



HAL
open science

AI-Powered Blockchain Technology in Industry 4.0, A Review

Mohsen Soori, Roza Dastres, Behrooz Arezoo

► **To cite this version:**

Mohsen Soori, Roza Dastres, Behrooz Arezoo. AI-Powered Blockchain Technology in Industry 4.0, A Review. Journal of Economy and Technology, 2024, 10.1016/j.ject.2024.01.001 . hal-04450244

HAL Id: hal-04450244

<https://hal.science/hal-04450244>

Submitted on 10 Feb 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



AI-powered blockchain technology in industry 4.0, a review

Mohsen Soori^{a,*}, Roza Dastres^b, Behrooz Arezoo^c

^a Department of Aeronautical Engineering, University of Kyrenia, Via Mersin 10, Kyrenia, North Cyprus, Turkey

^b Department of Computer Engineering, Cyprus International University, Via Mersin 10, North Cyprus, Turkey

^c CAD/CAPP/CAM Research Center, Department of Mechanical Engineering, Amirkabir University of Technology (Tehran Polytechnic), 424 Hafez Avenue, Tehran 15875–4413, Iran



ARTICLE INFO

Keywords:

Artificial Intelligence
Blockchain
AI-Powered Blockchain
Industry 4.0

ABSTRACT

Artificial Intelligence (AI) algorithms can be employed to enhance the security of the blockchain networks in the era of industry 4.0. Smart contracts, powered by blockchain, can be developed by using the AI capabilities. These contracts can execute themselves based on predefined conditions, automating various processes and reducing the need for intermediaries. Blockchain provides a transparent and immutable ledger for supply chain transactions. AI can be integrated to analyze this data, providing insights into the entire supply chain. This helps in tracking and tracing products, ensuring authenticity, and optimizing the supply chain based on data-driven decisions. AI algorithms can be employed to analyze data from the manufacturing process recorded on the blockchain. This allows for predictive maintenance and quality control, helping to identify and address issues before they result in defects or downtime. AI and blockchain can work together to secure the massive amount of data generated by IoT devices in an Industry 4.0 setting. Blockchain ensures the integrity and immutability of IoT data, while AI can analyze this data for insights and optimization. AI and blockchain can facilitate the creation of decentralized energy grids where AI algorithms optimize energy distribution and blockchain ensures transparent and secure energy trading through smart contracts. AI and blockchain can support decentralized and collaborative manufacturing networks where different entities can securely and efficiently collaborate on production processes. Blockchain enables individuals or organizations to securely monetize their data. AI can help analyze and determine the value of data, ensuring fair compensation in tokenized ecosystems. In this paper, applications of AI-Powered Blockchain Technology in Industry 4.0 is reviewed and discussed and future research works are also suggested. As a result, efficiency, transparency, and security across various industrial processes can be enhanced by analyzing the recent achievements in AI-Powered Blockchain Technology in Industry 4.0.

1. Introduction

The fourth industrial revolution, often referred to as Industry 4.0, is characterized by the integration of digital technologies into various aspects of manufacturing and industry. Industry 4.0 refers to the fourth industrial revolution, characterized by the integration of smart technologies, automation, and data exchange in various industries. AI-powered blockchain technology refers to the integration of artificial intelligence (AI) with blockchain systems to enhance the capabilities and functionalities of both technologies. Blockchain is a decentralized and distributed ledger technology that enables secure and transparent record-keeping of transactions

* Corresponding author.

E-mail addresses: Mohsen.soori@gmail.com, Mohsen.soori@kyrenia.edu.tr (M. Soori).

across a network of computers (Schönle et al., 2021). Blockchain is a decentralized and distributed ledger technology that enables secure and transparent record-keeping of transactions across a network of computers. It was originally designed as the underlying technology for the cryptocurrency Bitcoin, but its applications have expanded beyond digital currencies (da Rosa Righi et al., 2020). Industries such as finance, supply chain, healthcare, and more are exploring its potential to improve efficiency, reduce fraud, and enhance transparency in various processes. The processing of blockchain is shown in the Fig. 1 (Tyagi et al., 2023).

AI, on the other hand, involves the development of intelligent machines that can perform tasks that typically require human intelligence. Both AI and blockchain are cutting-edge technologies that, when combined, can offer innovative solutions to various challenges in different industries (Bodkhe et al., 2020).

AI-powered blockchain technology plays a significant role in the context of Industry 4.0, which refers to the fourth industrial revolution characterized by the integration of smart technologies, automation, and data exchange in manufacturing and other industries (Javaid et al., 2021). The combination of AI and blockchain offers several advantages, enhancing the efficiency, security, and transparency of various processes (Shrivastava et al., 2023). It enables new business models, enhances automation, and fosters innovation in how industries operate and collaborate (Fernandez-Carames and Fraga-Lamas, 2019).

AI algorithms can predict when machinery is likely to fail, enabling proactive maintenance. This information can be recorded on a blockchain, ensuring that the maintenance history is immutable (Zaman et al., 2023). This can lead to increased equipment reliability and reduced downtime (Rajmohan et al., 2020). Combining AI and blockchain in supply chain management can provide a transparent and traceable system. AI algorithms can analyze data from the supply chain, and this information can be stored securely on a blockchain. This ensures that every step in the supply chain is recorded, providing a tamper-proof and transparent history (Patil et al., 2023). Smart contracts, self-executing contracts with the terms of the agreement directly written into code, can be enhanced with AI. AI algorithms can help in the automatic execution of complex conditions, making transactions more efficient and reducing the need for intermediaries (Chauhan et al., 2023). AI and blockchain technologies can be integrated to improve interoperability between different systems and platforms (Narayan et al., 2022). This can facilitate seamless data exchange and collaboration across various components of Industry 4.0. Main Industry 4.0 technologies is shown in the Fig. 2 (Fernandez-Carames and Fraga-Lamas, 2019).

Main benefits (green lines) and challenges (red lines) for blockchain-based Industry 4.0 applications is shown in the Fig. 3 (Fernandez-Carames and Fraga-Lamas, 2019).

Several ways in which AI and blockchain intersect and contribute to the advancements in Industry 4.0 are discussed in the study in order to enhance the performances of Industry 4.0 using AI-Powered Blockchain Technology (Mhlanga, 2023).

The integration of AI-powered blockchain technology in Industry 4.0 presents various opportunities but also raises a number of problems and challenges (Tyagi et al., 2020). It is difficult to achieve decentralization and scalability at the same time. The decentralized aspect of blockchain technology is well understood, but getting great scalability without sacrificing decentralization is a

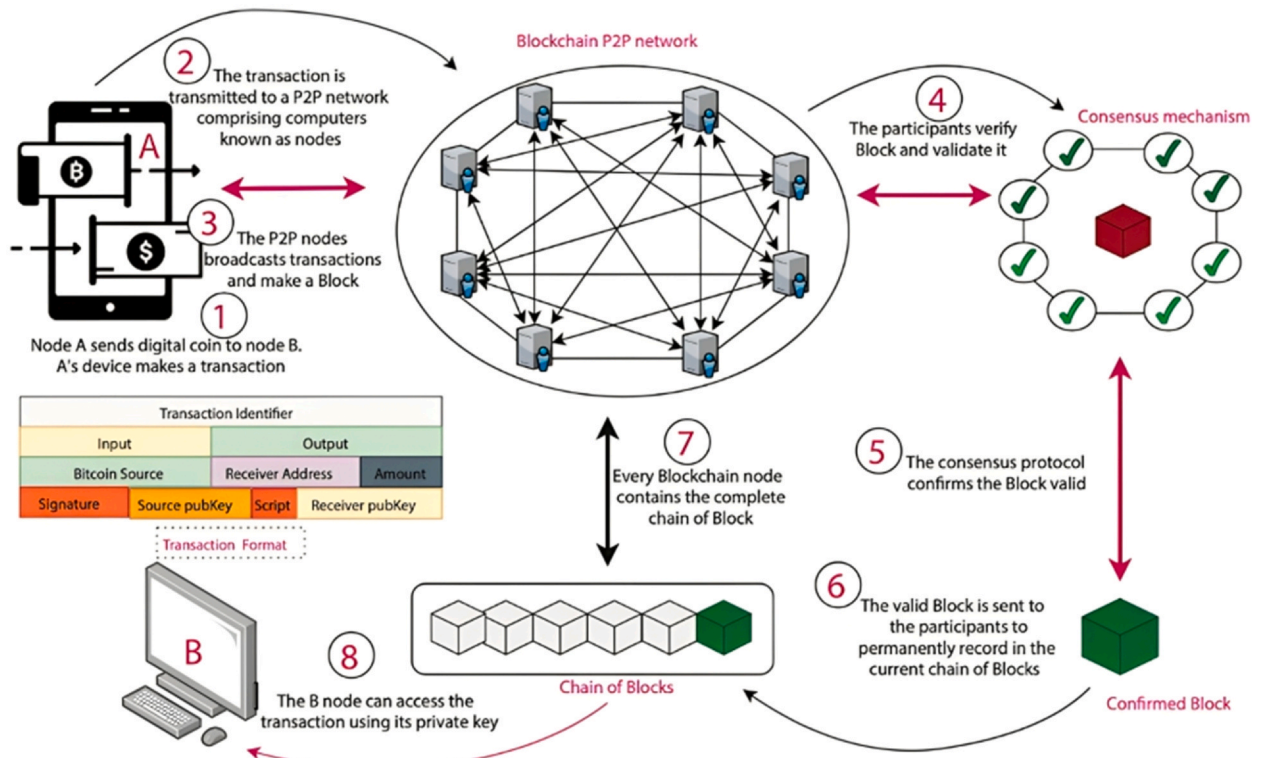


Fig. 1. The processing of blockchain (Tyagi et al., 2023).

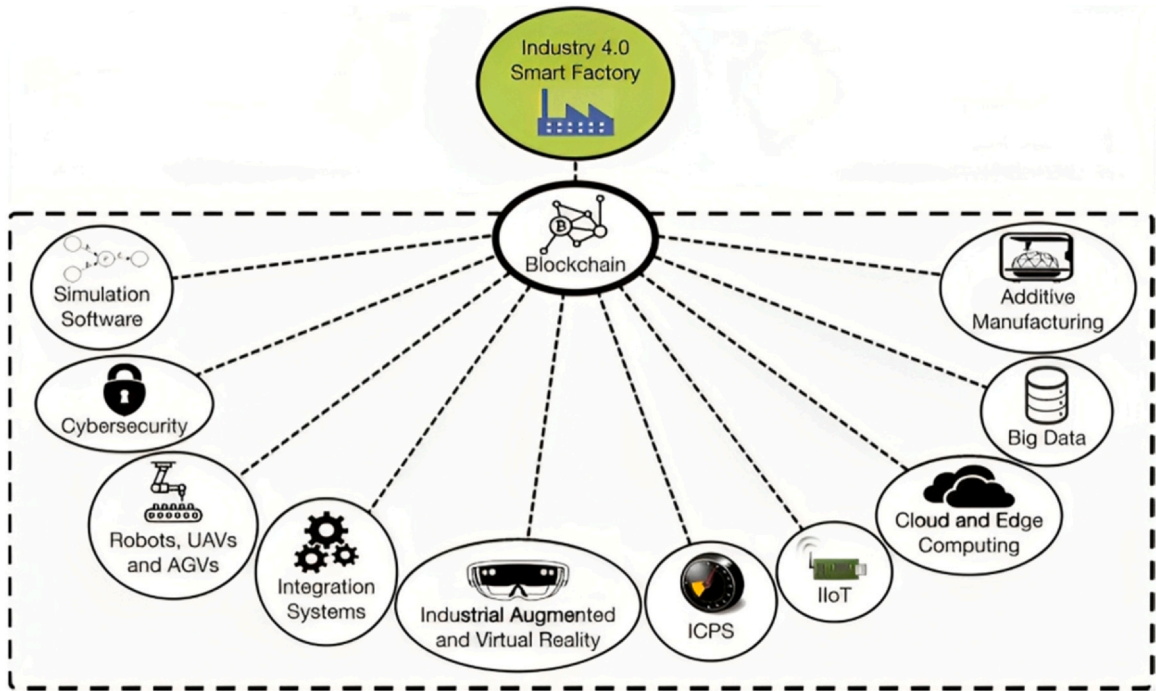


Fig. 2. Main Industry 4.0 technologies (Fernandez-Carames and Fraga-Lamas, 2019).

