative perception value" (l) and "most optimistic perception value" (u) provided by all experts for each indicator.

Step 2: Calculate using Formula (1). crisp value o_i.

$$d_A = \frac{L_A + M_A + U_A}{3} \tag{1}$$

Step 3: Use the Interquartile Range (IQR) to set a threshold for consensus values and identify the key indicators.

3.2 Steps of the Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) proposed by is a method for decision support, primarily applied to decision-making problems with uncertainty or multiple evaluation criteria. AHP hierarchically organizes complex and unstructured systems, assuming that the elements at each level are independent of each other. It involves evaluating the importance of each variable, followed by determining the priority weight and ranking of each variable, which helps the evaluator in reaching a conclusion (Di Mario *et al*., 2024).

The theoretical model of the Analytic Hierarchy Process (AHP) (Lai *et al*., 2022): The elements within a certain level are respectively.C_1, C_2, C_3, …, C_n, Using an element from the previous level as the evaluation criterion, the weight of each element is determined. W_1,W_1, W_3, … , Wn; A_j A_i and A_j The weight for each element is a_{ij}; The pairwise comparison matrix is. $C=[aij]$. The known weight is. W_1, W_2, W_3, … , W_n In this case, the pairwise comparison matrix. C Multiply by the weight vector. W Equals the order of the matrix. n Multiply by the weight vector. W:

$$C[aij]=\begin{pmatrix} a_{11} & a_{12} & a_{13} & \dots a_{1n} \\ a_{21} & a_{22} & a_{23} & \dots a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \dots a_{nn} \end{pmatrix} = \begin{pmatrix} w_1/w_1 & w_1/w_2 & w_2/w_3 & \dots w_1/w_n \\ w_2/w_1 & w_2/w_2 & w_2/w_3 & \dots w_2/w_n \\ w_3/w_1 & w_3/w_2 & w_3/w_3 & \dots w_3/w_n \\ \vdots & \vdots & \vdots & \vdots \\ w_n/w_1 & w_n/w_2 & w_2/w_n & \cdots w_n/w_n \end{pmatrix} \quad (1)$$

Among them $a_{ij} = \frac{w_i}{w_j}, a_{ij} = \frac{1}{a_{ji}}$,

$$W = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix}, i = 1, 2 \dots, n : j = 1, 2 \dots, n$$

Then

$$CW = \begin{pmatrix} w_1/w_1 & w_1/w_2 & w_2/w_3 & \dots w_1/w_n \\ w_2/w_1 & w_2/w_2 & w_2/w_3 & \dots w_2/w_n \\ w_3/w_1 & w_3/w_2 & w_3/w_3 & \dots w_3/w_n \\ \vdots & \vdots & \vdots & \vdots \\ w_n/w_1 & w_n/w_2 & w_2/w_n & \cdots w_n/w_n \end{pmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} nw_1 \\ nw_2 \\ nw_3 \\ \vdots \\ nw_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix} = nw \quad (2)$$

In practical applications, the pairwise comparison matrix established by the evaluator's subjective judgments is used to determine the results. It is already known that...aijThe estimated values, but the weights of each element w_i Under the condition that it is still unknown, the approximate value of the eigenvector. w_1', w_2', w_3', $\ldots w_n'$, It can be obtained by normalizing the geometric mean of the column vector (Teng & Tseng, 1989b):

$$Wi = \left(\prod_{j=1}^{n} aij\right)^{\frac{1}{n}} / \sum_{i=1}^{n} \left(\prod_{j=1}^{n} aij\right)^{\frac{1}{n}} \quad (3)$$

$$i = 1, 2, \mathrm{K}\ , n$$

Pairwise comparison matrix. C The maximum eigenvalue $\lambda'_{\max}$, It can be obtained from the following equation:

$$Let.\ \ CW' = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{bmatrix}$$

Then $$\lambda'_{\max} = \frac{1}{n}\left[\frac{x_1}{w_1}, \frac{x_2}{w_2}, \frac{x_3}{w_3}, \frac{x_n}{w_n'}\right]$$

The judgment of the overall preference and intensity relationship of the evaluator, in the theoretical model of the Analytic Hierarchy Process, indicates consistency if transitivity is satisfied (e.g., if A is twice as preferred as B, and B is three times as preferred as C, then A is six times as preferred as C). In this case, the maximum eigenvalue $\lambda'_{\max} = n$, However, due to the difficulty for the evaluator to determine consistency in situations with numerous factors, this can lead to the maximum eigenvalue of the pairwise comparison matrix $\lambda'_{\max} \neq n$。

Therefore, it is necessary to use the Consistency Index (C.I.) and Consistency Ratio (C.R.) to check whether the decision maker's judgments are consistent, in order to avoid incorrect weight information caused by inconsistent judgments from the evaluator, which could mislead important assessments.

