Automated Robotics, Blockchain, and AI in Revolutionary Manufacturing System

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Abstract
The core outcome of revolutionary manufacturing, usually known as Industry 4.0, is the development of intelligent factories. These factories leverage advanced robotics, big data, cloud computing, the robust security measures, smart sensors, the Internet of Things (IoT), and other cutting-edge technologies to enhance efficiency, safety, and cost-effectiveness. Robotics plays a vital role in Industry 4.0, offering extensive capabilities in manufacturing by improving automation, performing repetitive tasks with precision, and reducing operational costs. Another key technology driving the transformation of manufacturing is Artificial Intelligence powered block chain. In an Industry 4.0 environment, AI and block chain work together to secure the vast amounts of data generated by IoT devices. Blockchain ensures data integrity and immutability, while AI analyzes the data to optimize processes and extract valuable insights. AI algorithms also enhance blockchain security and facilitate the analysis of manufacturing data recorded over the blockchain, enabling predictive maintenance and the quality control. This proactive approach helps detect and resolve potential issues before they lead to defects or downtime. Additionally, smart contracts on the blockchain can autonomously execute predefined tasks, streamlining processes and reducing the need for intermediaries. This paper explores the applications of robotics and AI-powered block chain technology in Industry 4.0, discussing their impact and potential future research directions. These technologies enable automation, support hazardous and complex tasks, withstand extreme temperatures, and operate continuously over extended periods in assembly lines.

Keywords: Artificial Intelligence, Robotics, Blockchain, Industry 4.0

1.Introduction

The Fourth Industrial Revolution, commonly known as Industry 4.0, is defined by the integration of smart technologies, automation, and data exchange across
various sectors of manufacturing and industry. One emerging innovation in this space is AI-powered blockchain technology, which combines artificial intelligence (AI) with block chain systems to enhance their capabilities and functionalities.
Block chain is a decentralized and distributed ledger technology that ensures secure and transparent record-keeping of transactions across a network of computers [1]. Initially developed as the foundation for the cryptocurrency Bitcoin, blockchain technology has since evolved to support a wide range of applications beyond digital currencies [2].
Industrial automation refers to the use of control systems, like computers and robots, along with information technology to manage various industrial processes and machinery, reducing the need for human intervention. Today, robots play a crucial role in manufacturing, working alongside AI technology to make intelligent decisions and enhance productivity in production facilities.
This technology includes a wide ranges of applications, from basic mechanization to advanced robotics and artificial intelligence. Initially, automations in manufacturing began with mechanization, where machines are introduced to support manual tasks. However, modern automation has become far more advanced, incorporating AI and robotics to create systems that can operate independently, continuously learning, and adapting to improve performance. This transformation

DOI: https://doi.org/10.5281/zenodo.18410282

have led to the rise of smart factories, where inter connected machines communicate and collaborate to enhance efficiency and good productivity.

Fig. 2. Main Industry 4.0 technologies [3].

2.Need of artificial intelligence for industry 4.0

The use of artificial intelligence (AI) in manufacturing has significantly improved various aspects of the industry, from workforce planning to product designs. AI helps optimize performance, enhance product quality, and support employee well-being. Advances in AI play a key role in industrial development, enabling robots to handle complex computations and make real-time decisions based-on environmental data, contributing to the progress of Industry 4.0.

Industry 4.0 requires the development of interconnected factories that integrate seamlessly with the supply chain, design teams, production lines, and quality control systems. With the support of AI, these smart factories can generate valuable insights to enhance efficiency. To fully leverage the opportunities of Industry 4.0, manufacturers must adopt a holistic approach that considers entire production process, requiring collaboration across all the supply chain.

Currently, AI, machine learning (ML), and the Internet of Things (IoT) are primarily applied in asset management, supply chain optimization, and resource allocation. By integrating these technologies, manufacturers can improve asset tracking accuracy, enhance supply chain visibility, and optimize stock utilization. Machine learning techniques, such as predictive algorithms and AI-driven processes, contribute to better predictive maintenance and quality control [5].

Additionally, AI enables real-time monitoring of operational loads on the factory floor, improving production planning. When combinedwithoverall equipment effectiveness, machine learning can help manufacturers enhance productivity, implement preventive maintenance, and optimize asset utilization.

