Frontiers in Computer Science and Artificial Intelligence
ISSN: 2978-8048
DOI: 10.32996/fcsai
Journal Homepage: www.al-kindipublisher.com/index.php/fcsai

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| RESEARCH ARTICLE

Generative AI and IoT-Driven Autonomous Manufacturing Ecosystems Transition from Industry 4.0 to Industry 5.0

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| ABSTRACT
There are ongoing significant changes happening in the manufacturing sector due to fast-moving digital innovation. The introduction of the concept of smart manufacturing in the Industry 4.0 model happened due to the integration of the Internet of Things, cyber-physical systems, cloud computing, robotics, and big data analytics. Nonetheless, there are a number of drawbacks in conventional Industry 4.0 systems, such as low adaptability, a lack of human-focused collaboration, security issues, and dependency on existing automation schemes. Therefore, it is evident that Industry 5.0 is coming into play. This paper explores the potential of Generative Artificial Intelligence (Generative AI) and the Internet of Things (IoT) in creating autonomous manufacturing systems and facilitating the shift from Industry 4.0 to Industry 5.0. The use of Generative AI provides functionalities including autonomous decision-making, dynamic production planning, process optimization using artificial intelligence, and product design aided by artificial intelligence, whereas IoT offers features such as data gathering in real-time, machine connectivity, predictive maintenance, and decentralized communication in manufacturing systems. A conceptual and literature-based research approach is used in this paper to examine the current trends in smart manufacturing technologies and present a framework for the integration of Industry 5.0 manufacturing systems. Human-AI cooperation, intelligent automation, and sustainability are emphasized as important components in the future of manufacturing. The presented framework shows how Generative AI and IoT can transform the smart factory into an intelligent, autonomous, and sustainable manufacturing system.

| KEYWORDS
Industry 4.0, Industry 5.0, Smart manufacturing, IoT, sustainable manufacturing.

| ARTICLE INFORMATION
ACCEPTED: 15 April 2026 **PUBLISHED:** 23 May 2026 **DOI:** 10.32996/fcsai.2026.5.7.7

1. Introduction

The manufacturing sector has witnessed tremendous advancement in terms of technology during the last couple of decades, transitioning from mechanical production processes to intelligent manufacturing environments. The progression from Industry 1.0 to Industry 4.0 has revolutionized the functioning of industries by means of automation, digitization, robotics, and analytics. Industry 4.0 brought about the concept of smart manufacturing, where technologies like IoT, cyber-physical systems, cloud computing, artificial intelligence, big data analysis, and industrial automation were used. These technologies helped enhance factory performance in terms of productivity, efficiency, transparency, and flexibility via machine-to-machine communication [1].

In this context, IoT can be regarded as one of the key foundational components of contemporary smart manufacturing systems. IoT devices and smart sensors allow for constant monitoring of machine statuses, machine parameters, manufacturing processes, and machine states. With the help of real-time data obtained from connected manufacturing systems, it is possible to perform

predictive maintenance, quality assurance, supply chain management, and process optimization operations. Moreover, it is possible to use cloud and edge computing technologies to develop scalable infrastructures for processing and analyzing vast amounts of industrial data [2].

However, despite obvious benefits provided by the Fourth Industrial Revolution, there are certain limitations to existing manufacturing systems. Traditional systems of automation are highly rule-based and rely on historical data to predict future outcomes. Modern AI systems are only capable of predictive analytics, but not of autonomous reasoning and problem solving. Furthermore, contemporary manufacturing processes pose challenges that include cybersecurity concerns, interoperability problems, problems related to data management, workforce transition issues, and sustainability issues. Thus, Industry 5.0 became the new focus for many manufacturers [3].

Industry 5.0 involves the evolution of human-centered, sustainable, resilient, and smart manufacturing ecosystems where both humans and advanced AI systems work together for improved productivity and innovation. In contrast to Industry 4.0, which mainly revolves around automation and connectedness, Industry 5.0 seeks to leverage human ingenuity, cognitive intelligence, and advanced autonomy to optimize industrial processes. In such an environment, Generative Artificial Intelligence (Generative AI) has been recognized as a disruptive technology that can transform manufacturing ecosystems [4].