λ'_{max}The closer it is to n, the more consistent the evaluator's judgments are. This can be determined by...The closer it is to n, the more consistent the evaluator's judgments are, which can be determined by $\lambda'_{\max}$ The difference between n and $\lambda'_{\max} - n$， To understand the degree of judgment inconsistency.。 Teng & Tseng(1989b)Propose a consistency index for a pairwise comparison matrix.C.I. $= (\lambda'_{\max} - n) / (n-1) =$,

The average remaining eigenvalue represents the consistency ratio C.R.C.R.C.R., which, for matrices of the same order, is the ratio between the consistency index C.I.C.I.C.I. and the random consistency index R.I.R.I.R.I.. The consistency index of a randomly generated reciprocal matrix is called the random consistency index R.I.R.I.R.I.. The value of R.I.R.I.R.I. increases as the matrix order nnn increases, as shown in Table 1, which presents the average random consistency index derived from evaluation systems with ratios of 1/9,1/8,1/7,…,1,…,8,91/9, 1/8, 1/7, \dots, 1, \dots, 8, 91/9,1/8,1/7,…,1,…,8,9. When the consistency ratio is less than or equal to 0.1, it indicates that the judgments are consistent.

$$\text{Consistency Index C.I.} = \frac{\lambda_{\max} - n}{n-1}$$

$$\text{Consistency Ratio C.R.} = \frac{C..I.}{C.R.}$$

Table 1. Random Consistency Index (R.I.)

Order (of a matrix)	1	2	3	4	5	6	7	8	9	10	11
R.I	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.51

Data source: Saatyand Vargas (2001) Models, methods, concepts and applications of the analytic hierarchy process, Luwer Academic, B. M.

4. Research Findings and Discussion

This chapter will use the hierarchical framework established from the previous chapter's Fuzzy Delphi research results. Subsequently, a hierarchical questionnaire analysis will be conducted, where nine experts and scholars will assess the impact of the importance of criteria and sub-criteria to determine the weight and ranking of the sub-criteria under the criteria for the success factors of implementing Industry 5.0 in the flat metal manufacturing industry.

4.1 Establishing the Hierarchical Framework for the Success Factors of Implementing Industry 5.0 in the Flat Metal Manufacturing Industry

This study first applied relevant literature and invited 9 experts to participate and assist in the evaluation process. The group consisted of 3 professors from university engineering and management schools, 2 researchers from government-established industrial technology research institutes, 2 senior engineers from smart manufacturing system suppliers, and 2 CEOs from flat metal manufacturing companies. These experts had 15 to 30 years of experience in implementing smart manufacturing in the flat metal manufacturing industry. They came from diverse professional backgrounds and had practical experience in the adoption of Industry 4.0 technologies and smart manufacturing in the flat metal manufacturing industry, making them representative of the field of Industry 5.0. Each expert was then asked to assess the importance of each key factor based on their own experience and knowledge.

4.2 Use the Fuzzy Delphi Method (FDM) to Screen Important Attributes

This study first applied relevant literature and invited 9 experts to participate and assist in the evaluation process. The group consisted of 3 professors from university engineering and management schools, 2 researchers from government-established industrial technology research institutes, 2 senior engineers from smart manufacturing system suppliers, and 2 CEOs from the flat metal manufacturing industry. These experts had 15 to 30 years of experience in implementing smart manufacturing in the flat metal manufacturing industry. They came from diverse professional backgrounds and all had practical experience in implementing Industry 4.0 technologies and smart manufacturing in the flat metal manufacturing industry, making them representative of the field of Industry 5.0. Each expert was then asked to assess the importance of each key factor based on their own experience and knowledge.

A Fuzzy Delphi questionnaire survey was distributed to experts from four fields, including industry leaders from the flat metal manufacturing industry, experts from research institutions, professors from university engineering schools, and managers from companies providing smart manufacturing equipment and software-hardware integration. These experts have more than 10 years of extensive experience in the application of sustainable and smart manufacturing technologies. Among these experts, all are key drivers of the development of sustainable smart manufacturing in the flat metal manufacturing industry, dedicated to improving the production environment and the human-centric application of technologies. Experts were asked to assess the influencing factors of 5 criteria and their 25 sub-criteria items, using a 5-point scale to determine the relative importance of each factor. First, 9 experts explained and conducted preliminary testing on the 21 influencing factors in the survey content to ensure that all issues and terms were adequately explained and could be correctly understood by the respondents. After the testing was completed, the formal survey was sent to these 9 experts, and their responses were collected. To handle the uncertainty in the expert opinions, the data was converted into triangular fuzzy numbers. These fuzzy values were then defuzzified, and the influencing factors were filtered using a threshold of

Q2=4.01Q2 = 4.01Q2=4.01 based on the Fuzzy Delphi Method standards. The final selected key influencing factors were considered to be the 5 criteria and their 25 sub-criteria that impact the implementation of Industry 5.0 in the flat metal manufacturing industry, as shown in Table 2.