3.The Role of AI in Manufacturing

AI refers to ability of machines to exhibit human-like intelligence, enabling them to solve a wide range of

problems. In the production supply chains, AI technology can predict product demand by analyzing temporal, geographical, and the socio-economic factors using various algorithm. These predictions take into account macroeconomic trends and weather patterns to optimize supply chain efficiency.

AI plays vital role in transforming manufacturing through its applications in industrial automation. According to the World Economic Forum, the global AI market in manufacturing was valued at $3.2 billion in 2023 and is expected to grow to $20.8 billion by 2028. [6]

Machine learning and computer vision technologies enable robots and automation systems to perceive their surroundings, make informed decisions, and learn from experience. One key application is predictive maintenance, where AI analyzes sensor data to monitor equipment conditions and anticipate potential failures. This reduces downtime and extends machinery lifespan. AI also addresses several industry challenges, including skill shortages, complex decision-making, deployment difficulties, and knowledge management. By integrating AI into production plants, companies can transform their operational processes.

AI provides companies with advanced analytical capabilities to evaluate the performance of individual components, improving overall facility efficiency and product quality. Intelligent systems equipped with AI can detect abnormalities, track key parameters, and process large volumes of data. This data is then analyzed and shared across cloud-based networks for further optimization. Beyond manufacturing, AI is also used in the

DOI: https://doi.org/10.5281/zenodo.18410282

entertainment industry, where it helps content providers analyze user behavior and recommend shows tailored to individual preferences.

AI-driven quality control utilizes computer vision for real-time product inspection, ensures higher quality standards and reducing waste. Additionally, AI enhances supply chain management by analyzing large datasets to optimize inventory control and logistics, leading to cost savings and improved resource utilization. Machine learning further contributes by identifying inefficiencies in production processes, fostering continuous improvement and boosting productivity.

Enhancing Productivity and Precision

The integrations of advanced robotics and AI in manufacturing significantly improves both productivity and precision. Robots operate continuously without breaks, performing tasks with consistent accuracy and efficiency. This minimizes errors and increases overall manufacturing output.

Furthermore, AI enables real-time monitoring and control of production process. By analyzing data from sensors and machinery, AI systems can detect anomalies and make immediate adjustments to maintain optimal performance. This real-time feedback loop hence enhances operational efficiency while reducing material waste, ultimately improving manufacturing effectiveness.

Reducing Labor Costs

A key benefit to industrial automation and robotics is the reduction in labor costs. By automating repetitive and labor-intensive tasks, manufacturers can lessen their dependence on human labor, resulting in significant cost savings.

However, the move towards automation does not automatically lead to job losses. While some low-skilled jobs may be replaced, automation also creates new opportunities for higher-skilled roles. Workers are needed to design, program, and maintain automated systems, leading to the creation of new career paths within the manufacturing sector.

Impact on Quality and Competitiveness

The integration of IoT, AI, and the advanced robotics in manufacturing not only improves efficiency but significantly enhances product quality and competitiveness. With high real-time data collection and analysis, manufacturers can achieve higher quality control standards, reduce defects, and ensure consistency. AI-powered systems can predict also address potential issues before they occur, helping maintain high-quality levels throughout production.

Additionally, the ability to quickly adapt to market changes and customer demands through flexible and automated manufacturing processes allows companies to be competitive in a fast-changing market. These technological advancements help manufacturers produce superior products more quickly, providing a strong competitive advantage.

The future of manufacturing is closely linked to the continued development of industrial automation and robotics. As technology progresses, we can expect more advanced robots and AI systems capable of performing a wider variety of tasks.

The integration of IoT, 5G, and the blockchain into manufacturing is transforming the industry by improving connectivity, data exchange, and the operational flexibility. These technologies allow for real-time monitoring and control of manufacturing processes, leading to high significant gains in efficiency, quality, and flexibility.

Additionally, the quick return on investment (ROI) that companies are seeing demonstrates the transformative potential of these innovations. By optimizing operations and reducing downtime, manufacturers can also achieve significant cost savings and strengthen their competitive position. As these technologies continues to develop, they are likely to improve the capabilities and profitability of manufacturing businesses.

AI algorithms assist businesses in forecasting market fluctuations, enabling them to optimize production supply chains. This shift provides management with significant advantages, moving from a reactionary approach to a more proactive competitive stance. AI algorithm analyze market demand by identifying trends in positioning, socio-economic and also macroeconomic factors, environmental patterns, regulatory policies, customer behavior, and other variables.