While traditional AI systems lack the ability to create new content, autonomous decisions, intelligent suggestions, and adaptive manufacturing approaches, generative AI is different from them in that it uses advanced foundation models and deep learning algorithms to develop new things. Generative AI has numerous applications in manufacturing including intelligent design, process improvement, production scheduling, digital twin generation, autonomous fault detection, and adaptive manufacturing. The combination of generative AI and IoT technologies helps move manufacturing ecosystems beyond their current state of reactivity and semi-autonomy towards complete autonomy and self-optimization [5].

When it comes to IoT and Generative AI integration, there exists a high possibility of the creation of manufacturing systems that would involve real-time interactions between machines, sensors, robots, digital twins, and people. It can lead to an increase in flexibility, resilience, efficiency, and sustainability in manufacturing operations by providing the ability to conduct intelligent decision-making. Moreover, the combination of the two concepts makes it possible to implement the principles of the development of decentralized manufacturing systems with the ability of autonomous interaction [6][7].

The main purpose of this paper is the research into the potential contribution of Generative AI and IoT to the formation of autonomous manufacturing ecosystems and the transition from the era of Industry 4.0 to Industry 5.0. The analysis includes the overview of modern developments in smart manufacturing technologies, as well as the discussion of existing problems and potential opportunities related to intelligent and autonomous manufacturing ecosystems. The conceptual framework for Industry 5.0 manufacturing ecosystem has been proposed within the work.
The rest of the paper is structured as follows: The literature review section examines the previous studies concerning Industry 4.0, Internet of Things, Generative AI, and Industry 5.0 manufacturing system frameworks. The methodology section explains the conceptual framework for conducting the research and developing the framework. The discussion section examines the effects, benefits, and difficulties that Generative AI and Internet of Things bring into manufacturing ecosystems. Lastly, the conclusion section sums up the findings.

2. Literature Review

The emergence of Industry 4.0 led to a radical shift in manufacturing due to the adoption of digital technologies like IoT, cyber-physical systems, cloud computing, robotics, AI, and big data. These innovations helped in creating smart manufacturing environments where machines, sensors, and digital processes interacted with each other in order to increase efficiency, automation, and transparency in manufacturing. Out of these technologies, IoT is considered to be one of the key facilitators for smart manufacturing processes. Industrial IoT and smart sensors generate constant streams of operational data that provide information on machine status, production processes, temperature, vibrations, and condition of machinery [8][9].

Cyber-physical systems also have an important part to play in manufacturing environments within the Industry 4.0 framework since they combine physical processes and systems with computation and communication capabilities. Cyber-physical systems allow equipment to monitor their activities and engage in information exchange and adaptation depending on the current manufacturing process through the use of data from the actual process taking place. Cloud computing technology is also employed in manufacturing processes to provide flexible infrastructure for storing data and monitoring activities within manufacturing processes. This technology, however, suffers from latency in critical manufacturing processes, which gives rise to the need for edge computing [10][11][12].

Robotics and automation systems have now become an integral part of smart manufacturing systems as well. Industrial robots can be seen performing various tasks, such as welding, assembly, inspection, and materials handling. Cobots (collaborative robots) provide an opportunity to interact safely with machines in the same space as human beings. Even though robotic automation greatly increases the effectiveness and efficiency of the process, conventional robotic systems only perform on programmed commands [13].

Artificial intelligence has further optimized the manufacturing process with the use of predictive analysis, defect identification, and process optimization. Machine learning and deep learning models are typically utilized for quality control, production planning, and predictive maintenance. The AI models can analyze vast data in the manufacturing industry to detect patterns and predict equipment malfunctioning prior to failure. Nevertheless, traditional AI is very data-driven and goal-oriented, which makes them incapable of adapting to any changes in the industrial environment. Such constraints have fueled the exploration of Generative Artificial Intelligence [14][15][16].