This study invited 9 experts to participate in a roundtable meeting through an online invitation, where they were asked to select 21 sub-criteria from relevant literature that have a positive relationship with the adoption of Industry 5.0 in manufacturing. Subsequently, a Fuzzy Delphi Method (FDM) questionnaire was created based on these 25 sub-criteria, and the 9 experts were asked to fill out the questionnaire using their relevant professional knowledge and experience. As shown in Table 1, the experts evaluated each success factor based on their personal professional knowledge and work experience. The importance level of each success factor was categorized into five levels: "Very Low Importance (VLS)", "Low Importance (LS)", "Moderate Importance (S)", "High Importance (HS)", and "Very High Importance (VHS)", with corresponding scores ranging from 1 to 5. For example, Expert 1 rated the sub-criterion "C_{21}: Artificial Intelligence" under the criterion "C_2: Industrial Technology 4.0" as "Very High Importance" and assigned it a score of 4.63. Other success factors were evaluated in the same manner by the experts.

The survey results from the 9 experts show that under the criterion "C_1: Sustainability," the sub-criterion "C_{12}: Responsible Consumption and Production" was rated 4.01, with a geometric mean of 4.53 and the highest score being 4.63. The average of the top three values (I) was 4.49. The interquartile range (IQR) method was used to determine the threshold. After filtering through the analysis of the 9 experts and the Fuzzy Delphi questionnaire, the following relationships between the success factors for implementing Industry 5.0 in the flat metal manufacturing industry were established:"C_1: Sustainability" and its sub-criteria: "C_{11}: Industry, Innovation, and Infrastructure," "C_{12}: Responsible Consumption and Production," and "C_{13}: Sustainable Cities and Communities.""C_2: Industrial 4.0 Technologies" and its sub-criteria: "C_{21}: Artificial Intelligence," "C_{22}: Autonomous Robots," "C_{23}: Cybersecurity," and "C_{24}: Sensors and Actuators.""C_3: Organizational Resilience" and its sub-criteria: "C_{31}: Governance and Accountability," "C_{32}: Innovation," and "C_{33}: Adaptability.""C_4: Supply Chain Resilience" and its sub-criteria: "C_{41}: Agility," "C_{42}: Efficiency," "C_{43}: Visibility," "C_{44}: Coordination and Collaboration," "C_{45}: Information Sharing," "C_{46}: Risk Awareness," "C_{47}: Human Resource Management," "C_{48}: Trust," and "C_{49}: Sustainability."

"C_5: Human-Centric" and its sub-criteria: "C_{51}: Human-Machine Collaboration," "C_{52}: Human-Machine Interface," "C_{53}: User-Centered Design," "C_{54}: Safety Monitoring and Control," "C_{55}: Speed-Distance Monitoring," and "C_{56}: Organizational Collaboration."

Subsequent analysis using the Analytic Hierarchy Process (AHP) provides a concrete basis for future research.

Table 2. Fuzzy Delphi Threshold for the Success Factors of Implementing Industry 5.0 in the Flat Metal Manufacturing Industry

NO	TFN	o	ϑ	NO	TFN	o	ϑ
C_{11}	(4,4.64,5)	4.55	KEEP	C_{44}	(4,4.64,5)	4.55	KEEP
C_{12}	(3,4.04,5)	4.01	KEEP	C_{45}	(4,4.53,5)	4.51	KEEP
C_{13}	(3,3.82,5)	4.02	KEEP	C_{46}	(3,4.28,5)	4.09	KEEP
C_{21}	(4,4.42,5)	4.47	KEEP	C_{47}	(3,4.46,5)	4.15	KEEP
C_{22}	(3,4.11,5)	4.04	KEEP	C_{48}	(3,4.17,5)	4.06	KEEP
C_{23}	(3,4.25,5)	4.08	KEEP	C_{49}	(4,4.53,5)	4.51	KEEP
C_{24}	(4,4.64,5)	4.55	KEEP	C_{51}	(4,4.64,5)	4.55	KEEP
C_{31}	(3,4.07,5)	4.02	KEEP	C_{52}	(4,4.88,5)	4.63	KEEP
C_{32}	(4,4.42,5)	4.47	KEEP	C_{53}	(3,4.5,5)	4.17	KEEP
C_{33}	(3,4.07,5)	4.02	KEEP	C_{54}	(4,4.64,5)	4.55	KEEP
C_{41}	(3,4.28,5)	4.09	KEEP	C_{55}	(3,4.5,5)	4.17	KEEP
C_{42}	(4,4.31,5)	4.44	KEEP	C_{56}	(4,4.64,5)	4.55	KEEP
C_{43}	(4,4.2,5)	4.4	KEEP				