This advancement enables manufacturers to reduce production downtime, and improve the overall operational efficiency of manufacturing lines. Moreover, the application of AI and machine learning enhances quality control and standardization by generating predictive analyses of equipment performance, ultimately streamlining production processes.

DOI: https://doi.org/10.5281/zenodo.18410282

With AI integration, industries can make swift, data-driven decisions, simplify production workflows, reduce operational costs, and also improve customer service.

With an AI-enabled smart plant, manufacturing processes can operate more efficiently, reduce costs, and enhance customer service. Industries can minimize downtimes by predicting delays, manage inventory through stock tracking, forecast delivery times, and ensure the production of high-quality products. To monitor the production process and detect errors, such as microscopic cracks in manufacturing facilities, computer vision technology can be utilized. AI can also alert companies to potential issues on the production line that may lead to quality problems, allowing serious issues to be addressed early in the development of Industry 4.0 [7]

Manufacturing industries utilize this technology to create a virtual representation that mirrors the factory, product, or physical attributes. By employing cameras, sensors, and other data collection methods, it provides real-time insights. The integration of interactive and physical environments allows for plant monitoring, data analysis, and proactive issue resolution. The defect detection process in production lines has become more advanced. Computerized systems, equipped with deep neural network integrations, can identify surface defects such as scratches, cracks, and leaks. Data scientists train visual inspection systems to recognize these defects using image recognition, object identification, and instance segmentation algorithms

4.Major benefits/utilities of Robotics in Revolutionary manufacturing

Automation is becoming increasingly reliable compared to human workers. Robots are precisely designed to ensure consistent output and services without human error. The use of robots in industry has been established for several decades.

Although initial investment in industrial robots appear to be high, they typically provide a quick return on investment by lowering labor costs and reducing production times. Over the long term, the costs associated with operating and maintaining robots are usually lower than those of employing a human to perform the same tasks.

Industrial robots can carry out multiple functions simultaneously, allowing facility managers to make better use of floor space. Substituting large multi-core computing systems with existing programmable logic controllers (PLCs), efficiency can be enhanced. Major food companies have integrated robots into their processing facilities, where these machines undertake various task using vision technology, cameras, and artificial intelligence. They can perform cutting, measuring, packing, and also palletizing operations.

Industries equipped with numerous sensors can monitor machines and manufacturing processes in real-time to avoid defects in output services. Machine vision robots are capable of executing complex optical tasks with high precision, allowing for the immediate detection and correction of microscopic structural defects or slight color differences, thus maintaining quality performance [8][9].

The automobile industry has been a significant driver of industrial robotics, as it uses the majority of the robots in operation today. One of the most common robotic tasks in car manufacturing is body welding, where two metal pieces are fused together at a single point. This is achieved by transmitting a high electrical current and low voltage between two opposite electrodes, with the parts to be connected placed in between [10],

In addition to welding, robots are used for tasks such as screwing, assembly, marking, manipulation, and quality control within the automotive industry. While automation changes the nature of work, it also created significant profit opportunities in manufacturing. Collaborative robots, a widely used form of automation, are becoming more flexible as their technology matures, enabling them to take on more innovative tasks.

Industrial robotics plays a key role in helping various manufacturing sector increase efficiency and improve product quality by automating production processes.

4.1 Internet of robotic things (IoRT)

The integration of IoT with manufacturing robotics is known as the Internet of Robotic Things (IoRT). This integration enables robots to track their surroundings, merge sensor data, utilize both local and distributed information to determine actions, and it interact with

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physical objects in real time. Through IoT, robots can function autonomously by collecting data from their sensors, storing it, or transmitting live data as needed [11].

The convergence of robotics and IoT is driven by interconnected objectives. While IoT emphasizes ubiquitous sensing, control, and data recording, robotics focuses on development, interaction, and autonomous functionality. Combining these technologies into an Internet of Robotic Things provides significant advantages.

Continuous advancement in robotics technology are making these systems more accessible and cost-effective.

4.2 Cobots

Collaborative robots, or cobots, are designed to interact with human, enhancing human capabilities in a safe and efficient manner. These human-robot partnerships allow humans to direct robots, control processes, or even learn from them. In contrasts, traditional robotic systems do not involve human-robot collaboration typically operate independently within enclosed spaces. Such systems may be programmed to stop when a person enters their working area, leading to delays in operations. These interruptions can be avoided by using cobots, which are specifically designed for safe human interaction.