Generative AI is a major leap forward compared to other AI technologies due to its capacity for creating intelligent recommendations, intelligent solutions, and intelligent decisions. Generative AI in manufacturing could be used for AI-enabled design of products, production scheduling, production optimization, and intelligent decision-making. Intelligent design software could automatically design intelligent geometries of products in accordance with their functional, material, and production constraints [17][18].

In addition, the integration of Generative AI is useful for the digital twin system as well, allowing for simulation and prediction of manufacturing processes based on the information acquired. Digital twin technology supported by artificial intelligence is used to predict risks, optimize the workflow process and suggest solutions before executing. Moreover, Generative AI promotes human-machine collaboration through interaction via natural language between employees and the manufacturing process. Virtual assistants powered by AI can provide assistance on how to operate a specific machine or offer troubleshooting support [19].

Industry 5.0 has several distinctions compared to Industry 4.0. First, while Industry 4.0 relies primarily on the introduction of automation and communication processes between machines, the new paradigm puts more emphasis on incorporating human skills and cognitive abilities along with the automation capabilities. Another distinguishing factor is the increased attention to sustainability issues as the topic becomes increasingly urgent in manufacturing. Resilience of the manufacturing ecosystem also appears to be one of the key concerns in industry 5.0 environment [20][21].

Despite considerable progress in the field of smart manufacturing systems, a number of research areas remain open for exploration. Current researches mostly deal with the application of either AI or IoT technology alone instead of looking into the possibilities of autonomous smart manufacturing systems that can incorporate both Generative AI and IoT technologies together. Also, not much research work has been done regarding the issues related to AI ethics, cybersecurity, workforce readiness, and the implementation process of Industry 5.0 [22][23].

3. Methodology

In this research work, conceptual and literature-based methodologies are used to analyze the application of Generative Artificial Intelligence and Internet of Things in the development of autonomous manufacturing ecosystems as well as from Industry 4.0 to Industry 5.0. This research mainly emphasizes the examination of the advancements in smart manufacturing technologies, identification of significant challenges in current industries, and design of an integrated theoretical framework for future intelligent manufacturing systems.

This research methodological approach uses secondary data collection and analysis of relevant literature. The main aim of this research methodology is to gather useful knowledge and information related to Industry 4.0, Industry 5.0, Internet of Things, artificial intelligence, Generative Artificial Intelligence, cloud manufacturing, cyber-physical systems, and smart factories. This literature analysis aims at understanding the current trend of manufacturing industry development and its challenges.

The criteria for choosing relevant literature involved identifying publications from reputable journals and industrial journals linked to advanced manufacturing processes. Literature pertaining to topics like predictive maintenance, intelligent manufacturing, industrial IoT, autonomous robotics, digital twin, cloud edge computing, and sustainable manufacturing systems was considered. The studies dealing with the constraints of Industry 4.0 systems as well as the emergence of Industry 5.0 technology to facilitate human-centric and resilient manufacturing were especially considered.

The comparison analysis approach was employed to analyze the distinctions between Industry 4.0 and Industry 5.0 manufacturing systems. Parameters that were analyzed included automation, human machine interface, decision intelligence, sustainability, flexibility, and resilience of operations. This analysis was used to determine the technical gaps present within smart manufacturing systems, in addition to possible contributions by Generative AI and IoT toward autonomous manufacturing processes.

Using the results of literature review and analysis, the conceptual framework for Generative AI and IoT autonomous manufacturing ecosystems was proposed. Specifically, the suggested conceptual framework is made up of several integrated layers that would allow implementing intelligent manufacturing processes. In this case, the first of such layers is a data collection layer, which includes IoT devices and machines gathering real-time data about the state of manufacturing processes including the condition of machines, operation parameters, power consumption, performance, etc.