Note: The threshold values are Q1: 3.62, Q2: 4.01.

4.3 Analysis of the Analytic Hierarchy Process (AHP)

After the expert evaluation through the Fuzzy Delphi Method, this study established a hierarchical framework for the success factors of implementing Industry 5.0 in the flat metal manufacturing industry, based on the five major criteria: "C_1: Sustainability," "C_2: Industrial 4.0 Technologies," "C_3: Organizational Resilience," "C_4: Supply Chain Resilience," and "C_5: Human-Centric," along with their respective sub-criteria. The relevant meanings of each criterion and sub-criterion were also discussed and explained in the literature review. Subsequently, the hierarchical questionnaire data was analyzed, and the Super Decisions software was used for computation to derive the decision factors for successfully implementing smart manufacturing in the metal manufacturing industry, including the weight ratios and rankings of each criterion and sub-criterion. As shown in Figure 1.

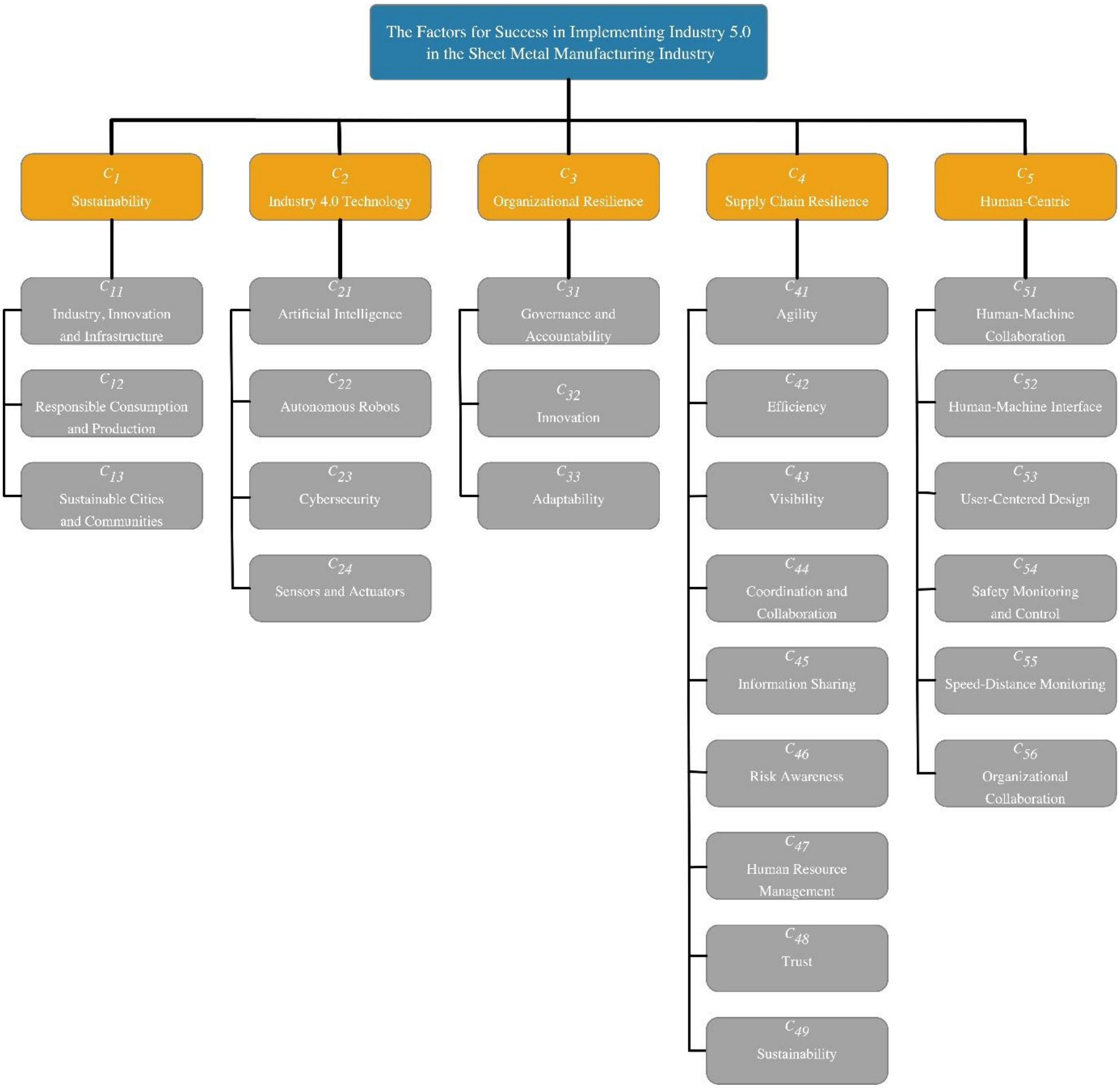

Figure 1. Hierarchical Framework of the Success Factors for Implementing Industry 5.0 in the Flat Metal Manufacturing Industry

4.4 AHP Analysis (Analytic Hierarchy Process Analysis)

A total of 9 expert questionnaires were distributed and all were returned. Using the Super Decisions software, the success factors for implementing Industry 5.0 in the flat metal manufacturing industry were calculated. The results show that the C.I. values of all pairwise comparison matrices were less than 0.1, meeting the consistency requirement.

4.4.1 Analysis of the Weight Values of Each Criterion for the Success Factors of Implementing Industry 5.0 in the Flat Metal Manufacturing Industry

The empirical analysis results show that the criterion "C_5: Human-Centric Technology"

(0.043) has the highest level of importance, followed by "C_2: Industrial Technology 4.0" (0.041), "C_4: Supply Chain Resilience" (0.365), and "C_1: Sustainability" (0.322). The least emphasized criterion is "C_3: Organizational Resilience" (0.229). The empirical results indicate that respondents place the most importance on "C_5: Human-Centric Technology" (0.043), as shown in Table 3.

Table 3. Consolidated Table of the Weight Values and Ranking of Each Criterion for the Success Factors of Implementing Industry 5.0 in the Flat Metal Manufacturing Industry