In a fully automated facility without human presence, a cobot would require less supervision compared to one operating alongside humans. However, cobots in safety-critical environments need advanced signaling, high bandwidth, low latency, and also rapid decision-making capabilities supported by powerful computational systems.

The integration of cobots across various industries is progressing rapidly. Improvements in response time, movement precision, alignment accuracy, and human-like interaction are driving advancements in cobot technology. Additionally, brain-computer interfaces have seen significant developments in recent years. With the ability to accurately interpret brain signals and transmit them to robots, future cobots may be able to collaborate with humans in entirely new ways.

Cobotics is a key innovation in intelligent manufacturing, enhancing competitiveness and efficiency in global production market. Unlike traditional robots, cobots are lightweighted and easy to configure. Their primary function is to collaborate with humans, improving automation in a stable and cost-effective manner[12].

Cobots are widely used across various industries, including life sciences, automotive, engineering, electronics, aerospace, packaging, chemicals, and also healthcare. Their ability to integrate human labor with automation provides businesses with a competitive advantage. Additionally, cobots are user-friendly, reliable, safe, and precise. Compared to conventional robots, they are also more affordable while delivering consistent performance.

By automating repetitive tasks, cobots allow human workforce to focus on more complex, high-priority activities, ultimately enhancing productivity and efficiency in industrial settings

5.Benefits and challenges of blockchain integration in manufacturing

The integration of AI-powered block chain technology in Industry 4.0 offers numerous opportunities but also presents several challenges[13]. One major issue is achieving both decentralization and scalability simultaneously. While blockchain is inherently decentralized, ensuring high scalability without compromising this decentralization remains a persistent challenge [14].

Although blockchain guarantees data immutability and transparency, it also raises privacy concerns. Finding a balance between data security and the transparency inherent in block chain is a significant challenge [15][16].

Additionally, integrating block chain and AI systems with existing technological standards can be complex. Ensuring interoperability between various systems is crucial for seamless data exchange and collaboration, despite the difficulties involved [17].

The regulatory landscape for AI and block chain continues to evolve, requiring companies to navigate legal frameworks and ensure compliance while also leveraging the benefits of these technologies [18]. Furthermore, the energy consumptions of block chain consensus mechanisms has raised environmental concerns. Balancing the computational demands of AI and blockchain with energy efficiency remains an ongoing challenge [19].

A fundamental aspect of block chain technology is the use of smart contracts, which must be both reliable and secure. Ensuring the

DOI: https://doi.org/10.5281/zenodo.18410282

accuracy of smart contracts, especially those incorporating AI algorithms, is a complex task that requires rigorous auditing [20].

The successful implementations of AI-powered block chain solutions demands specialized expertise, which may not be widely available. Addressing the skills gap and training professionals in both AI and blockchain technologies remains an ongoing challenge.

Additionally, the integration of AI with blockchain raises ethical concerns, including biases in AI algorithms and the implications of decentralized autonomous organizations. Balancing technological advancements with ethical considerations is essential for the responsible deployment of AI-powered blockchain technology in Industry 4.0 [21]

5.1 Smart Contracts

Smart contracts are self-executing agreement with terms embedded directly into code, enabling automation in manufacturing, supply chain, and various industries [**22**]. This automation minimizes reliance on intermediaries, streamlining operations and also reducing costs. AI enhance smart contract by making them more adaptive and intelligent, allowing for real-time adjustments based on incoming data. By integrating AI, these contracts can execute automatically when predefined conditions are met, further optimizing business processes and reducing manual intervention [23]

5.2 Supply Chain Management

The integration of AI and blockchain in supply chain management enhances transparency, efficiency, and also security. AI can process the vast amount of data recorded on the block chain, providing insights into supply chain operations). This enables businesses to detect inefficiencies, prevent fraud, and optimize logistics [24]. AI techniques, such as image recognition, can verify product authenticity by analyzing features like packaging, labels, and also serial numbers. Machine learning algorithms optimize supply chain routes, scheduling, and inventory management by analyzing real-time data and making informed decisions. These models can also be deployed at different points in the supply chain to support localized decision-making [25]. Additionally, machine learning analyze historical data, including customer behaviour, market trends, and equally external factors, to accurately predict future demand.