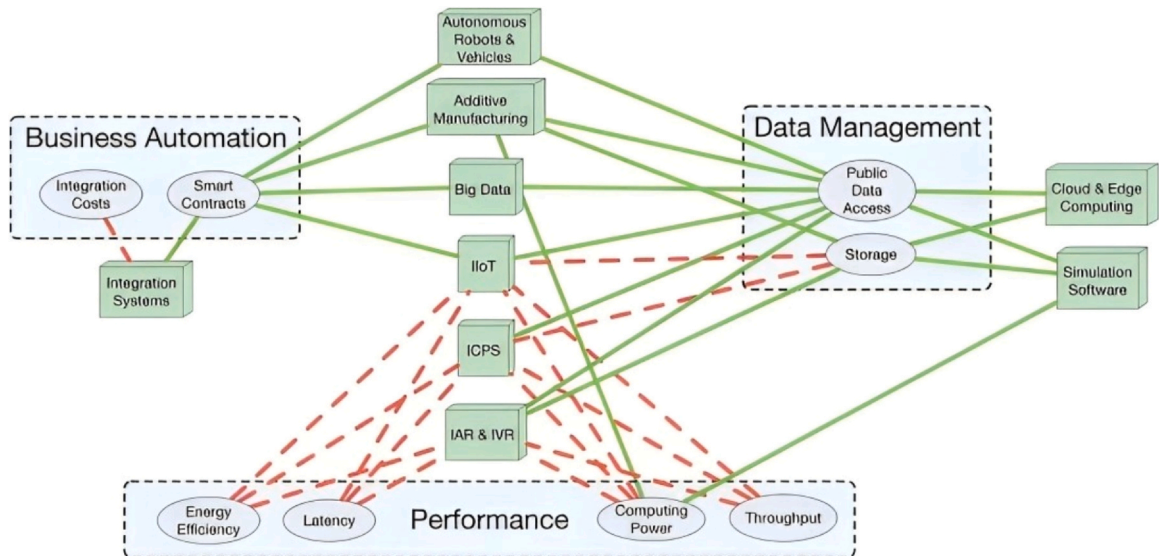


Fig. 3. Main benefits (green lines) and challenges (red lines) for blockchain-based Industry 4.0 applications (Fernandez-Carames and Fraga-Lamas, 2019).

persistent problem (Zarrin et al., 2021). While blockchain ensures data immutability and transparency, there is a conflict with privacy concerns (Leng et al., 2020). Balancing the need for data security and privacy with the transparency inherent in blockchain poses a significant challenge (Aoun et al., 2021). It can prove challenging to integrate blockchain and AI systems with current standards and technology. Although it is a difficult process, achieving interoperability between many systems is essential for smooth data interchange and cooperation (Al-Rakhami and Al-Mashari, 2022). The evolving regulatory landscape for both AI and blockchain technologies poses challenges as companies need to navigate through various legal frameworks and comply with regulations while leveraging the benefits of these technologies (de Almeida et al., 2021). The energy consumption associated with blockchain consensus mechanisms has raised environmental concerns. Balancing the energy efficiency of AI and blockchain systems with their computational requirements is a challenge (Li et al., 2023). A crucial component of blockchain technology is smart contracts which should be trustworthy and safe. Assuring the accuracy of smart contracts, particularly those that use AI algorithms, is a challenging undertaking that needs meticulous auditing (Gami et al., 2023). The implementation

of AI-powered blockchain solutions requires a specific skill set that may not be readily available. Bridging the skill gap and educating professionals in both AI and blockchain technologies is an ongoing challenge (Bellagarda and Abu-Mahfouz, 2022). The use of AI in conjunction with blockchain raises ethical concerns, such as bias in AI algorithms and the ethical implications of decentralized autonomous organizations. Striking a balance between innovation and ethical considerations is challenging in order to implement the AI AI-Powered blockchain technology in industry 4.0 (Shinde et al., 2023).

Meta-heuristic algorithms for assessing the collapse risk of steel moment frame mid-rise buildings is presented by Karimi Ghaleh Jough and Şensoy (Jough and Şensoy, 2016) in order to provide a modified approach to risk management in steel moment frames. Steel Moment-Resisting Frame Dependability via Interval Analysis using the FCM-PSO Method is studied by Karimi Ghaleh Jough and Şensoy (Karimi Ghaleh Jough and Şensoy, 2020) to enhance accuracy and decrease execution time in calculation of seismic fragility curves. Evaluation of non-structural masonry walls' out-of-plane behavior with FE simulations is presented by Karimi Ghaleh Jough and Golhashem (Karimi Ghaleh Jough and Golhashem, 2020) in order to minimize self-weight axial compression of the walls using contemporary lightweight masonry modules. Karimi Ghaleh Jough and Beheshti Aval (Karimi Ghaleh Jough and Beheshti Aval, 2018) implemented an Fuzzy C-means algorithm-based system for adaptive neuro-fuzzy inference to develop a seismic fragility curve for an SMRF structure, thereby incorporating epistemic uncertainty and improving calculation accuracy. Ghasemzadeh et al. (Ghasemzadeh et al., 2022) provided a framework for identifying and contextualizing infrastructure project variables in order to highlight and demonstrate the current deficiency in BIM adoption for infrastructure projects. Treating Epistemic Uncertainty in Seismic Collapse via a group data handling algorithm method In comparison to the aforementioned approaches, Karimi Ghaleh Jough et al. (Karimi Ghaleh Jough et al., 2021) introduced fragility, which increases power and output accuracy and precision while maintaining the same computing time. Karimi Ghaleh Jough and Ghasemzadeh (Karimi Ghaleh Jough and Ghasemzadeh, 2023) provide a method called Unpredictability Steel Moment Frame Interval Analysis via 3D Fragility Curve Construction, which tries to drive 3D-fragility curves with more accuracy and in less time. Karimi Ghaleh Jough (Karimi Ghaleh Jough, 2023) examines the role of steel wallposts in the out-of-plane behavior of non-structural masonry walls in order to give reduced modification factors in masonry walls with wallposts.

Soori et al (Soori et al., 2017, 2014, 2013, 2016; Soori and Arezoo, 2023a). proposed virtual machining methods for improving and assessing CNC machining in virtual settings. Soori et al (Soori et al., 2023a). investigated the use of artificial intelligence and machine learning to CNC machine tools in order to increase efficiency and profitability in component production processes. In order to enhance the functionality of machined parts, Soori and Arezoo (Soori and Arezoo, 2022a) examined the subject of residual stress measurement and reduction in machining operations. In order to analyze and enhance performances of virtual machining systems in CNC machining operations, recent achievements from the published papers are reviewed by Soori and Arezoo (Soori and Arezoo, 2020). To analyze and minimize deflection errors in five axis CNC milling operations of impeller blades, applications of virtual machining systems is developed by Soori and Asmael (Soori and Asmael, 2021).

To enhance the integrity of the surface and reduce residual stress while grinding Inconel 718, Soori and Arezoo (Soori and Arezoo, 2022b) recommended employing the Taguchi optimization approach to determine the ideal machining settings. Dastres and Soori (Dastres and Soori, 2021a) examined how to utilize advancements in web-based decision support systems to provide solutions for data warehouse administration through support for decision-making. Dastres and Soori (Dastres and Soori, 2021a) examined uses of artificial neural networks to investigate methods to implement them to increase the efficacy of products. Dastres and Soori (Dastres and Soori, 2021b) suggested using communication systems in environmental issues to reduce the detrimental impacts of technology development on natural disasters.

Dimensional, geometrical, tool deflection, and thermal defects have been modified by Soori and Arezoo (Soori and Arezoo, 2023a) to improve accuracy in 5-axis CNC milling processes. Recent developments in published articles are examined by Soori et al (Soori et al., 2023a). in order to evaluate and enhance deep learning, machine learning, and artificial intelligence's effects on advanced robots. Soori and Arezoo (Soori and Arezoo, 2023b) created a virtual machining system application to investigate if the tool life and cutting temperature throughout milling operations are influenced by the cutting parameters. Soori and Arezoo (Soori and Arezoo, 2023a) investigated how coolant affected the cutting temperature, surface roughness, and tool wear when turning Ti6Al4V alloy. Soori et al (Soori et al., 2023b). studied how to improve quality control and streamline part production operations in industry 4.0 smart factories by utilizing the Internet of Things. To reduce the amount of wear on cutting tools while drilling, Soori and Arezoo (Soori and Arezoo, 2023a) proposed a virtual machining system. Soori and Arezoo (Soori and Arezoo, 2023b) reduced surface roughness and residual stress to raise the overall quality of products made with abrasive water jet cutting. In order to improve the precision of five-axis milling operations for turbine blades, Soori (Soori, 2023) calculates and compensates for deformation errors. Soori and Arezoo (Soori and Arezoo, 2023c) studied the application of the finite element approach in CNC machine tool modification in order to assess and improve accuracy in CNC machining processes and components. Soori et al (Soori et al., 2023a). studied several energy use optimization techniques in order to assess and optimize energy consumption in industrial robots. Soori et al (Soori et al., 2023b). examined the negative and positive aspects of virtual manufacturing systems in order to assess and improve the part production process in Industry 4.0. In order to develop the supply chain management in advanced manufacturing, artificial neural networks are studied by Soori et al (Soori et al., 2023c).

Applications of AI-Powered blockchain technology in industry 4.0 are reviewed and addressed in this article, and recommendations for further study are also made. A review study on AI-Powered Blockchain Technology applications in Industry 4.0 is conducted by reviewing and evaluating books, conference papers, and scholarly publications. The paper surveys the current state-of-the-art applications, challenges, and opportunities presented by the AI-powered blockchain technology in Industry 4.0. This review synthesizes the current state of AI-powered blockchain technology in Industry 4.0, offering insights into the transformative potential and challenges that lie ahead. It explores emerging trends, research gaps, and potential future developments in the dynamic landscape of AI-powered Blockchain applications. The review also addresses the evolution of consensus mechanisms and smart contract

functionalities, showcasing advancements that leverage the collaborative potential of AI and blockchain technologies. Furthermore, the paper discusses the ethical implications and privacy concerns associated with the integration of AI and blockchain in Industry 4.0. It explores strategies for mitigating risks and ensuring responsible deployment of these technologies, emphasizing the need for ethical frameworks and regulatory standards. So, the findings contribute to the ongoing discourse on the integration of these technologies, guiding researchers, practitioners, and policymakers towards harnessing the full capabilities of AI and Blockchain for the next phase of industrial evolution. Therefore, by examining the most current advancements in AI-Powered Blockchain Technology in Industry 4.0, efficiency, transparency, and security across a range of industrial processes can be improved.

2. Smart contracts

Smart contracts, which are self-executing contracts with the terms of the agreement directly written into code, can automate various processes in manufacturing, supply chain, and other industries (Shojaeinasab et al., 2022). This automation reduces the need for intermediaries, streamlining operations and reducing costs (Nuttah et al., 2023). AI can enhance these contracts by making them more adaptive and intelligent, allowing for dynamic adjustments based on real-time data. This combination allows for automated execution of contracts based on predefined conditions, reducing the need for intermediaries and streamlining business processes (Timucin and BİROĞUL, 2021). AI can be used to optimize and automate these contracts based on predefined conditions. This can streamline processes, reduce errors, and enhance efficiency in various industrial applications (Grıda and Mostafa, 2023). AI algorithms integrated with blockchain can provide real-time monitoring of smart contracts, allowing for better tracking of production processes, deliveries, and payments (ElMamy et al., 2020). Here's an overview of how AI-Powered Blockchain can enhance the industry 4.0 in domains of smart contracts and automation:

1. Automated and Trustworthy Execution: Smart contracts are self-executing contracts with the terms of the agreement directly written into code. AI algorithms can be integrated into smart contracts to automate decision-making processes. This ensures that the terms of the contract are executed without the need for intermediaries, reducing the risk of errors and fraud (Tadaka, 2020).
2. Dynamic and Adaptive Contracts: AI can enhance smart contracts by making them more dynamic and adaptive (Sultana et al., 2020). Machine learning algorithms can analyze data and adjust contract terms based on changing conditions, ensuring that agreements remain relevant and effective in dynamic business environments (Tan et al., 2022).
3. Enhanced Security: Blockchain's decentralized and cryptographic nature ensures the security and immutability of smart contracts. AI can further enhance security by providing advanced threat detection and prevention mechanisms, making it more challenging for malicious actors to exploit vulnerabilities (Lin et al., 2018).