Criterion	Weight value	Ranking
C_1: Sustainability	0.322	4
C_2: Industrial Technology 4.0	0.041	2
C_3: Organizational Resilience	0.229	5
C_4: Supply Chain Resilience	0.365	3
C_5: Human-Centric Technology	0.043	1

Note: The values in parentheses represent the ranking of the weight values.

4.4.1.1 Analysis of the Weight Values of Each Sub-criterion under the Criterion "C_1: Sustainability"

The empirical analysis results show that "C_{11}: Industry, Innovation, and Infrastructure" (0.437) is the most important to the respondents, followed by "C_{13}: Sustainable Cities and Communities" (0.358). The least emphasized is "C_{12}: Responsible Consumption and Production" (0.205), as shown in Table 4.

Table 4. Consolidated Table of the Weight Values and Ranking Analysis of Each Sub-Criterion under the Criterion "C_1: Sustainability"

Sub-criterion	Weight value	Ranking
C_{11}: Industry, Innovation, and Infrastructure	0.437	1
C_{12}: Responsible Consumption and Production	0.205	3
C_{13}: Sustainable Cities and Communities	0.358	2

Note: The values in parentheses represent the ranking of the weight values.

4.4.1.2 Analysis of the Weight Values of Each Sub-criterion under the Criterion "C_2: Industrial Technology 4.0"

The empirical analysis results show that "C_{21}: Artificial Intelligence" (0.463) is the most important to the respondents, followed by "C_{22}: Autonomous Robots" (0.242), "C_{23}: Cybersecurity" (0.158), and "C_{24}: Sensors and Actuators" (0.137). The least emphasized is "C_{24}: Sensors and Actuators" (0.137), as shown in Table 5.

Table 5. Consolidated Table of the Weight Values and Ranking Analysis of Each Sub-Criterion under the Criterion "C_2: Industrial Technology 4.0."

Sub-criterion	Weight value	Ranking
C_{21}: Artificial Intelligence	0.463	1
C_{22}: Autonomous Robots	0.242	2
C_{23}: Cybersecurity	0.158	3
C_{24}: Sensors and Actuators	0.137	4

Note: The values in parentheses represent the ranking of the weight values.

4.4.1.3 Analysis of the Weight Values of Each Sub-criterion under the Criterion "C_3: Organizational Resilience"

The empirical analysis results show that "C_{32}: Innovation" (0.393) is the most important to the respondents, followed by "C_{33}: Adaptability" (0.341), and the least emphasized is "C_{31}: Governance and Accountability" (0.266), as shown in Table 6.