5.3 Predictive Maintenance

Predictive maintenance leverages data, machine learning, and equally artificial intelligence (AI) to anticipate equipment or machinery failures, enabling timely maintenance interventions. AI algorithms analyze sensor data collected from machinery and equipment, securely storing this information on the blockchain. Predictive maintenance models utilize this data to forecast potential failures, facilitating proactive maintenance, minimizing downtime, and improving operational efficiency. Through machine learning, AI can detect patterns and anomalies in sensor data, providing accurate failure predictions [26]. This proactive approach reduces maintenance costs and operational disruptions compared to reactive strategies. Implementing predictive maintenance in AI-powered block chain technology within Industry 4.0 offers significant benefits, enhancing reliability and efficiency.

5.4 Quality Control

Blockchain enhances data integrity by offering a tamper-resistant and transparent ledger, ensuring that quality-related data remains unaltered. AI algorithms can process and analyze data from sensors and IoT devices in manufacturing process to identify product defects. When integrated with blockchain, this data is secured, maintaining both its integrity and immutability. This combination is particularly beneficial in industries where maintaining high-quality standards is essential. Moreover, integrating predictive maintenance data with block chain creates a secure and transparent record of equipment history, maintenance activities, and also performance metrics. This ensures an immutable record of product quality throughout the production process. For Industry 4.0, quality control in AI-powered blockchain systems is vital to maintain the reliability, security, and efficiency of operations

5.5 Decentralized Decision-Making

In Industry 4.0, decentralized decision-making leverages AI and blockchain technologies to automate and enhance decision-making processes without relying on centralized

DOI: https://doi.org/10.5281/zenodo.18410282

authorities. By combining AI with blockchain, decentralized autonomous organizations (DAOs) can be created, where decisions are also made through smart contracts and AI-driven algorithms. This integration streamlines decision-making and minimizes the need for centralized control in specific business operations [27]

5.6 Data Security and Privacy through Immutable Records

Block chain offers a decentralized and tamper-proof ledger, improving data security and trust. When integrated with AI-powered block chain technology, immutable records further strengthen data security and privacy within Industry 4.0. The immutability of blockchain ensures, once data is recorded, it cannot be changed, providing a secure foundation for data. Its cryptographic capabilities enhance the security of data exchanges between different entities within the supply chain, which is essential for safeguarding sensitive information [28]. AI can complement these efforts by bolstering cybersecurity measures, offering a robust defense against cyber threats. Additionally, AI algorithms can analyze shared data for valuable insights while preserving its security [29]. Machine learning algorithms, in particular, benefits from secure and reliable data sources, making blockchain an ideal platforms for storing and sharing data in Industry 4.0 applications.

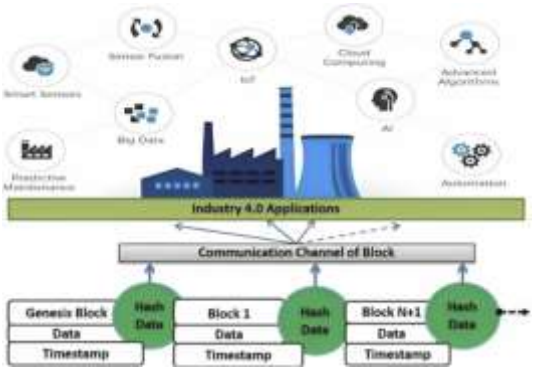

Fig. 1. Blockchain-based security approach in industry 4.0 [30]

5.7 Energy Trading

Energy trading within the framework of AI-powered Block chain Technology in Industry 4.0 leverages advanced technologies that enhances the efficiency, transparency, and also decentralization of energy transactions. Industry 4.0, which represents the fourth industrial revolution, involves the integration of smart technologies, automation, and also data exchange across various sectors, including energy [31]. In the realm of smart grids and energy trading, AI and blockchain can collaborate to optimize energy use, support peer-to-peer energy trading, ensure secure and transparent transactions among connected devices. In energy-intensive industry, AI algorithms can analyze patterns in energy consumptions. Blockchain technology can provide a transparent and auditable record of energy transactions while promoting energy-efficient practices through incentivization [32].