Blockchain-based digital twins in industry 4.0 is shown in Fig. 4 (Yaqoob et al., 2020).

In summary, the combination of AI and blockchain in Industry 4.0, especially in the realms of smart contracts and automation, leads to increased efficiency, transparency, and security in industrial processes.

3. Supply chain management

Combining AI and blockchain in supply chain management can lead to increased transparency efficiency, and security. AI can analyze the vast amount of data generated by the blockchain, providing valuable insights into the supply chain (Prause, 2019). This helps in identifying inefficiencies, reducing fraud, and optimizing the overall supply chain process (Mehta et al., 2021). Artificial intelligence, through image recognition and other techniques, can be employed to verify the authenticity of physical products by analyzing features such as packaging, labels, or serial numbers. Machine learning algorithms can optimize supply chain routes, scheduling, and inventory management by analyzing real-time data and making data-driven decisions (Chen et al., 2023). Machine learning models can be deployed at various points in the supply chain to make localized decisions based on real-time data (Kashem et al., 2023). Machine learning models can analyze historical data, including customer behavior, market trends, and external factors, to make accurate predictions about future demand (Fernández-Caramés et al., 2019). This helps in minimizing excess inventory or stockouts. Artificial intelligence, particularly machine learning algorithms, can analyze the vast amounts of data stored on the blockchain to identify patterns, anomalies, and trends (Benzidia et al., 2021). This analysis contributes to better decision-making and risk management. Also, it can be particularly beneficial in verifying the authenticity of products and ensuring compliance with quality standards (Lee et al., 2019). By recording all transactions and events in a secure and transparent manner, blockchain supports the optimization efforts of AI by providing a reliable source of data. This reliable data is crucial for forecasting demand and optimizing inventory levels (Xu et al., 2022). The synergy between AI and blockchain enhances decision-making, automates processes, and improves overall supply chain performance (Faridi et al., 2020; Nuhıu and Aliu, 2023).

4. Predictive maintenance

Predictive maintenance involves using data, machine learning, and artificial intelligence (AI) to predict when equipment or machinery is likely to fail, allowing for maintenance to be performed just in time. AI algorithms can analyze data from sensors connected to machinery and equipment. This data can be stored securely on the blockchain (Sang et al., 2020). Predictive maintenance models can then use this information to predict when equipment is likely to fail, allowing for proactive maintenance, reducing downtime, and optimizing operations (Sang et al., 2021). By utilizing machine learning models, AI can identify patterns and

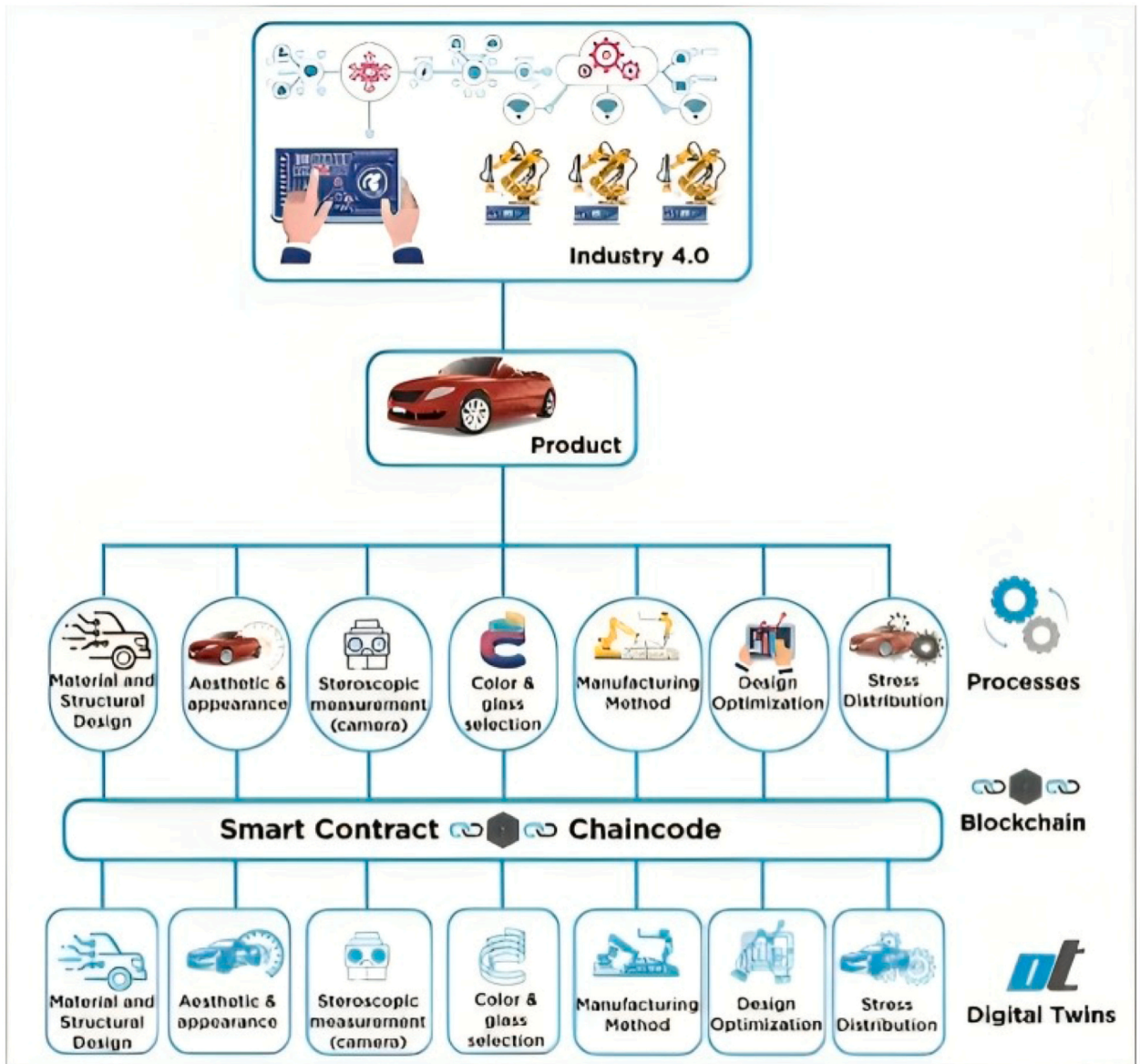


Fig. 4. Blockchain-based digital twins in industry 4.0 (Yaqoob et al., 2020).

anomalies in the data to predict when equipment is likely to fail (Rahman et al., 2021). This enables proactive maintenance rather than reactive, reducing downtime and costs (Lee et al., 2019). Applying predictive maintenance to AI-Powered Blockchain Technology in the context of Industry 4.0 can offer several advantages:

1. **Increased Reliability and Uptime:** Predictive maintenance helps in identifying potential issues before they result in system failure. This is crucial for AI-powered blockchain technology in Industry 4.0, where continuous operation and reliability are essential (Oladapo et al., 2023).
2. **Cost Reduction:** Performing maintenance only when needed reduces unnecessary downtime and maintenance costs. AI algorithms can analyze historical data, system logs, and real-time performance metrics to optimize maintenance schedules and minimize costs (ElMamy et al., 2020).
3. **Data-Driven Insights:** AI can analyze large volumes of data generated by AI-powered blockchain systems. By monitoring patterns and anomalies, it can provide valuable insights into the health of the system, helping operators make informed decisions (El Akrami et al., 2023).
4. **Proactive Problem Resolution:** Predictive maintenance enables proactive problem resolution by identifying potential issues early on. This is particularly important in Industry 4.0, where interconnected systems require a proactive approach to prevent cascading failures (Bandari and Comprehensive, 2021).

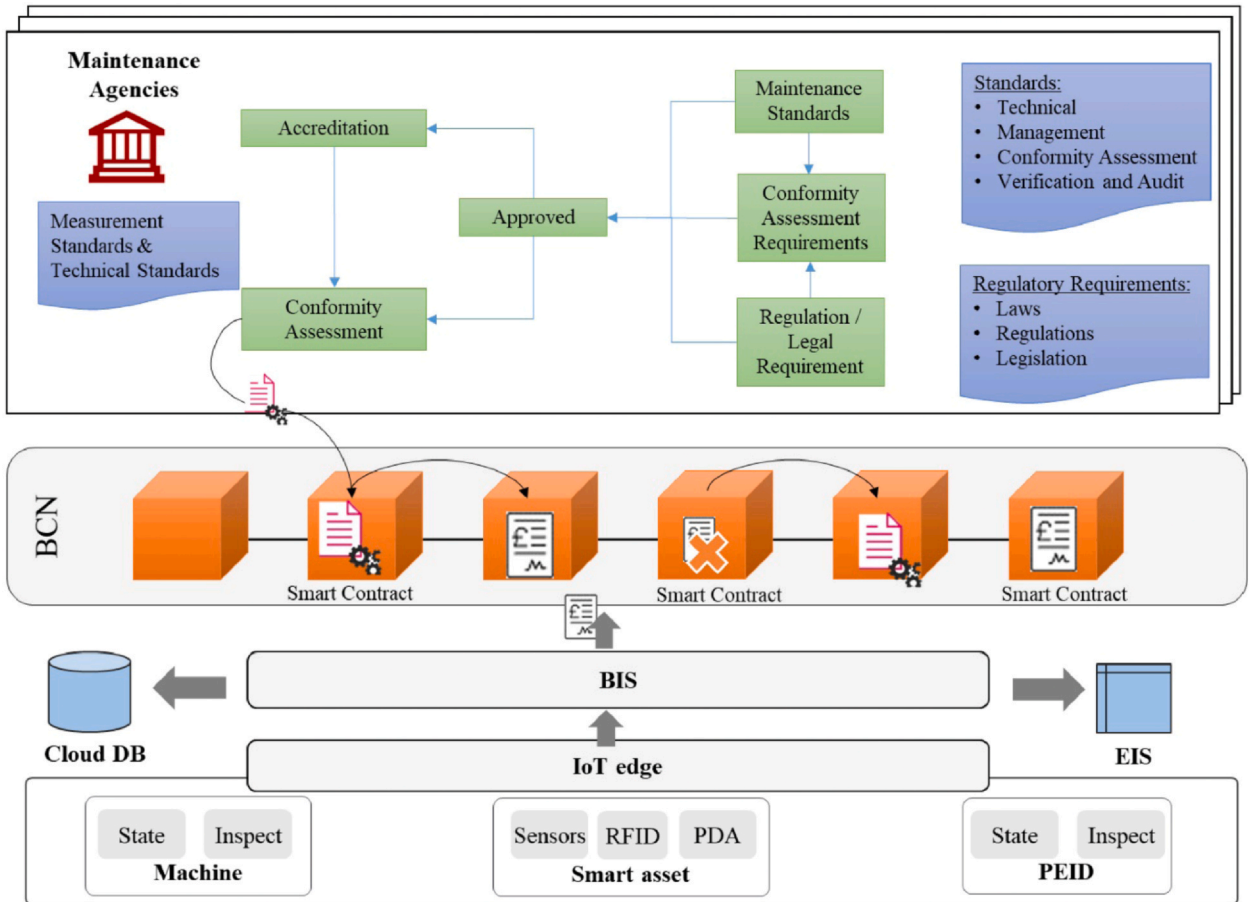


Fig. 5. Blockchain-enabled proactive maintenance service (Liu et al., 2020).

5. **Optimized Performance:** Continuous monitoring and analysis of system performance allow for optimization of AI algorithms and blockchain processes. This can lead to improved efficiency, faster transaction processing, and better overall system performance (Abidi, 2022).
6. **Integration with Blockchain Smart Contracts:** Smart contracts in blockchain can be utilized to automate certain aspects of the predictive maintenance process (Keleko et al., 2022). For instance, a smart contract could automatically trigger a maintenance request or order replacement parts when a predefined threshold is reached.
7. **Real-time Monitoring:** AI algorithms can provide real-time monitoring of critical parameters, allowing for immediate response to any deviations from normal operating conditions. This helps in preventing unexpected system failures and ensuring the integrity of blockchain transactions (Shahbazi and Byun, 2021).
8. **Long-Term Asset Management:** Predictive maintenance facilitates long-term asset management by predicting the remaining useful life of equipment (Tsaramiris et al., 2022). This information is valuable for planning and budgeting for future upgrades or replacements, contributing to the sustainability of Industry 4.0 technologies (Esmaeilian et al., 2020).
9. **Enhanced Security:** Predictive maintenance can also contribute to the security of AI-powered blockchain systems. By monitoring for unusual patterns or activities, it can help identify potential security threats or attacks, enabling timely responses to protect the integrity of the blockchain.
10. **Adaptability and Scalability:** AI algorithms can adapt to changing conditions and scale across diverse environments. This adaptability is crucial for Industry 4.0 applications, where technology landscapes are dynamic and evolving. Blockchain-enabled proactive maintenance service is shown in Fig. 5 (Liu et al., 2020).