Table 6. Consolidated Table of the Weight Values and Ranking Analysis of Each Sub-Criterion under the Criterion "C_3: Organizational Resilience"

Sub-criterion	Weight value	Ranking
C_{31}: Governance and Accountability	0.266	3
C_{32}: Innovation	0.393	1
C_{33}: Adaptability	0.341	2

Note: The values in parentheses represent the ranking of the weight values.

4.4.1.4 Analysis of the Weight Values of Each Sub-criterion under the Criterion "C4: Supply Chain Resilience"

The empirical analysis results show that "C_{49}: Sustainability" (0.252) is the most important to the respondents, followed by "C_{45}: Information Sharing" (0.19), "C_{42}: Efficiency" (0.095), "C_{46}: Risk Awareness" (0.094), "C_{41}: Agility" (0.081), "C_{47}: Human Resource Management" (0.077), "C48: Trust" (0.076), and "C_{43}: Visibility" (0.072). The least emphasized is "C_{44}: Coordination and Collaboration" (0.063), as shown in Table 7.

Table 7. Consolidated Table of the Weight Values and Ranking Analysis of Each Sub-Criterion under the Criterion "C_4: Supply Chain Resilience"

Sub-criterion	Weight value	Ranking
C_{41}: Agility	0.081	5
C_{42}: Efficiency	0.995	3
C_{43}: Visibility	0.072	8
C_{44}: Coordination and Collaboration	0.063	9
C_{45}: Information Sharing	0.190	2
C_{46}: Risk Awareness	0.094	4
C_{47}: Human Resource Management	0.077	6
C_{48}: Trust	0.076	7
C_{49}: Sustainability	0.252	1

Note: The values in parentheses represent the ranking of the weight values.

Based on the research findings, the success factors for implementing Industry 5.0 in the flat metal manufacturing industry, along with the weight values and importance rankings of the relevant criteria and sub-criteria derived from the expert hierarchical questionnaire, are presented in Table 9.

In terms of criterion ranking, the order of importance is as follows: "C_5: Human-Centric Technology" (0.043) is considered the most important, followed by "C_2: Industrial Technology 4.0" (0.041), "C_4: Supply Chain Resilience" (0.365), and "C_1: Sustainability" (0.322). The least emphasized criterion is "C_3: Organizational Resilience" (0.229). The empirical results indicate that respondents place the highest importance on "C_5: Human-Centric Technology" (0.043). Based on the experts' evaluations, the average score for the criteria shows that "C_5: Human-Centric Technology" is considered the most critical factor for the success of implementing Industry 5.0 in the flat metal manufacturing industry.

Table 9. Weight Values and Importance Rankings of the Criteria and Sub-Criteria for the Success Factors of Implementing Industry 5.0 in the Flat Metal Manufacturing Industry

The criteria for the success factors of implementing Industry 5.0 in the flat metal manufacturing industry.	Measurement Criteria	Weight Value	Importance Ranking	Overall Ranking
	C_{51}: Human-Machine Collaboration	0.422	1	3
	C_{52}: Human-Machine Interface	0.263	2	8
	C_{53}: User-Centered Design	0.099	3	16
C_5: Human-Centric Technology	C_{54}: Safety Monitoring and Control	0.082	4	18
(0.043) (1)	C_{55}: Speed-Distance Monitoring	0.071	5	23
	C_{56}: Organizational Collaboration	0.063	6	24
	C_{21}: Artificial Intelligence	0.463	1	1
C_2: Industrial Technology 4.0	C_{22}: Autonomous Robots	0.242	2	10
(0.041) (2)	C_{23}: Cybersecurity	0.158	3	13
	C_{24}: Sensors and Actuators	0.137	4	14
	C_{41}: Agility	0.081	5	19
	C_{42}: Efficiency	0.995	3	15
	C_{43}: Visibility	0.072	8	22
C_4: Supply Chain Resilience	C_{44}: Coordination and Collaboration	0.063	9	24
(0.365) (3)	C_{45}: Information Sharing	0.190	2	12
	C_{46}: Risk Awareness	0.094	4	17
	C_{47}: Human Resource Management	0.077	6	20
	C_{48}: Trust	0.076	7	21
	C_{49}: Sustainability	0.252	1	9
	C_{11}: Industry, Innovation, and Infrastructure	0.437	1	2
C_1: Sustainability	C_{12}: Responsible Consumption and Production	0.205	3	11
(0.322) (4)	C_{13}: Sustainable Cities and Communities	0.358	2	5
	C_{31}: Governance and Accountability	0.266	3	7
C_3: Organizational Resilience	C_{32}: Innovation	0.393	1	4
(0.229) (5)	C_{33}: Adaptability	0.341	2	6

Note: The values in parentheses represent the ranking of the weight values.