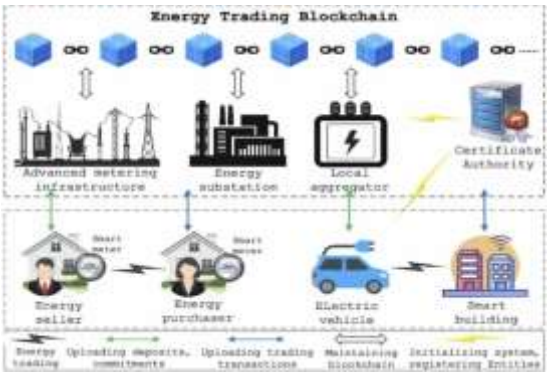

Fig. 2. Blockchain-Enabled Secure Energy Trading With Verifiable Fairness in Industrial Internet of Things [33**].**

5.8 Product Lifecycle Management

Product Lifecycle Management (PLM) for AI-powered Blockchain Technology in Industry 4.0 integrates advanced technologies by improving the development, deployment, and also management of products throughout their entire lifecycle [34]. Blockchain's immutability provides a secure, tamper-proof record of the products lifecycle. AI can utilize the data for predictive maintenance, quality enhancements, and overall lifecycle optimization.

5.9 Conceptualization and Design

AI Integration for Design Optimization: Deploy AI algorithms to optimize products design by analyzing historical data, customer feedback, and also market trends. Block chain for Intellectual Property Protection: Use block chain to time-stamp and secure intellectual property rights, ensuring traceability and preventing unauthorized use [35].

DOI: https://doi.org/10.5281/zenodo.18410282

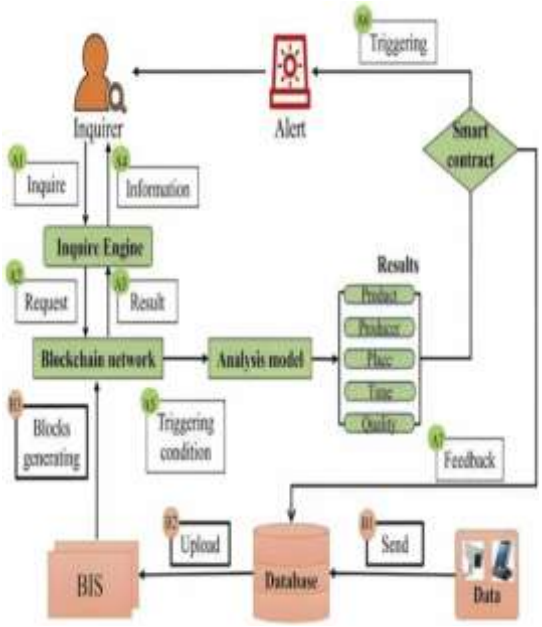

Fig. 3. Blockchain-enabled product lifecycle management [33].

6.Significant Advancements in Industry 4.0 Through Artificial Intelligence

The successful introduction of autonomous vehicles and robots highlights the effective integration of AI and machine learning (ML). The use of sensors in conjunction with ML allows for continuous evaluation during each phase of development. One of the industry's common challenges is aligning supply with demand, and ML integration helps address this by optimizing energy requirement. AI technologies are also employed to enhance user service; for instance, AI-driven chatbots on e-commerce sites are designed to answer common consumer queries instantly. The agricultural sector has seen a rise in the use of advanced tractors and smart harvesting machines. In the financial sector, AI plays a crucial role in fraud detection [15]

AI is also integral to the operation of self-driving or semi-autonomous vehicles. These vehicles, connected to networks, can operate under varying road conditions. AI systems in these vehicles predict driver actions, classify passengers, assess road conditions, and monitor traffic to optimize driving performance. Autonomous vehicles are poised to be a key innovation in the automotive industry. While AI-powered self-driving vehicles are still in the research and testing phase in many countries, they hold the potential to also replace manual driving and improve road safety. AI's role in the immobilizing sector offers valuable resources for agents, brokers, and customers. AI-powered platforms assist dealers and agents in finding the right solutions for customers interested in purchasing or selling assets.

Industrial companies are investing in automated AI vehicles to streamline logistics and manage delivery centers, thereby reducing reliance on human drivers. Additionally, AI systems equipped with predictive analytics can effectively forecast products demand.