In summary, predictive maintenance for AI-Powered Blockchain Technology in Industry 4.0 offers a proactive and data-driven approach to ensure the reliability, security, and optimal performance of these advanced systems. By leveraging the capabilities of AI, organizations can enhance the efficiency of maintenance processes and maximize the benefits of their Industry 4.0 investments.

5. Quality control

Blockchain ensures the integrity of data by providing a tamper-resistant and transparent ledger. AI algorithms can process data related to product quality, inspecting and analyzing it for defects. AI can analyze data from sensors and IoT devices deployed in manufacturing processes. Combining this with blockchain ensures the integrity and immutability of quality-related data. This is particularly important for industries where maintaining quality standards is crucial. Integrating this predictive maintenance data with blockchain can provide a secure and transparent record of equipment history, maintenance activities, and performance metrics (Gaikwad and Khang, 2023). The results can be recorded on the blockchain, providing an immutable record of product quality throughout the manufacturing process. Quality control for AI-powered blockchain technology in Industry 4.0 is crucial to ensure the reliability, security, and efficiency of the systems (Shah et al., 2022). Here are several key aspects to consider:

1. **Data Quality and Integrity:** for the data accuracy, ensure that the data fed into the blockchain and AI systems is accurate. Inaccurate data can lead to faulty decisions and compromise the integrity of the blockchain. Also, for the data consistency, maintain consistency across the data stored on the blockchain (Tyagi, 2024). any discrepancies can impact the performance of AI algorithms and compromise the reliability of the system (Latif, 2023).
2. **Smart Contract Audits:** Conduct thorough audits of smart contracts deployed on the blockchain. This includes checking the code for vulnerabilities and ensuring that the logic of the smart contracts aligns with the intended functionality. Implement automated tools for smart contract analysis to identify potential issues and vulnerabilities (Alhabatah et al., 2023).
3. **Security Measures:** Implement robust security measures for both AI and blockchain components. This includes encryption, secure key management, and access control mechanisms to protect sensitive information and prevent unauthorized access. Regularly update and patch software to address security vulnerabilities. This is particularly important for blockchain nodes and AI algorithms that may be exposed to evolving threats (Sasikumar et al., 2023).
4. **Consensus Mechanism:** Choose an appropriate consensus mechanism for the blockchain network. Different industries and use cases may require different consensus algorithms. Ensure that the chosen mechanism aligns with the specific requirements of the application.
5. **Scalability:** Test the scalability of both the AI and blockchain components. As Industry 4.0 applications often involve large amounts of data and complex computations, it's essential to ensure that the technology can scale to meet growing demands.
6. **Interoperability:** Ensure interoperability between AI and blockchain components and with other systems in the Industry 4.0 ecosystem. This is important for seamless data exchange and collaboration between different entities in the supply chain (Usmani et al., 2023).
7. **Regulatory Compliance:** Stay informed about relevant regulations and standards in the industry. Ensure that the AI-powered blockchain technology complies with legal requirements and industry standards.
8. **Continuous Monitoring and Auditing:** Implement continuous monitoring of the AI and blockchain systems. Regularly audit the systems for any anomalies, potential security breaches, or deviations from expected behavior. Use tools and analytics to track and analyze system performance, identifying areas for improvement or optimization (Abdulrahman et al., 2023).
9. **User Training and Awareness:** Provide training to users and stakeholders about the AI-powered blockchain technology. Awareness of security best practices and proper usage can mitigate risks associated with human error.
10. **Documentation and Transparency:** Maintain detailed documentation of the AI algorithms, blockchain protocols, and any updates or modifications made to the system. Transparency is crucial for accountability and traceability (Singh et al., 2022).

Implementing a comprehensive quality control framework for AI-powered blockchain technology involves a combination of technical measures, rigorous testing, and adherence to best practices. Regular updates and improvements should be made based on ongoing monitoring and feedback from the system's users and stakeholders.

6. Decentralized decision-making

Decentralized decision-making for AI-powered blockchain technology in Industry 4.0 involves combining artificial intelligence (AI) and blockchain to enhance and automate decision-making processes in a decentralized manner. AI and blockchain can be combined to create decentralized autonomous organizations where decisions are made based on smart contracts and AI algorithms (Aiello et al., 2021). This can streamline decision-making processes and reduce the need for centralized authorities in certain aspects of business operations (Nuhui and Aliu, 2023). Here's a breakdown of key concepts and considerations in this context:

1. **Blockchain Technology:** Blockchain is a distributed ledger technology that operates on a decentralized network of nodes. This ensures that there is no single point of control, making it resistant to tampering and fraud. These are self-executing contracts with the terms of the agreement directly written into code. Smart contracts facilitate and automate the execution of predefined actions when specific conditions are met (Nuhui and Aliu, 2023).
2. **Artificial Intelligence (AI):** AI, and specifically machine learning algorithms, can analyze vast amounts of data to identify patterns, trends, and insights. AI algorithms can be designed to make decisions based on data inputs, learning from experience and improving over time (Trakadas et al., 2020).
3. **Integration of AI and Blockchain in Industry 4.0:** Blockchain ensures data integrity and security, while AI processes data to derive meaningful insights. This combination enhances the reliability of decision-making processes. The transparent nature of blockchain

allows for the tracking and auditing of decisions made by AI algorithms, contributing to accountability and trust (Javaid et al., 2022).

4. Decentralized Decision-Making: Each node in a decentralized blockchain network can host an AI algorithm, allowing for autonomous decision-making at the edge of the network. Blockchain's consensus mechanisms determine how decisions are made across the network (Ahmad et al., 2022). This decentralized decision-making process helps in achieving agreement without the need for a central authority (Siddiqui and Haroon, 2022).
5. Challenges and Considerations: As the volume of data and transactions increases, scalability becomes a challenge for both AI and blockchain technologies. Ensuring that different AI algorithms and blockchain networks can seamlessly work together is crucial for widespread adoption. Adhering to industry regulations and standards is essential, especially in sectors with strict compliance requirements (Salah et al., 2019).
6. Supply Chain Management: Utilizing AI and blockchain for transparent and traceable supply chain operations (Patil et al., 2023).
7. Smart Contracts in Manufacturing: Implementing smart contracts for automated and self-executing agreements in manufacturing processes.
8. Quality Control: AI algorithms can analyze production data, while blockchain ensures the integrity of quality-related information (Lal et al., 2023).

In conclusion, the integration of AI and blockchain in Industry 4.0 offers the potential for more secure, transparent, and efficient decentralized decision-making processes. However, it also requires addressing various technical and regulatory challenges to fully realize its benefits.

7. Data security and privacy by immutable records

Blockchain provides a decentralized and tamper-resistant ledger that enhances data security and trust. Combining AI-powered blockchain technology with immutable records can enhance data security and privacy in the context of Industry 4.0. Blockchain's immutability ensures that once data is recorded, it cannot be altered. Blockchain's cryptographic features enhance the security of data sharing among different entities in the supply chain (Rahman et al., 2021). This is crucial for maintaining the security and privacy of sensitive information (Gupta et al., 2020). AI can be employed to enhance cybersecurity measures, creating a robust defense against cyber threats. AI algorithms can help in analyzing this shared data for insights without compromising its security (Adhikari and Winslett, 2019). AI algorithms, particularly those used in machine learning, can benefit from secure and reliable data sources, making blockchain a suitable platform for storing and sharing data in Industry 4.0 applications. Here's a breakdown of how this integration can work:

1. Immutable Records on Blockchain: Blockchain is a decentralized and distributed ledger that records transactions across a network of computers. Once data is recorded in a block and added to the chain, it becomes extremely difficult to alter. This immutability ensures the integrity of the data (Joshi et al., 2022).
2. Smart Contracts for Automation: Smart contracts are self-executing contracts with the terms of the agreement directly written into code. These contracts can automate various processes in Industry 4.0, such as supply chain management, quality control, and more. AI algorithms can be integrated into smart contracts to enable intelligent decision-making based on predefined rules (Timuçin and Biroğul, 2023).
3. Enhanced Security with Cryptography: Blockchain relies on cryptographic techniques to secure transactions. Each participant in the network has a unique private key, and the data is encrypted. This cryptographic layer adds an extra level of security, making it challenging for unauthorized entities to access or tamper with the data.
4. Decentralization for Resilience: Traditional centralized systems are vulnerable to single points of failure. In a decentralized blockchain network, there's no single point of control, making it more resistant to attacks. This decentralized nature enhances the resilience of the system, reducing the risk of data breaches (Silva et al., 2020).
5. Permissioned Blockchains: Industry 4.0 may require permissioned blockchains where access to the network is restricted to authorized participants. This helps in maintaining control over who can read or write to the blockchain, contributing to data privacy (Mendoza Arvizo et al., 2023).
6. Privacy-Preserving AI Techniques: Employ privacy-preserving AI techniques to ensure that sensitive data used in AI algorithms remains confidential. This includes methods like federated learning, homomorphic encryption, and secure multi-party computation, which allow AI models to be trained on decentralized data without exposing individual data points (Erdem et al., 2019).
7. Auditability and Transparency: Blockchain provides a transparent and auditable history of transactions. Every change made to the data is recorded and time-stamped, allowing for a complete audit trail. This transparency ensures accountability and helps in compliance with regulations (Mushtaq and Haq, 2019).
8. Consensus Mechanisms: Blockchain networks use consensus mechanisms to validate transactions and agree on the state of the ledger. Consensus adds another layer of security by ensuring that all participants in the network agree on the validity of transactions (Tanwar et al., 2020).
9. Regular Security Audits: Regularly audit the security of the blockchain network and AI algorithms. This includes vulnerability assessments, penetration testing, and continuous monitoring to identify and address potential security threats (Picone et al., 2021).

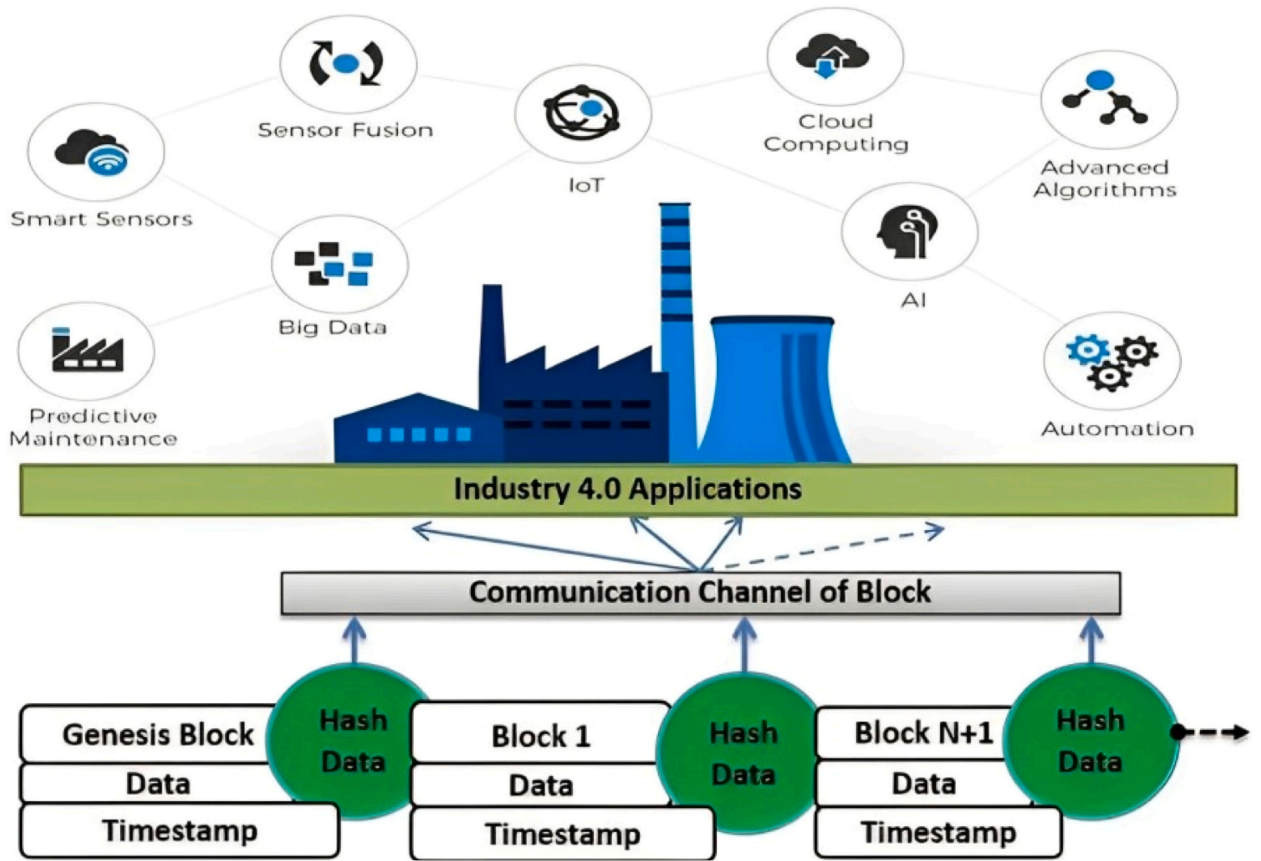


Fig. 6. Blockchain-based security approach in industry 4.0 (Rahman et al., 2020).