5. Conclusions and Recommendations

5.1 Conclusion

5.1.1 Sustainability

When examining the implementation of Industry 5.0, the importance ranking of the criteria provides a reference for strategy formulation. The results indicate that "C_{11}: Industry, Innovation, and Infrastructure" (0.437) is considered the most important, highlighting its central role in driving economic development and technological innovation. Following this is "C_{13}: Sustainable Cities and Communities" (0.358), emphasizing the significance of urban and community sustainability in the overall strategy. In contrast, "C_{12}: Responsible Consumption and Production" (0.205) is deemed relatively less important, reflecting that this area has not yet received sufficient attention. In the future, priority should be given to innovative developments in industry and infrastructure, while gradually advancing sustainable development in cities and communities to achieve a balanced and long-term strategic approach.

5.1.2 Industrial Technology 4.0

In the context of Industry 5.0 technology applications, the importance of artificial intelligence and automation technologies has become increasingly prominent. The results show that "C_{21}: Artificial Intelligence" (0.463) is considered the most important, reflecting its central role in driving smart transformation. Following this is "C_{22}: Autonomous Robots" (0.242), highlighting the critical role of automated machinery in efficiency and precision. "C_{23}: Cybersecurity" (0.158) and "C_{24}: Sensors and Actuators" (0.137) are relatively less important, with "C_{24}: Sensors and Actuators" rated as the least important.In summary, future efforts should prioritize the application of artificial intelligence and autonomous robots, while simultaneously strengthening cybersecurity measures and gradually enhancing other technological elements to achieve comprehensive integration and upgrading of smart technologies.

5.1.3 Organizational Resilience

In the advancement of Industry 5.0, innovation and adaptability are regarded as key driving forces. The results show that "C_{32}: Innovation" (0.393) is considered the most important by respondents, highlighting its central role in enhancing competitiveness and achieving smart transformation. Following this is "C_{33}: Adaptability" (0.341), emphasizing the critical importance of flexibility in responding to rapidly changing market environments. In contrast, "C_{31}: Governance and Accountability" (0.266) is relatively less emphasized, reflecting its secondary position in current strategic considerations.In the future, efforts should focus on promoting innovation, strengthening enterprises' ability to adapt to market changes, and gradually improving governance and accountability mechanisms to achieve comprehensive and balanced development goals.

5.1.4 Supply Chain Resilience

When exploring the key success factors in the context of Industry 5.0, sustainability and efficiency emerge as central focuses. The results show that "C_{49}: Sustainability" (0.252) is considered the most important by respondents, highlighting its crucial role in achieving long-term goals. This is followed by "C_{42}: Efficiency" (0.095), "C_{44}: Coordination and Collaboration" (0.063), and "C_{43}: Visibility" (0.072), emphasizing the importance of information flow and efficiency improvement in business operations."C_{46}: Risk Awareness" (0.094) and "C_{41}: Agility" (0.081) indicate that the ability to respond to uncertainty retains certain value. However, "C_{44}: Coordination and Collaboration" (0.063) and "C_{45}: Information Sharing" (0.19) are considered the least important, reflecting their lower priority in strategic considerations. Therefore, future strategies should prioritize sustainability as the core focus while strengthening information sharing and efficiency management. Additionally, efforts should gradually enhance risk response capabilities and agility to establish a comprehensive and efficient Industry 5.0 development system.

5.1.5 Human-Centric Technology

In the implementation of Industry 5.0, human-machine interaction technology has become a critical pillar in advancing smart manufacturing. The results show that "C_{51}: Human-Machine Collaboration" (0.422) is considered the most important by respondents, reflecting its central role in improving efficiency and enabling intelligent transformation. This is followed by "C_{52}: Human-Machine Interface" (0.263), highlighting the necessity of enhancing human-machine interaction experiences."C_{53}: User-Centered Design" (0.099), "C_{54}: Safety Monitoring and Control" (0.082), and "C_{55}: Speed-Distance Monitoring" (0.071) also demonstrate relative importance. However, "C_{56}: Organizational Collaboration" (0.063) is deemed the least important, indicating its lower priority in current strategies. Overall, future efforts should prioritize the development of human-machine collaboration and interfaces while simultaneously optimizing safety and user experience. These steps will establish a solid foundation for the comprehensive realization of Industry 5.0.