AI applications in manufacturing collects data from various sources and use it to accurately forecast products demand based on the available evidence. These AI systems can manage order records and facilitate the installation or uninstallation of stock. It stands out as one of the most effective technologies for production management, market management, and also inventory management. By analyzing historical product price data, machine learning algorithm predict product pricing. These algorithms can employ neural networks and deep modeling techniques to recognize images and oversee predictive model learning.

AI also aids robots in detecting tiny air bubbles and determining the location of gas leaks. It efficiently identifies problem areas and production line, significantly reducing labor costs and detection errors, while gathering data from the entire production chains. In the Industry 4.0 environment, sensors integrated into each hardware component enable machine-to-machine communication. Furthermore, machine learning, supported by data-physical systems and cloud computing, ensures seamless connectivity between humans, machines, and resources. As a result, all elements in the production processes, including vehicles, manufacturing lines, factories, and facilities, can closely be interconnected.

References

[1] Schönle, D., Wallis, K., Stodt, J., Reich, C., Welte, D., Sikora, A., Industry use cases on blockchain technology, in: Industry Use Cases on Blockchain Technology Applications in IoT and the Financial Sector, IGI Global, 2021, pp. 248–276.

[2] R. Dastres, M. Soori, Artif. Neural Netw.

DOI: https://doi.org/10.5281/zenodo.18410282

Syst., Int. J. Imaging Robot. (IJIR), 21 (2021), pp. 13-25
[3] T.M. Fernandez-Carames, P. Fraga-Lamas , A review on the application of blockchain to the next generation of cybersecure industry 4.0 smart factories Ieee Access, 7 (2019), pp. 45201-45218
[5] Javaid et al., 2021 M. Javaid, A. Haleem, R.P. Singh, S. Khan, R. Suman, Blockchain technology applications for Industry 4.0: a literature-based review
[6] ELGI: Always better, Industry 4.0: Revolutionizing Manufacturing with IoT, AI, and Advanced Robotics . 08 August 2024
[7] Mohd Javaid, Abid Haleem, Ravi Pratap Singh, Rajiv Suman, Substantial capabilities of robotics in enhancing industry 4.0 implementation, Cognitive Robotics, Volume 1, 2021,Pages 58-75,
[8]
E. Erős, M. Dahl, A. Hanna, P.L. Götvall, P. Fa lkman, K. Bengtsson, Development of an industry 4.0 demonstrator using sequence planner and ROS2 Robot Operating System (ROS), Springer, Cham (2021), pp. 3-29
[9]
A.M. Ghouri, V. Mani, Z. Jiao, V.G. Venkatesh , Y. Shi, S.S. Kamble, An empirical study of real-time information-receiving using industry 4.0 technologies in downstream operations. Technol Forecast Soc Change, 165 (2021), Article 120551
[10] T. Brogårdh, Present and future robot control development—an industrial perspective, Ann Rev Control, 31 (1) (2007), pp. 69-79
[11] S. Bag, S. Gupta, S. Kumar, Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development Int. J. Prod. Econ., 231 (2021), Article 107844
[12] P. Francesco, G.G. Paolo, AURA: an example of collaborative robot for automotive and general industry applications. Proc. Manuf., 11 (2017), pp. 338-345
[13] A.K. Tyagi, S. Aswathy, A. Abraham, Integrating blockchain technology and artificial intelligence: Synergies perspectives challenges and research directions. J. Inf. Assur. Secur., 15 (2020), p. 1554
[14] J. Zarrin, H. Wen Phang, L. Babu Saheer, B. Zarrin, Blockchain for decentralization of internet: prospects, trends, and challenges Clust. Comput., 24 (2021), pp. 2841-2866
[15]
J. Leng, S. Ye, M. Zhou, J.L. Zhao, Q. Liu, W. Guo, W. Cao, L. Fu, Blockchain-secured smart manufacturing in industry 4.0: a survey IEEE Trans. Syst., Man, Cybern.: Syst., 51 (2020), pp. 237-252
[16]
A. Aoun, A. Ilinca, M. Ghandour, H. Ibrahim, A review of Industry 4.0 characteristics and challenges, with potential improvements using blockchain technology Comput. Ind. Eng., 162 (2021), Article 107746
[17] M. Al-Rakhami, M. Al-Mashari,Interoperability approaches of blockchain technology for supply chain systems Bus. Process Manag. J., 28 (2022), pp. 1251-1276