10. Legal and Regulatory Compliance: Ensure that the implementation complies with relevant legal and regulatory frameworks, especially concerning data protection and privacy laws. This is crucial for gaining trust from stakeholders and avoiding legal consequences. Blockchain-based security approach in industry 4.0 is shown in the Fig. 6 (Rahman et al., 2020).

By combining the strengths of AI-powered blockchain technology with immutable records, you can create a robust system for data security and privacy in the Industry 4.0 landscape. However, it's essential to stay vigilant and adapt to evolving security challenges and regulatory requirements.

8. Digital assets

AI-powered blockchain technology plays a significant role in Industry 4.0 by enhancing security, efficiency, and transparency in various processes. Digital assets in this context refer to the data, tokens, and smart contracts that leverage AI and blockchain integration (Pfeiffer and Bugeja, 2021). Blockchain facilitates the tokenization of physical and digital assets (Lage, 2019). AI algorithms can analyze patterns and behaviors related to tokenized assets, providing insights for better asset management and investment decisions (Rathore, 2023). Here are some key digital assets associated with AI-powered blockchain technology in Industry 4.0:

1. Smart Contracts: Self-executing contracts with the terms of the agreement directly written into code. Automate and enforce contractual agreements, reducing the need for intermediaries and streamlining processes.
2. AI Algorithms and Models: Machine learning algorithms and models that analyze and derive insights from data. Enhance decision-making processes, predictive analytics, and optimization within various industries (Pandey et al., 2023).
3. Tokenized Assets: Digital representations of physical or digital assets on a blockchain. Facilitate the fractional ownership and transfer of assets, enabling liquidity and transparency (Darwish, 2023; Mufitah, 2023).
4. Decentralized Identity: Digital identities stored on a blockchain, providing secure and verifiable user information. Enhance security, privacy, and interoperability in identity management across Industry 4.0 systems (Siddique et al., 2023).
5. Supply Chain Traceability Tokens: Tokens that represent the provenance and movement of products within a supply chain. Improve transparency, reduce fraud, and enhance the efficiency of supply chain management (Tsolakis et al., 2023).

6. Data Marketplace Tokens: Tokens used to buy and sell data on decentralized marketplaces. Incentivize data sharing, enable data monetization, and ensure data integrity through blockchain (Thangadurai et al., 2022).
7. Decentralized Autonomous Organizations (DAOs): Organizations represented by rules encoded as a computer program that is transparent, controlled by organization members, and not influenced by a central government. Facilitate decentralized decision-making, governance, and resource allocation (Raja et al., 2020).
8. Immutable Audit Trails: Permanent, unchangeable records of transactions and activities. Ensure transparency, accountability, and auditability in various processes, including financial transactions and compliance (Kumar and Sharma, 2023).
9. AI-Generated NFTs (Non-Fungible Tokens): Unique digital assets representing ownership or proof of authenticity. Enable the creation, ownership, and trading of unique AI-generated digital assets, fostering innovation in digital art and media (Adu et al., 2023).
10. Decentralized Data Storage: Distributed storage solutions where data is broken into pieces and stored across multiple nodes. Enhance data security, privacy, and resilience against data breaches (Marechaux, 2019).

Integrating these digital assets into Industry 4.0 processes can lead to more efficient, secure, and transparent systems, fostering innovation and collaboration across various industries. However, it's essential to consider regulatory and ethical considerations as AI-powered blockchain technologies continue to evolve.

9. Energy trading

Energy trading in the context of AI-powered Blockchain Technology in Industry 4.0 involves the use of advanced technologies to facilitate more efficient, transparent, and decentralized energy transactions. Industry 4.0 refers to the fourth industrial revolution, characterized by the integration of smart technologies, automation, and data exchange in various industries, including energy (Borowski, 2021). In the context of smart grids and energy trading, AI and blockchain can work together to optimize energy consumption, enable peer-to-peer energy trading, and ensure transparent and secure transactions between connected devices (Wang and Su, 2020). In energy-intensive industries, AI algorithms can analyze energy consumption patterns (Venkatesh et al., 2023). Blockchain can be used to create a transparent and auditable record of energy transactions and to incentivize energy-efficient practices (Otoum et al., 2022). Here's how AI-powered Blockchain Technology can be applied to energy trading in the Industry 4.0 landscape:

1. Smart Contracts and Automation: Utilize smart contracts, self-executing contracts with the terms of the agreement directly written into code, to automate energy trading processes. This reduces the need for intermediaries and ensures that agreements are executed automatically when predefined conditions are met (Teufel et al., 2019).
2. Decentralization and Peer-to-Peer Trading: Leverage blockchain's decentralized nature to enable peer-to-peer energy trading. This allows consumers and producers to directly exchange energy without the need for centralized authorities. AI algorithms can optimize these transactions based on real-time data, considering factors such as demand, supply, and pricing (Esmat et al., 2021).
3. AI Analytics for Predictive Modeling: Implement AI algorithms to analyze vast amounts of data from IoT devices, sensors, and other sources. This data can be used to create predictive models for energy consumption, production, and pricing (Popkova et al., 2023). AI can help anticipate fluctuations in supply and demand, allowing for proactive decision-making in energy trading (Ghobakhloo and Fathi, 2021).
4. Energy Grid Optimization: Use AI to optimize the energy grid by dynamically managing the distribution of energy based on real-time demand and supply conditions. This can prevent overloads, reduce energy losses, and enhance the overall efficiency of the grid (Alsamhi et al., 2022).
5. Tokenization of Energy Assets: Tokenize energy assets using blockchain technology. This involves representing ownership or access rights to energy sources as digital tokens. AI can then be used to manage and trade these tokens efficiently, enabling fractional ownership and facilitating investment in renewable energy projects (Brilliantova and Thurner, 2019).
6. Transparent and Auditable Transactions: Blockchain ensures transparency and immutability of transactions. AI algorithms can be used to audit and analyze these transactions, providing insights into the integrity of the energy trading process. This transparency helps build trust among participants in the energy ecosystem (Teisserenc and Sepasgozar, 2021).
7. Dynamic Pricing Mechanisms: Employ AI to develop dynamic pricing mechanisms that adjust in real-time based on supply, demand, and other relevant factors. This flexibility can lead to more efficient allocation of resources and encourage responsible energy consumption (Lage, 2019).
8. Cybersecurity and Privacy: Use AI for enhancing cybersecurity measures to safeguard the integrity of the blockchain and protect sensitive energy-related data (Salama et al., 2023). Privacy-preserving AI techniques can also be applied to ensure the confidentiality of user information (Ahmad et al., 2022).
9. Interoperability with Existing Systems: Ensure that AI-powered blockchain solutions are interoperable with existing energy infrastructure and systems. This facilitates a smooth transition and integration of these technologies into the Industry 4.0 framework (Pustišek et al., 2021).

Blockchain-Enabled Secure Energy Trading With Verifiable Fairness in Industrial Internet of Things is shown in Fig. 7 (Li et al., 2020).

By combining AI and blockchain technologies in energy trading within the Industry 4.0 paradigm, there is the potential to create a more resilient, efficient, and sustainable energy ecosystem (Srivastava et al., 2024).

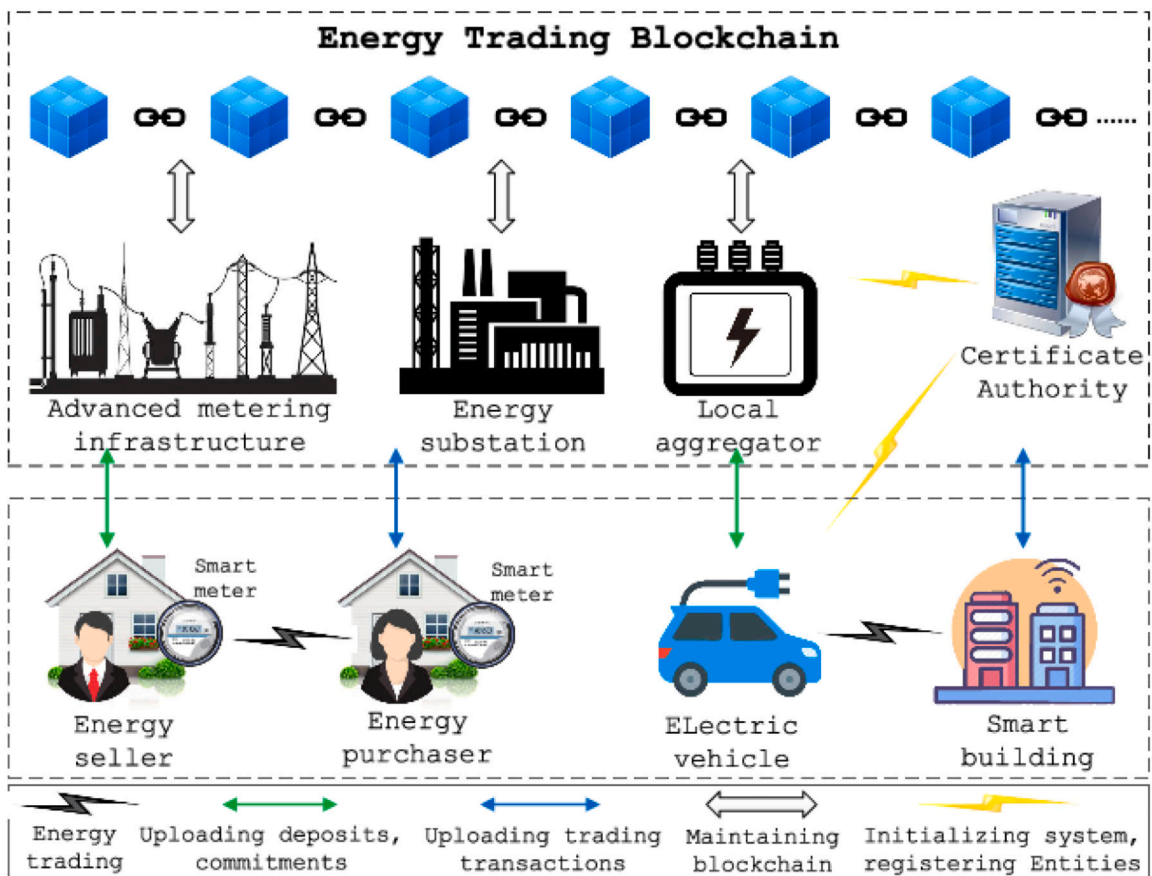


Fig. 7. Blockchain-Enabled Secure Energy Trading With Verifiable Fairness in Industrial Internet of Things (Li et al., 2020).