Further, there is a communication and computing layer integrating cloud computing technology with edge computing solutions to transmit, store, and analyze collected industrial data. The next layer is an intelligence layer incorporating AI technologies to make manufacturing processes autonomous, efficient, optimized, predictive, and adaptable through the analysis of manufacturing data with AI-based decision making, digital twin implementation, and manufacturing planning. Finally, the last layer is the execution layer consisting of robotic systems, collaborative robots, automated machinery, and other manufacturing systems able to perform manufacturing operations autonomously based on AI-driven decisions.

The fifth and final layer is the Human-Centric Collaboration Layer that highlights the significance of the human element in the Industry 5.0 manufacturing ecosystem. It facilitates human-machine collaboration through artificial intelligence-assisted guidance, operation assistance, and cognitive decision-making. Sustainability aspects like energy optimization and waste minimization are considered within the proposed architecture.

In summary, the proposed methodology adopts a well-structured theoretical approach to comprehend the potential of Generative AI and IoT in transforming the conventional smart factory into an autonomous, adaptable, and sustainable Industry 5.0 manufacturing ecosystem.

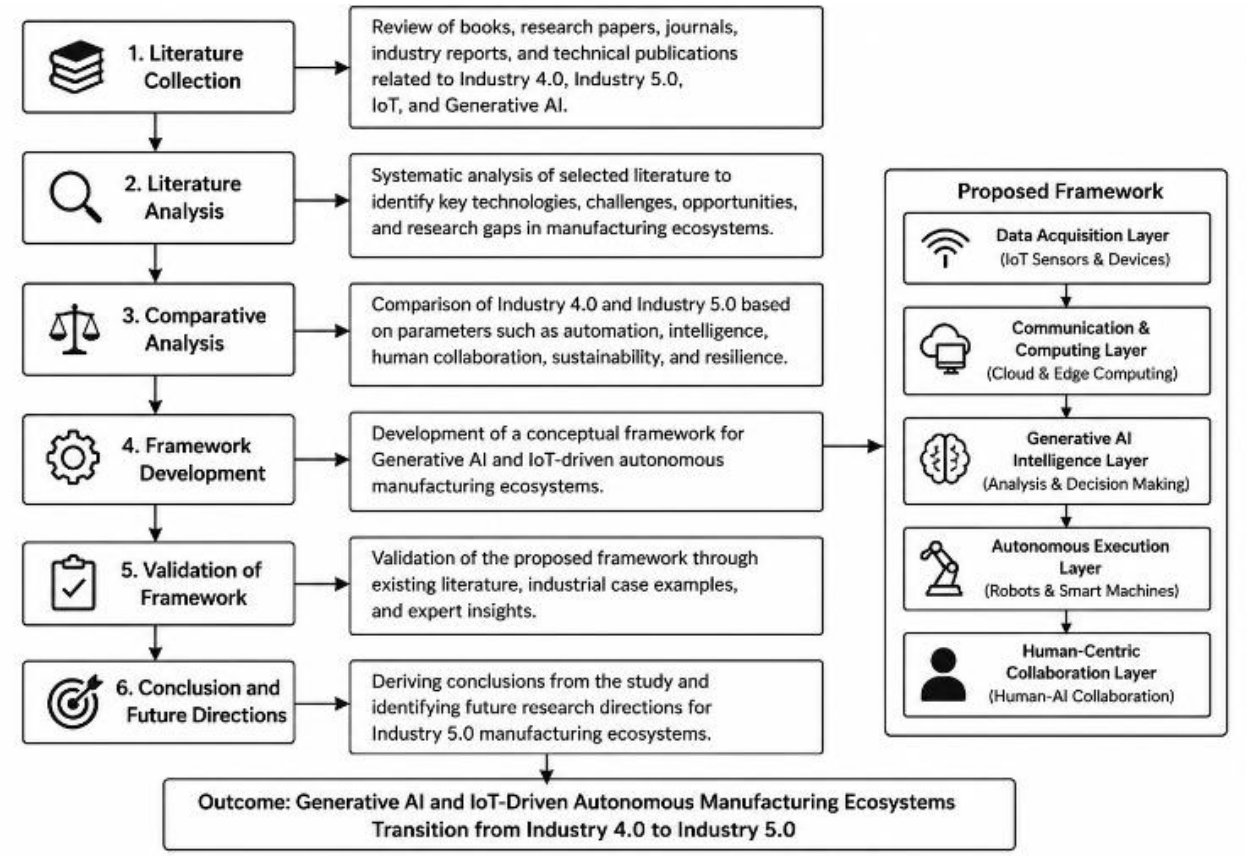

Fig 1: Methodology

The methodology diagram provides a systematic research method to design Generative AI and IoT-based autonomous manufacturing ecosystems from Industry 4.0 to Industry 5.0. First, literature is collected from journal articles, academic papers, and industry reports on Industry 4.0, Industry 5.0, IoT, and Generative AI, followed by a literature review to extract the relevant technologies, issues, possibilities, and research gaps of manufacturing systems. Then, a comparison study is performed between Industry 4.0 and Industry 5.0 based on the aspects of automation, intelligence, sustainability, resilience, and human collaboration. On the basis of the comparison study, a conceptual framework is proposed, which contains five major layers: the first layer is the data acquisition layer, which utilizes IoT devices; the second layer is the communication and computing layer, which employs cloud and edge computing; the third layer is the Generative AI intelligence layer, which implements machine learning and deep learning algorithms; the fourth layer is the autonomous execution layer, which incorporates robots and smart machines; and the fifth layer is the human-centric collaboration layer, which enables human-machine interaction. Finally, the conceptual framework will be validated through literature reviews, industrial cases, and experts' views, and then conclusions will be drawn.

4. Discussion