5.1.6 The Weight Values of the Five Criteria

In the context of implementing Industry 5.0 in the flat metal manufacturing industry, the importance ranking of the criteria provides guidance for developing strategic directions. Based on the research results, the expert hierarchical questionnaire reveals that "C_5: Human-Centric Technology" (0.043) is considered the most important criterion, highlighting the critical role of human-centered technology applications in achieving smart manufacturing. This is followed by "C2: Industrial Technology 4.0" (0.041) and "C_4: Supply Chain Resilience" (0.365), emphasizing the importance of technological innovation and supply chain stability in advancing Industry 5.0."C_1: Sustainability" (0.322) is also regarded as essential, though its relative weight is slightly lower. The least emphasized criterion is "C_3: Organizational Resilience" (0.229). Overall, the results indicate that respondents place the highest importance on human-centric technology. It is recommended that future strategies focus on developing human-centered technologies, supported by industrial technology innovation and supply chain resilience building, while integrating sustainability principles into development goals to achieve a successful transition to Industry 5.0.

Case 1: Smart Equipment Manufacturer

The smart equipment manufacturer focuses on developing IoT modules, intelligent sensors, and other technologies to support Industry 4.0 transformation. Interviewees indicated that the adoption of smart manufacturing technologies has improved equipment efficiency and market competitiveness, particularly in responding to customer needs and driving technological innovation. The company gradually achieved intelligent upgrades by investing resources in phases, strengthening internal processes, and enhancing employee skills, thereby maintaining a leading position in the market through differentiated products.

Case 2: Metal Processing Enterprise (Sheet Metal and Casting)

The metal processing enterprise implemented automation and intelligent inspection technologies in its production processes, which effectively improved process precision and reduced costs. Interviewees stated that predictive maintenance reduced downtime losses and significantly increased material utilization. Smart manufacturing technologies enabled the company to respond quickly to customized demands, shorten delivery cycles, and improve product quality and customer satisfaction—demonstrating advantages of high-efficiency and flexible production. Based on the above summary, it can be concluded that the evaluation framework for the key decision factors in the successful adoption of smart manufacturing in the metal manufacturing industry is feasible. Related enterprises or vendors may refer to this framework as a reference for their future R&D and sales strategies in successfully implementing smart manufacturing in the metal sector.

5.2 Managerial Implications

The flat metal manufacturing industry should adopt human-centric technology as a core strategy for implementing Industry 5.0, focusing on the synergistic development of technology and human resources. Emphasis should be placed on enhancing human-machine collaboration and user-centered design to improve production efficiency and employee satisfaction. Concurrently, it is crucial to accelerate the advancement of Industry 4.0 technologies, leveraging digitalization and automation to achieve intelligent and precise production processes. In addition, enhancing supply chain resilience is essential. Companies should establish flexible and robust supply chain management systems to strengthen risk resistance and market adaptability. On this foundation, incorporating sustainability principles is imperative to promote green manufacturing and energy efficiency, ensuring resource utilization is both efficient and environmentally friendly.

Finally, while organizational resilience carries relatively lower weight, it remains indispensable for addressing unforeseen challenges and fostering internal collaboration. Companies are advised to gradually improve governance structures and internal communication mechanisms to achieve comprehensive and balanced development goals. These strategies will provide a solid foundation for companies to enhance competitiveness and achieve sustainable operations while implementing Industry 5.0.

5.3 Future Recommendations

Future efforts should focus on comprehensively strengthening sustainability and the application of human-centric technology, deeply integrating these elements into all aspects of the flat metal manufacturing industry. Companies should continuously promote green production technologies and energy-saving, carbon-reduction measures while incorporating more intelligent and humanized technological solutions into product design and manufacturing processes. Additionally, accelerating digital transformation and the innovative application of Industry 4.0 technologies, such as artificial intelligence, automation, and the Internet of Things (IoT), will further enhance the efficiency and intelligence of production processes. Enhancing organizational and supply chain resilience is another key priority. Companies need to establish flexible and robust supply chain management mechanisms to address market fluctuations and unforeseen challenges, ensuring operational stability. Furthermore, strengthening risk management and emergency response mechanisms will improve adaptability to uncertain environments. Future initiatives should also actively promote cross-sector collaboration. By working with other industries, academic institutions, and government entities, companies can integrate resources for innovative research and practice, learning from successful global case studies to maintain a leading position in the Industry 5.0 progression. Implementing these recommendations will create more value for the flat metal manufacturing industry in the Industry 5.0 era and foster the sustainable development of the entire sector.

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