10. Collaborative manufacturing

Collaborative manufacturing in the context of AI-powered Blockchain Technology in Industry 4.0 represents a convergence of advanced technologies to enhance efficiency, transparency, and trust in the manufacturing process (Wan et al., 2022). Collaborative manufacturing involves the integration of various stakeholders, including manufacturers, suppliers, customers, and even machines, to work together seamlessly (Carey, 2022). This collaborative approach enhances flexibility, efficiency, and responsiveness in the production process. AI and blockchain can enable collaborative manufacturing where different entities within a supply chain can securely share information and collaborate in a trusted environment, improving efficiency and reducing the risk of fraud. Blockchain facilitates decentralized and secure collaboration between different parties in the manufacturing process. AI algorithms can optimize production processes, and the decentralized nature of blockchain ensures data integrity and security (Huang et al., 2021). Collaborative manufacturing for AI-powered Blockchain Technology in Industry 4.0 holds the promise of creating more efficient, transparent, and trustworthy manufacturing ecosystems (Bellavista et al., 2021). However, addressing the associated challenges and ensuring seamless integration is key to realizing these benefits.

11. Product lifecycle management

Product Lifecycle Management (PLM) for AI-powered Blockchain Technology in Industry 4.0 involves the integration of advanced technologies to enhance the development, deployment, and management of products throughout their lifecycle (Darwish, 2023). Blockchain's immutability ensures a tamper-proof record of the entire product lifecycle (Pathan et al., 2023). AI can leverage this data for predictive maintenance, quality improvements, and overall optimization of the product lifecycle.

12. Conceptualization and design

- AI Integration for Design Optimization: Implement AI algorithms to optimize product design based on historical data, customer feedback, and market trends.
- Blockchain for Intellectual Property Protection: Use blockchain to timestamp and secure intellectual property rights, ensuring traceability and preventing unauthorized use (Barton et al., 2022).

1. Prototyping and Development:
 - Smart Contracts for Supply Chain Management: Utilize smart contracts on the blockchain to automate and secure transactions within the supply chain, ensuring transparency and traceability (Ghildiyal et al., 2023).
 - AI for Predictive Maintenance: Implement AI algorithms to analyze real-time data from sensors embedded in products, predicting maintenance needs and minimizing downtime (Barton et al., 2022).
2. Testing and Validation:
 - Blockchain for Quality Assurance: Use blockchain to create an immutable record of testing and validation processes, ensuring the integrity of data and certifications.
 - AI for Automated Testing: Employ AI-driven testing tools to automate and optimize the testing phase, reducing time and costs (Onik et al., 2018).
3. Production and Manufacturing:
 - AI-Powered Predictive Analytics: Utilize AI algorithms to optimize production schedules, predict equipment failures, and enhance overall manufacturing efficiency (Srivastava et al., 2024).
 - Blockchain for Supply Chain Traceability: Implement blockchain to provide end-to-end traceability in the supply chain, ensuring the authenticity of components and raw materials (Ghildiyal et al., 2023).
4. Distribution and Logistics:
 - Blockchain for Logistics Optimization: Use blockchain to optimize logistics operations, ensuring real-time tracking of products and minimizing errors in shipments.
 - AI for Demand Forecasting: Implement AI algorithms to analyze market trends, predict demand fluctuations, and optimize inventory management (Li and Mardani, 2023).
5. Utilization and Maintenance:
 - Blockchain for Service History: Maintain a secure and transparent service history on the blockchain, enabling efficient maintenance and reducing downtime (Javaid et al., 2022).
 - AI-Based Customer Support: Implement AI-powered chatbots or virtual assistants to enhance customer support and provide predictive maintenance guidance (Jena and Dash, 2021).
6. End-of-Life and Disposal:
 - Blockchain for Recycling and Disposal: Use blockchain to track the end-of-life process, ensuring proper recycling and disposal in compliance with environmental regulations (Venkatesh et al., 2023).
 - AI for Sustainability Analysis: Implement AI algorithms to assess the environmental impact of the product throughout its lifecycle, aiding in sustainable product development (Darwish, 2023; Wahab and Nor, 2023).
7. Continuous Improvement:
 - Blockchain for Feedback Loops: Utilize blockchain to collect and securely store customer feedback, enabling continuous improvement based on real-world usage.
 - AI for Process Optimization: Implement AI algorithms to analyze data collected across the product lifecycle, identifying opportunities for process optimization and innovation (Darwish, 2023).

Blockchain-enabled product lifecycle management is shown in Fig. 8 (Li et al., 2022).

By combining AI and blockchain technologies within the framework of PLM, companies can streamline processes, enhance collaboration, ensure data integrity, and ultimately improve the overall efficiency and effectiveness of product development in the context of Industry 4.0.

13. Challenges of ai-powered blockchain technology in Industry 4.0

AI-powered blockchain technology holds great potential in the context of Industry 4.0, which involves the integration of digital technologies into various aspects of manufacturing and supply chains (Silva et al., 2020). However, there are several challenges that need to be addressed for the successful implementation of AI-powered blockchain in Industry 4.0 (Aoun et al., 2021). Despite the potential benefits, challenges such as scalability, interoperability, and regulatory concerns need to be addressed. Additionally, the energy consumption associated with some blockchain consensus mechanisms is a consideration that needs attention. Implementing AI on a blockchain network can be computationally intensive, and scalability remains a challenge (Su et al., 2023). Researchers and developers are working on solutions to make AI applications more efficient within blockchain frameworks (Aoun et al., 2021; Jha et al., 2023). As with any emerging technology, regulatory frameworks need to catch up. The legal and regulatory aspects of deploying AI and blockchain in Industry 4.0 need careful consideration. Some of these challenges include:

1. Scalability: Blockchain networks often face scalability issues, especially when handling a large number of transactions. The integration of AI could potentially increase the computational load, making it essential to address scalability concerns (Akram et al., 2020).
2. Interoperability: Ensuring seamless integration with existing systems and technologies within Industry 4.0 can be challenging. AI-powered blockchain solutions need to be compatible with various protocols and standards (Kumar et al., 2023a).

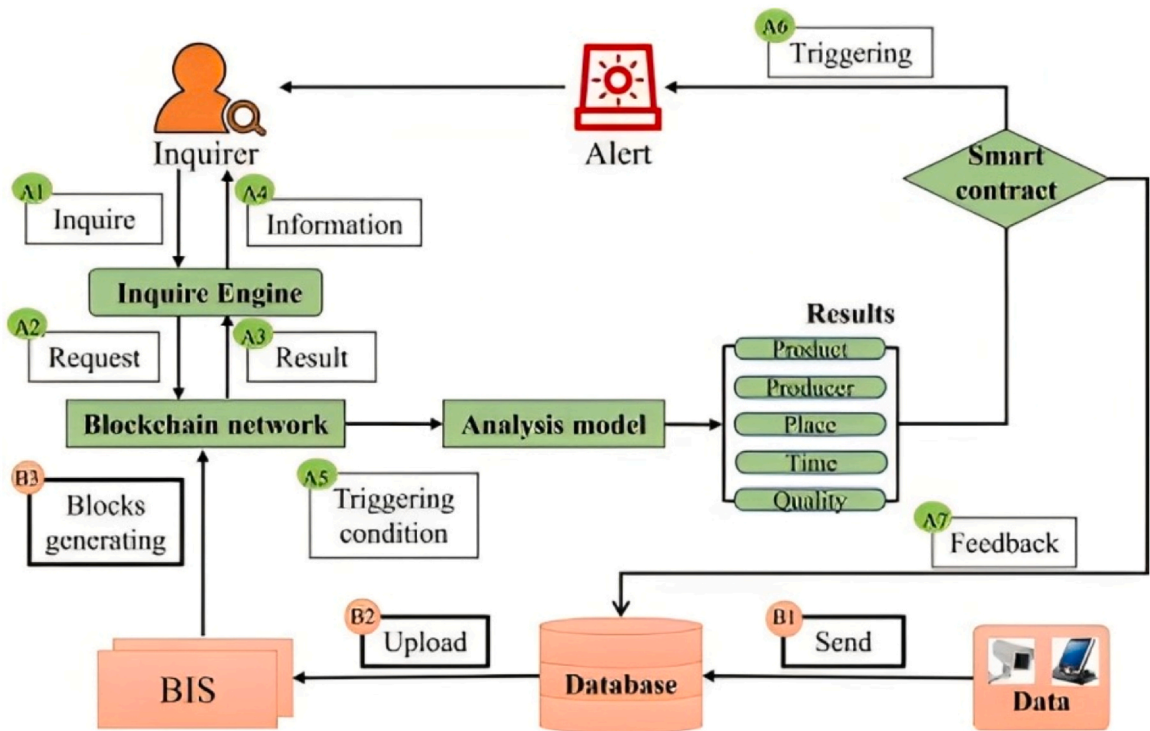


Fig. 8. Blockchain-enabled product lifecycle management (Li et al., 2022).

3. **Data Privacy and Security:** Industry 4.0 involves the exchange of sensitive data. Ensuring the privacy and security of this data is crucial (Ur et al., 2023). AI algorithms operating on the blockchain must comply with data protection regulations and maintain the confidentiality of business-critical information (Taherdoost, 2022; Das et al., 2023).
4. **Smart Contracts Complexity:** Smart contracts play a vital role in automating processes on the blockchain. However, creating complex smart contracts that involve AI algorithms introduces challenges in terms of reliability, auditing, and debugging (Demertzis et al., 2020).
5. **Energy Consumption:** Blockchain networks, particularly those using proof-of-work consensus mechanisms, can be energy-intensive. Incorporating AI algorithms may increase computational requirements, adding to the overall energy consumption. Developing energy-efficient solutions is essential (Sasikumar et al., 2023).
6. **Regulatory Compliance:** The integration of AI and blockchain in Industry 4.0 may face regulatory challenges (Mourtzis et al., 2022). Ensuring compliance with evolving regulations and standards is critical to gaining widespread acceptance (Lypnytskyi, 2019).
7. **Skill Gap:** There is a shortage of skilled professionals who are well-versed in both AI and blockchain technologies. Bridging this skill gap is crucial for the successful development and implementation of AI-powered blockchain solutions (Chae and Olson, 2022).
8. **Costs and Investment:** Implementing AI-powered blockchain solutions requires a significant initial investment. Companies may be hesitant to adopt these technologies without clear evidence of long-term benefits and cost savings (Zhang et al., 2020).
9. **Trust and Adoption for Industry Adoption:** Convincing industries to adopt AI-powered blockchain solutions can be challenging. Establishing trust in the reliability, security, and benefits of these technologies is crucial for widespread adoption (Singh, 2020).
10. **Ethical Considerations:** AI algorithms, if not carefully designed, can perpetuate biases present in the data they are trained on. Ensuring fairness and ethical considerations in AI applications on the blockchain is important, especially in critical industries.

Addressing these challenges requires collaborative efforts from researchers, industry professionals, and policymakers to create a robust and sustainable ecosystem for AI-powered blockchain technology in Industry 4.0.

14. Conclusion

AI-powered blockchain technology plays a significant role in the evolution of Industry 4.0, which refers to the fourth industrial revolution characterized by the integration of digital technologies into manufacturing and other industrial processes. The integration of AI and blockchain in Industry 4.0 holds significant promise for enhancing security, transparency, and efficiency across various sectors (Varadam et al., 2024). The integration of AI-powered blockchain technology in Industry 4.0 marks a transformative leap toward a more efficient, secure, and intelligent industrial landscape. This synergy harnesses the strengths of both AI and blockchain,

paving the way for unprecedented advancements in various sectors. However, it's essential to monitor ongoing developments, address challenges, and ensure a supportive regulatory environment for the widespread adoption of these technologies.

AI can be used to detect and prevent fraudulent activities, secure smart contracts, and identify anomalies in the network. AI algorithms can automate complex processes by learning from historical data and making predictions. This can lead to increased efficiency and reduced manual intervention in various Industry 4.0 processes. Blockchain ensures data integrity, and AI can be employed for advanced data analysis (Vegesna and Blockchain, 2023). This combination is particularly powerful in scenarios where accurate and trustworthy data is crucial, such as supply chain management or quality control in manufacturing. AI algorithms can analyze historical data stored on the blockchain to make predictions about future trends, helping industries make informed decisions and optimize their operations (Kumar et al., 2023b).

The marriage of AI and blockchain fosters enhanced data security, transparency, and traceability, crucial factors in the evolving digital economy. By leveraging AI algorithms, industries can derive actionable insights from the wealth of data stored in blockchain ledgers, enabling smarter decision-making and predictive analytics. This not only optimizes operational processes but also contributes to resource efficiency and cost reduction (Gad et al., 2022). Moreover, the decentralized and tamper-resistant nature of blockchain ensures the integrity of data, mitigating the risk of fraud and unauthorized access. Smart contracts, enabled by blockchain, automate and enforce agreements, reducing the need for intermediaries and streamlining business processes. This not only accelerates transactions but also engenders a more trustful and collaborative ecosystem (Schiliro, 2022).