The combination of Generative AI technology and IoT technology will greatly influence manufacturing ecosystems because it will facilitate intelligent, autonomous, and adaptive manufacturing processes. Industry 4.0 was able to usher in intelligent manufacturing processes using digitization, automation, and information management. However, Industry 5.0 demands manufacturing processes that are human-centric, resilient, sustainable, and collaborative. Based on the findings from the literature review, it is evident that the combination of Generative AI and IoT technologies can be the basis for Industry 5.0.

The use of generative AI results in enhanced capabilities compared to standard AI due to the provision of features like self-learning and reasoning, intelligent recommendations creation, process optimization, and contextual decision-making. Generative AI has a variety of applications in the field of manufacturing such as improved manufacturing planning and scheduling, design optimization, quality control, and predictive maintenance. Contrary to the standard AI approaches whose core function is prediction from existing data sets, generative AI technologies can provide an optimized approach to manufacturing that is responsive to current conditions.

The application of IoT technology enhances manufacturing intelligence even further since it helps collect real-time data about equipment, sensors, robots, and industrial machines constantly. With IoT manufacturing systems, industries get the opportunity to observe how equipment works, what happens in processes and procedures, and how resources are used. In combination with data collected in real-time through IoT applications and Generative AI algorithms, industries will be able to build autonomous and self-optimized production environments.

One of the benefits of Generative AI technologies applied in manufacturing and IoT manufacturing systems is their ability to operate in an efficient manner in a predictive and preventive way. In smart manufacturing environments, industries get the chance to notice any anomalies before they happen, detect issues before they become a problem, and make sure that processes run efficiently.

Another significant element in the move from Industry 4.0 to Industry 5.0 involves the focus on cooperation between man and machine as opposed to replacing one entirely. Industry 5.0 introduces the notion of collaborative intelligence, which involves working together as human beings and intelligent machines for superior performance and innovation. Generative AI will assist workers through technical advice, intelligent suggestions, automatic documentation, and virtual operation support. Collaborative robots and manufacturing systems that utilize AI technology can increase safety in the factory environment, ease operator strain, and boost efficiency, all while retaining human intelligence.