[18] P.G.R. de Almeida, C.D. dos Santos, J.S. Farias, Artificial intelligence regulation: a framework for governance. Ethics Inf. Technol., 23 (2021), pp. 505-525,
[19]
J. Li, M.S. Herdem, J. Nathwani, J.Z. Wen, Methods and applications for Artificial Intelligence, Big Data, Internet Things, Block smart Energy Manag., Energy AI, 11 (2023), Article 100208
[20]
B. Gami, M. Agrawal, D.K. Mishra, D. Quasi m, P.S. Mehra, Artificial intelligence-based blockchain solutions for intelligent healthcare: a comprehensive review on privacy preserving techniques. Trans. Emerg. Telecommun. Technol., 34 (2023), Article e4824
[21] N.K. Shinde, A. Seth, P. Kadam, Exploring the synergies: a comprehensive survey of blockchain integration with artificial intelligence, Mach. Learn., IoT Divers. Appl., Mach. Learn. Optim. Eng. Des. (2023), pp. 85-119
[22]A. Shojaeinasab, T. Charter, M. Jalayer, M . Khadivi, O. Ogunfowora, N. Raiyani, M. Yag houbi, H. Najjaran, Intelligent manufacturing execution systems: a systematic review, J. Manuf. Syst., 62 (2022), pp. 503-522
[23] T. Timuçin, S. Biroğul, Collaborative smart contracts (CoSC): example of real estate purchase and sale (s), J. Supercomput. (2023), pp. 1-20
[24]
D. Mehta, S. Tanwar, U. Bodkhe, A. Shukla, N . Kumar, Blockchain-based royalty contract transactions scheme for Industry 4.0 supply-

DOI: https://doi.org/10.5281/zenodo.18410282

chain management, Inf. Process. Manag., 58 (2021), Article 102586
[25]
M.A. Kashem, M. Shamsuddoha, T. Nasir, A. A. Chowdhury, Supply chain disruption versus optimization: a review on artificial intelligence and blockchain Knowledge, 3 (2023), pp. 80-96
[26]
Z. Rahman, I. Khalil, X. Yi, M. Atiquzzaman, Blockchain-based security framework for a critical industry 4.0 cyber-physical system, IEEE Commun. Mag., 59 (2021), pp. 128-134
[27] A. Nuhiu, F. Aliu, The Benefits of Combining AI and Blockchain in Enhancing Decision-Making in Banking Industry. Integrating Blockchain and Artificial Intelligence for Industry 4.0 Innovations, Springer (2023), pp. 305-326
[28] R. Gupta, S. Tanwar, N. Kumar, S. Tyagi, Blockchain-based security attack resilience schemes for autonomous vehicles in industry 4.0: a systematic review, Comput. Electr. Eng., 86 (2020), Article 106717
[29] Adhikari, A., Winslett, M., A hybrid architecture for secure management of manufacturing data in industry 4.0, in: 2019 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), IEEE, 2019, pp. 973–978.
[30] P.F. Borowski, Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector
[30] Rahman, A., Sara, U., Kundu, D., Islam, S., Islam, M.J., Hasan, M., Rahman, Z., Nasir, M.K., Distb-sdoindustry: Enhancing security in industry 4.0 services based on distributed blockchain through software defined networking-iot enabled architecture, arXiv preprint arXiv:2012.10011, (2020).
[31] P.F. Borowski, Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector
[32] S. Otoum, I.Al Ridhawi, H. Mouftah, A federated learning and blockchain-enabled sustainable energy trade at the edge: a framework for industry 4.0, IEEE Internet Things J., 10 (2022), pp. 3018-3026
[33] Z. Li, Z. Tian, L. Wang, R.Y. Zhong, Blockchain-enabled product lifecycle management
in: Design and Operation of Production Networks for Mass Personalization in the Era of Cloud Technology, Elsevier (2022), pp. 349-379
[34] Darwish, D., Blockchain and Artificial Intelligence for Business Transformation Toward Sustainability, in: Blockchain and its Applications in Industry 4.0, Springer, 2023, pp. 211–255.
[35]
M. Barton, R. Budjac, P. Tanuska, G. Gaspar, P . Schreiber, Identification overview of Industry 4.0 essential attributes and resource-limited embedded artificial-intelligence-of-things devices for small and medium-sized enterprises.

DOI: https://doi.org/10.5281/zenodo.18410282