In Industry 4.0, where interconnected devices and systems generate vast amounts of data, the AI-blockchain convergence provides a robust framework for managing, analyzing, and securing this data. From supply chain management to smart manufacturing, the synergy of AI and blockchain enhances the overall resilience and responsiveness of industrial processes (Sharma et al., 2021). However, challenges such as regulatory uncertainties, interoperability issues, and ethical concerns must be addressed to unlock the full potential of this integration. As the technology matures, collaborations between industries, policymakers, and technology developers will be essential in establishing standards and frameworks that ensure responsible and ethical deployment. In summary, AI-powered blockchain technology stands as a cornerstone for the evolution of Industry 4.0, offering a foundation for unprecedented innovation and efficiency (Garces et al., 2023). As organizations navigate this technological frontier, strategic investments, collaborative initiatives, and a commitment to ethical practices will be imperative to fully harness the transformative power of AI and blockchain in shaping the future of industries.

15. Future research work directions

Researchers and industry professionals continue to explore ways to harness the synergies between AI and blockchain for maximum efficiency and innovation. Ongoing research, development, and collaboration between industry and technology experts are essential for realizing the full potential of AI-powered blockchain in the context of Industry 4.0. Future research in this area can explore several directions to further enhance the integration of AI and blockchain technologies. Here are some potential research directions:

1. Scalability and Performance Optimization: Investigate ways to improve the scalability and performance of AI-powered blockchain networks. This includes optimizing consensus algorithms, enhancing transaction processing speeds, and reducing latency (Vashishth et al., 2024).
2. Interoperability: Explore methods to enhance interoperability between different AI and blockchain platforms. Developing standards and protocols that enable seamless communication and data exchange across diverse systems can be crucial for widespread adoption.
3. Privacy and Security: Address privacy concerns associated with the use of AI and blockchain. Develop advanced cryptographic techniques and privacy-preserving algorithms to protect sensitive data while still allowing for meaningful analysis and insights (Wu et al., 2023).
4. Smart Contracts Evolution: Enhance smart contract capabilities by integrating advanced AI techniques. This could involve the development of more complex and dynamic smart contracts that can adapt to changing conditions or learn from historical data (Tyagi et al., 2020; Singh et al., 2020).
5. Decentralized AI Models: Explore the development of decentralized AI models that can operate on blockchain networks. This could involve the creation of AI models that are distributed across a network of nodes, providing a more resilient and secure infrastructure for machine learning.
6. Energy Efficiency: Investigate methods to improve the energy efficiency of AI-powered blockchain networks. This is particularly important given the environmental concerns associated with some blockchain consensus mechanisms (Hemamalini et al., 2024).
7. Regulatory Frameworks: Research the development of regulatory frameworks that address the unique challenges posed by AI-powered blockchain applications. This includes considerations related to data privacy, legal enforceability of smart contracts, and accountability in decentralized systems (Habbal et al., 2024).
8. Use Cases in Specific Industries: Conduct industry-specific research to identify and develop AI-powered blockchain applications tailored to the needs of particular sectors, such as healthcare, supply chain, finance, and manufacturing.
9. User Experience and Adoption: Explore ways to improve the user experience and facilitate the adoption of AI-powered blockchain solutions. This could involve developing user-friendly interfaces, educational initiatives, and strategies to overcome barriers to entry.
10. Ethical Implications: Investigate the ethical implications of combining AI and blockchain, especially in terms of bias in AI models, transparency in decision-making processes, and accountability in decentralized systems (Saheb et al., 2022).

11. Hybrid Approaches: Research hybrid approaches that combine the strengths of traditional centralized systems with decentralized AI-powered blockchain networks. This could involve creating systems that leverage blockchain for specific aspects while maintaining centralization where necessary (Jabarulla and Lee, 2021).
12. Governance Models: Explore governance models for AI-powered blockchain networks. This includes mechanisms for decision-making, protocol upgrades, and addressing disputes within decentralized ecosystems.

By exploring these research directions, scholars and practitioners can contribute to the development of more robust, efficient, and ethically sound AI-powered blockchain technologies for the Industry 4.0 era.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Abdulrahman, Y., Arnaoutović, E., Parezanović V., Svetinovic, D., AI and Blockchain Synergy in Aerospace Engineering: An Impact Survey on Operational Efficiency and Technological Challenges, *IEEE Access*, (2023).
- Abidi, M.H., Mohammed, M.K., Alkhalefah, H., 2022. Predictive maintenance planning for industry 4.0 using machine learning for sustainable manufacturing. *Sustainability* 14, 3387.
- 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.
- Adru, S.L., Johnson, S., Hemalatha, M., 2023. AI and Blockchain Based Platform for Empowering Content Creators: Enabling NFT-Driven Content Sharing, Inspiration Generation, and Collaborative Interaction, in: 4th International Conference on Smart Electronics and Communication (ICOSEC) 2023. IEEE, pp. 666–673.
- Ahmad, T., Zhu, H., Zhang, D., Tariq, R., Bassam, A., Ullah, F., AlGhamdi, A.S., Alshamrani, S.S., 2022. Energetics Systems and artificial intelligence: Applications of industry 4.0. *Energy Rep.* 8, 334–361.
- Aiello, G., Benítez, J., Carpitella, S., Certa, A., Enea, M., Izquierdo, J., La Cascia, M., 2021. A decision support system to assure high-performance maintenance service. *J. Qual. Maint. Eng.* 27, 651–670.
- Akram, S.V., Malik, P.K., Singh, R., Anita, G., Tanwar, S., 2020. Adoption of blockchain technology in various realms: opportunities and challenges. *Secur. Priv.* 3, e109.
- Al-Rakhami, M., Al-Mashari, M., 2022. Interoperability approaches of blockchain technology for supply chain systems. *Bus. Process Manag. J.* 28, 1251–1276.
- Alsamhi, S.H., Shvetsova, A.V., Shvetsova, S.V., Hawbani, A., Guizani, M., Alhartomi, M.A., Ma, O., 2022. Blockchain-empowered security and energy efficiency of drone swarm consensus for environment exploration. *IEEE Trans. Green. Commun. Netw.* 7, 328–338.
- Althabatah, A., Yaqot, M., Menezes, B., Kerbache, L., 2023. Transformative procurement trends: integrating industry 4.0 technologies for enhanced procurement processes. *Logistics* 7, 63.
- Aoun, A., Ilinca, A., Ghandour, M., Ibrahim, H., 2021. A review of Industry 4.0 characteristics and challenges, with potential improvements using blockchain technology. *Comput. Ind. Eng.* 162, 107746.
- Bandari, V., Comprehensive, A., 2021. Review of AI applications in automated container orchestration. *Predict. Maint., Secur. Compliance, Resour. Optim., Contin. Deploy. Test., Int. J. Intell. Autom. Comput.* 4, 1–19.
- Barton, M., Budjac, R., Tanuska, P., Gaspar, G., Schreiber, P., 2022. Identification overview of Industry 4.0 essential attributes and resource-limited embedded artificial-intelligence-of-things devices for small and medium-sized enterprises. *Appl. Sci.* 12, 5672.
- Bellagarda, J.S., Abu-Mahfouz, A.M., 2022. An updated survey on the convergence of distributed ledger technology and artificial intelligence: Current state, major challenges and future direction. *IEEE Access* 10, 50774–50793.
- Bellavista, P., Esposito, C., Foschini, L., Giannelli, C., Mazzocca, N., Montanari, R., 2021. Interoperable blockchains for highly-integrated supply chains in collaborative manufacturing. *Sensors* 21, 4955.
- Benzidia, S., Makaoui, N., Subramanian, N., 2021. Impact of ambidexterity of blockchain technology and social factors on new product development: a supply chain and Industry 4.0 perspective. *Technol. Forecast. Soc. Change* 169, 120819.
- Bodkhe, U., Tanwar, S., Parekh, K., Khanpara, P., Tyagi, S., Kumar, N., Alazab, M., 2020. Blockchain for industry 4.0: a comprehensive review. *IEEE Access* 8, 79764–79800.
- Borowski, P.F., 2021. Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector. *Energies* 14, 1885.
- Brilliantova, V., Thurner, T.W., 2019. Blockchain and the future of energy. *Technol. Soc.* 57, 38–45.
- Carey, B., 2022. Metaverse technologies, behavioral predictive analytics, and customer location tracking tools in blockchain-based virtual worlds. *Rev. Contemp. Philos.* 188–204.
- Chae, B., Olson, D., 2022. Technologies and applications of Industry 4.0: insights from network analytics. *Int. J. Prod. Res.* 60, 3682–3704.
- Chauhan, S., Singh, R., Gehlot, A., Akram, S.V., Twala, B., Priyadarshi, N., 2023. Digitalization of supply chain management with industry 4.0 enabling technologies: a sustainable perspective. *Processes* 11, 96.
- Chen, K., Golhar, D.Y., Banerjee, S., 2023. Blockchain applications and challenges for supply chain and Industry 4.0: a literature review. *Int. J. Appl. Decis. Sci.* 16 (1), 41.
- da Rosa Righi, R., Alberti, A.M., Singh, M., 2020. *Blockchain technology for Industry 4.0*. Springer.
- 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.
- Das, L., Bibhu, V., Logeswaran, R., Dadhich, K., Sharma, B., 2023. AI Model for Blockchain Based Industrial IoT and Big Data. In: *Concepts, Methodologies, Tools, and Applications. AI Models for Blockchain-Based Intelligent Networks in IoT Systems* Springer, pp. 55–81.
- Dastres, R., Soori, M., 2021a. *Artif. Neural Netw. Syst., Int. J. Imaging Robot. (IJIR)* 21, 13–25.
- Dastres, R., Soori, M., 2021a. Advances in web-based decision support systems. *Int. J. Eng. Future Technol.* 19, 1–15.
- Dastres, R., Soori, M., 2021b. The role of information and communication technology (ICT) in environmental protection. *Int. J. Tomogr. Simul.* 35, 24–37.
- de Almeida, P.G.R., dos Santos, C.D., Farias, J.S., 2021. Artificial intelligence regulation: a framework for governance. *Ethics Inf. Technol.* 23, 505–525.
- Demertzis, K., Iliadis, L., Tziritas, N., Kikiras, P., 2020. Anomaly detection via blockchain deep learning smart contracts in industry 4.0. *Neural Comput. Appl.* 32, 17361–17378.
- El Akrami, N., Hanine, M., Flores, E.S., Aray, D.G., Ashraf, I., *Unleashing the potential of blockchain and machine learning: Insights and emerging trends from bibliometric analysis*, *IEEE Access*, (2023).
- ElMamy, S.B., Mrabet, H., Gharbi, H., Jemai, A., Trentesaux, D., 2020. A survey on the usage of blockchain technology for cyber-threats in the context of industry 4.0. *Sustainability* 12, 9179.
- Erdem, A., Yildirim, S.O., Angin, P., 2019. Blockchain for ensuring security, privacy, and trust in IoT environments: the state of the art. *Secur., Priv. Trust IoT Environ.* 97–122.