There is a need for sustainability in the manufacturing environments of Industry 5.0. Autonomous intelligent systems powered by Generative AI and the Internet of Things (IoT) technology will play a key role in optimizing energy use, minimizing wastage of resources, and ensuring efficient manufacturing operations through real-time adjustments. The technology can be employed to support circular manufacturing practices.

However, several issues are associated with the implementation of Generative AI and the Internet of Things-based manufacturing ecosystem. One of the main issues includes cybersecurity threats due to enhanced integration between production processes and IT solutions. IoT-based smart manufacturing facilities produce significant amounts of sensitive information about industrial operations, which calls for enhanced cybersecurity. In addition, the need for high financial investments to implement the system might discourage manufacturers from implementing highly efficient autonomous manufacturing facilities.

One more significant issue involves insufficient expertise of personnel working in manufacturing facilities and interacting with industry 5.0 solutions. In particular, employees will need to gain necessary skills to work with AI systems, data management

technologies, Internet of Things-based applications, and intelligent automation. Ethical implications associated with these aspects also should be addressed.

In conclusion, the use of Generative AI and IoT in conjunction is indeed a key milestone towards realizing Intelligent, Resilient, and Sustainable manufacturing ecosystems for Industry 5.0. The technologies will indeed create a self-optimizing manufacturing ecosystem that can improve efficiencies, adaptive manufacturing, and human-AI interactions.

5. Conclusion

Digital technologies' fast development is driving modern manufacturing systems to evolve from traditional automation systems into intelligent and autonomous manufacturing systems. The concept of Industry 4.0 set up the basis for smart manufacturing by introducing IoT, cyber physical systems, cloud computing, robotics, and artificial intelligence. The increasing need for adaptable decisions, human interaction, sustainability, and robust manufacturing have led the evolution from Industry 4.0 to Industry 5.0. This research explores the potential of Generative Artificial Intelligence and IoT technologies in realizing autonomous manufacturing ecosystems that can support such industry evolution.

Through this study, we have found out that the use of IoT technologies can be seen as creating a platform to facilitate the collection of real-time data from industries, communication between machines, monitoring for future predictions, and providing visibility of operations within the manufacturing plants. On the other hand, Generative AI provides intelligent decision-making abilities, adaptive production planning, self-optimization, AI-powered product design generation, and predictive operations management. The combination of these two technologies will make manufacturing systems become smarter and more interconnected.

Additionally, the study underlined the significance of adopting Industry 5.0 guidelines, such as human and machine collaboration, sustainable production, and resilience in manufacturing processes. Unlike Industry 4.0, which concentrates on automation and connectivity, Industry 5.0 emphasizes collaborative intelligence in which humans and intelligent systems collaborate to achieve improved innovations, productivity, and workplace safety. The utilization of generative AI assistance systems and collaborative robots will be very helpful for boosting workforce productivity without compromising the creative capacity of humans.

Moreover, the proposed framework illustrates how a combination of IoT devices, cloud-edge computing technology, Generative AI intelligence systems, autonomous robots, and collaboration layers can effectively facilitate future smart factory development. Such autonomous manufacturing systems can offer better predictive maintenance, energy efficiency, resource optimization, and adaptive operations while contributing to sustainable industrial growth.

Although there exist ample possibilities when it comes to Generative AI and IoT integration, issues such as cybersecurity threats, infrastructure investments, workforce skills acquisition, data management, and ethical AI implementation are crucial areas of concern in the industrial application of this technology. Hence, it is essential for further research to center on designing robust, scalable, interpretable, and sustainable Industry 5.0 manufacturing systems.

In summary, Generative AI and IoT are the primary technological enablers of the evolution from Industry 4.0 to Industry 5.0. The integration of these technologies holds the key to realizing an autonomous manufacturing system that is adaptable, resilient, human-centric, and sustainable.

Funding: This research received no external funding
Conflicts of Interest: The authors declare no conflict of interest.
Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers.

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