- Esmailian, B., Sarkis, J., Lewis, K., Behdad, S., 2020. Blockchain for the future of sustainable supply chain management in Industry 4.0. *Resour., Conserv. Recycl.* 163, 105064.
- Esmat, A., de Vos, M., Ghiassi-Farrokhfal, Y., Palensky, P., Epema, D., 2021. A novel decentralized platform for peer-to-peer energy trading market with blockchain technology. *Appl. Energy* 282, 116123.
- Faridi, M.S., Ali, S., Duan, G., Wang, G., 2020. Blockchain and IoT based textile manufacturing traceability system in industry 4.0. in: *International conference on security, privacy and anonymity in computation, communication and storage*. Springer, pp. 331–344.
- Fernandez-Carames, T.M., Fraga-Lamas, P., 2019. A review on the application of blockchain to the next generation of cybersecure industry 4.0 smart factories. *Ieee Access* 7, 45201–45218.
- Fernández-Caramés, T.M., Blanco-Novoa, O., Froiz-Míguez, I., Fraga-Lamas, P., 2019. Towards an autonomous industry 4.0 warehouse: A UAV and blockchain-based system for inventory and traceability applications in big data-driven supply chain management. *Sensors* 19, 2394.
- Gad, A.G., Mosa, D.T., Abualigah, L., Abohany, A.A., 2022. Emerging trends in blockchain technology and applications: a review and outlook. *J. King Saud. Univ. -Comput. Inf. Sci.* 34, 6719–6742.
- Gaikwad, L., Khang, A., 2023. AI Powered Workforce Management in Industry 4.0 Era. in: *Designing Workforce Management Systems for Industry 4.0*. CRC Press, pp. 35–46.
- Gami, B., Agrawal, M., Mishra, D.K., Quasim, D., Mehra, P.S., 2023. Artificial intelligence-based blockchain solutions for intelligent healthcare: a comprehensive review on privacy preserving techniques. *Trans. Emerg. Telecommun. Technol.* 34, e4824.
- Garces, E., Li, S., Daim, T.U., 2023. Cybersecurity and Technology Convergence: Analysis of AI, Blockchain, and IoT Using SNA. In: *A Technology Landscape Analysis*. Cybersecurity Springer, pp. 39–70.
- Ghasemzadeh, B., Celik, T., Karimi Ghaleh Jough, F., et al., 2022. Road map to BIM use for infrastructure domains: Identifying and contextualizing variables of infrastructure projects. *Scientia Iranica* 29 (6), 2803–2824.
- Ghildiyal, Y., Singh, R., Alkhayyat, A., Gehlot, A., Malik, P., Sharma, R., Akram, S.V., Alkawai, L.M., 2023. An imperative role of 6G communication with perspective of industry 4.0: challenges and research directions. *Sustain. Energy Technol. Assess.* 56, 103047.
- Ghobakhloo, M., Fathi, M., 2021. Industry 4.0 and opportunities for energy sustainability. *J. Clean. Prod.* 295, 126427.
- Grida, M., Mostafa, N.A., 2023. Are smart contracts too smart for Supply Chain 4.0? A blockchain framework to mitigate challenges. *J. Manuf. Technol. Manag.* 34, 644–665.
- Gupta, R., Tanwar, S., Kumar, N., Tyagi, S., 2020. Blockchain-based security attack resilience schemes for autonomous vehicles in industry 4.0: a systematic review. *Comput. Electr. Eng.* 86, 106717.
- Habbal, A., Ali, M.K., Abuzaraida, M.A., 2024. Artificial Intelligence Trust, Risk and Security Management (AI TRiSM): frameworks, applications, challenges and future research directions. *Expert Syst. Appl.* 240, 122442.
- Hemamalini, V., Mishra, A.K., Tyagi, A.K., Kakulapati, V., 2024. Artificial intelligence–blockchain-enabled–internet of things-based cloud applications for next-generation society. *Autom. Secur. Comput. -Generation Syst.* 65–82.
- Huang, Z., Shen, Y., Li, J., Fey, M., Brecher, C., 2021. A survey on AI-driven digital twins in industry 4.0: smart manufacturing and advanced robotics. *Sensors* 21, 6340.
- Jabarulla, M.Y., Lee, H.-N., 2021. A blockchain and artificial intelligence-based, patient-centric healthcare system for combating the COVID-19 pandemic: Opportunities and applications. *Healthc., MDPI* 1019.
- Javaid, M., Haleem, A., Singh, R.P., Suman, R., 2022. Artificial intelligence applications for industry 4.0: a literature-based study. *J. Ind. Integr. Manag.* 7, 83–111.
- Javaid, M., Haleem, A., Singh, R.P., Khan, S., Suman, R., 2021. Blockchain technology applications for Industry 4.0: a literature-based review. *Block.: Res. Appl.* 2, 100027.
- Jena, A.K., Dash, S.P., 2021. Blockchain technology: introduction, applications, challenges. In: *Blockchain Technology: Applications and Challenges* Springer, pp. 1–11.
- Jha, M.K., Yogeshwari, A., Rubini, P., Singh, M., 2023. Convergence of IoT and AI in metaverse: challenges and opportunities. In: *5th International Conference on Inventive Research in Computing Applications (ICIRCA) 2023*. IEEE, pp. 1462–1467.
- Joshi, S., Pise, A.A., Shrivastava, M., Revathy, C., Kumar, H., Alsetoohy, O., Akwafo, R., 2022. Adoption of blockchain technology for privacy and security in the context of industry 4.0. *Wirel. Commun. Mob. Comput.* 2022.
- Jough, F.K.G., Şensoy, S., 2016. Prediction of seismic collapse risk of steel moment frame mid-rise structures by meta-heuristic algorithms. *Earthq. Eng. Eng. Vib.* 15, 743–757.
- Karimi Ghaleh Jough, F., 2023. The contribution of steel wallposts to out-of-plane behavior of non-structural masonry walls. *Earthq. Eng. Eng. Vib.* 1–20.
- Karimi Ghaleh Jough, F., Beheshti Aval, S., 2018. Uncertainty analysis through development of seismic fragility curve for an SMRF structure using an adaptive neuro-fuzzy inference system based on fuzzy C-means algorithm. *Scientia Iranica* 25 (6), 2938–2953.
- Karimi Ghaleh Jough, F., Şensoy, S., 2020. Steel moment-resisting frame reliability via the interval analysis by FCM-PSO approach considering various uncertainties. *J. Earthq. Eng.* 24 (1), 109–128.
- Karimi Ghaleh Jough, F., Golhashem, M., 2020. Assessment of out-of-plane behavior of non-structural masonry walls using FE simulations. *Bullet. Earthq. Eng.* 18 (14), 6405–6427.
- Karimi Ghaleh Jough, F., Ghasemzadeh, B., 2023. Uncertainty Interval Analysis of Steel Moment Frame by Development of 3D-Fragility Curves Towards Optimized Fuzzy Method. *Arab. J. Sci. Eng.* 1–18.
- Karimi Ghaleh Jough, F., Veghar, M., Beheshti-Aval, S.B., 2021. Epistemic Uncertainty Treatment Using Group Method of Data Handling Algorithm in Seismic Collapse Fragility. *Lat. Am. J. Solids Struct.* 18, e355.
- Kashem, M.A., Shamsuddoha, M., Nasir, T., Chowdhury, A.A., 2023. Supply chain disruption versus optimization: a review on artificial intelligence and blockchain. *Knowledge* 3, 80–96.
- Keleko, A.T., Kamsu-Foguem, B., Ngouna, R.H., Tongne, A., 2022. Artificial intelligence and real-time predictive maintenance in industry 4.0: a bibliometric analysis, AI and Ethics. 2, 553–577.
- Kumar, L., Sharma, R.K., 2023. Exploring research issues and potential future directions in industry 4.0 adoption in SMEs: a comprehensive analysis and integration. *FIIB Bus. Rev.* 23197145231203512.
- Kumar, S., Lim, W.M., Sivarajah, U., Kaur, J., 2023b. Artificial intelligence and blockchain integration in business: trends from a bibliometric-content analysis. *Inf. Syst. Front.* 25, 871–896.
- Lage, O., **Blockchain: from industry 4.0 to the machine economy**, in: *Computer Security Threats*, IntechOpen, 2019.
- Lal, B., Kumar, M.A., Chintham, N., Pokhriyal, S., 2023. Development of Product Quality with Enhanced Productivity in Industry 4.0 with AI Driven Automation and Robotic Technology. In: *Second International Conference on Augmented Intelligence and Sustainable Systems (ICAISS) 2023*. IEEE, pp. 184–189.
- Latif, H., 2023. Advancing data integrity in banking: AI/ML solutions and best practice. *Int. J. Comput. Sci. Technol.* 7, 185–203.
- Lee, J., Azamfar, M., Singh, J., 2019. A blockchain enabled cyber-physical system architecture for industry 4.0 manufacturing systems. *Manuf. Lett.* 20, 34–39.
- Leng, J., Ye, S., Zhou, M., Zhao, J.L., Liu, Q., Guo, W., Cao, W., Fu, L., 2020. Blockchain-secured smart manufacturing in industry 4.0: a survey. *IEEE Trans. Syst., Man, Cybern.: Syst.* 51, 237–252.
- Li, J., Herdem, M.S., Nathwani, J., Wen, J.Z., 2023. Methods and applications for Artificial Intelligence. *Big Data, Internet Things, Block smart Energy Manag., Energy AI* 11, 100208.
- Li, M., Hu, D., Lal, C., Conti, M., Zhang, Z., 2020. Blockchain-enabled secure energy trading with verifiable fairness in industrial Internet of Things. *IEEE Trans. Ind. Inform.* 16, 6564–6574.
- Li, Y., Mardani, A., 2023. Digital twins and blockchain technology in the industrial Internet of Things (IIoT) using an extended decision support system model: Industry 4.0 barriers perspective. *Technol. Forecast. Soc. Change* 195, 122794.
- Li, Z., Tian, Z., Wang, L., Zhong, R.Y., 2022. Blockchain-enabled product lifecycle management. in: *Design and Operation of Production Networks for Mass Personalization in the Era of Cloud Technology*. Elsevier, pp. 349–379.

- Lin, C., He, D., Huang, X., Choo, K.-K.R., Vasilakos, A.V., 2018. BSEfn: A blockchain-based secure mutual authentication with fine-grained access control system for industry 4.0. *J. Netw. Comput. Appl.* 116, 42–52.
- Liu, X., Wang, W.M., Guo, H., Barenji, A.V., Li, Z., Huang, G.Q., 2020. Industrial blockchain based framework for product lifecycle management in industry 4.0. *Robot. Comput. -Integr. Manuf.* 63, 101897.
- Lypnyskiy, D.V., 2019. Opportunities and challenges of blockchain in industry 4.0. *Econ. Ind.* 82–100.
- Marechaux, J.-L., Towards advanced artificial intelligence using blockchain technologies, *IEEE Blockchain Technical Briefs*, (2019).
- Mehta, D., Tanwar, S., Bodkhe, U., Shukla, A., Kumar, N., 2021. Blockchain-based royalty contract transactions scheme for Industry 4.0 supply-chain management. *Inf. Process. Manag.* 58, 102586.
- Mendoza Arvizo, A.L., Avelar Sosa, L., García Alcaraz, J.L., Cruz-Mejía, O., 2023. Beneficiary contracts on a lightweight blockchain architecture using smart contracts: a smart healthcare system for medical records. *Appl. Sci.* 13, 6694.
- Mhlanga, D., 2023. Block chain technology for digital financial inclusion in the industry 4.0, towards sustainable development? *Front. Block* 6, 1035405.
- Mourtzis, D., Angelopoulos, J., Panopoulos, N., 2022. A literature review of the challenges and opportunities of the transition from industry 4.0 to society 5.0. *Energies* 15, 6276.
- Muftah, R.J., Blockchain Technology and Its Synergy with Bitcoin, Information Technology Psychology, and AI: A Comprehensive Review, (2023).
- Mushtaq, A., Haq, I.U., 2019. Implications of blockchain in industry 4.0. in: *International Conference on Engineering and Emerging Technologies (ICEET) 2019*. IEEE, pp. 1–5.
- Narayan, R., Gehlot, A., Singh, R., Akram, S.V., Priyadarshi, N., Twala, B., 2022. Hospitality feedback system 4.0: digitalization of feedback system with integration of industry 4.0 enabling technologies. *Sustainability* 14, 12158.
- Nuhui, A., Aliu, F., 2023. The Benefits of Combining AI and Blockchain in Enhancing Decision-Making in Banking Industry. In: *Integrating Blockchain and Artificial Intelligence for Industry 4.0 Innovations* Springer, pp. 305–326.
- Nuttah, M.M., Roma, P., Nigro, G.L., Perrone, G., 2023. Understanding blockchain applications in Industry 4.0: from information technology to manufacturing and operations management. *J. Ind. Inf. Integr.* 33, 100456.
- Oladapo, K.A., Adedeji, F., Nzenwata, U.J., Quoc, B.P., Dada, A., 2023. Fuzzified Case-Based Reasoning Blockchain Framework for Predictive Maintenance in Industry 4.0. In: *Data Analytics and Computational Intelligence: Novel Models, Algorithms and Applications* Springer, pp. 269–297.
- Onik, M.M.H., Miraz, M.H., Kim, C.-S., A recruitment and human resource management technique using blockchain technology for industry 4.0, in: *Smart Cities Symposium 2018, IET*, 2018, pp. 1–6.
- Otoun, S., Ridhawi, I.A.I., Mouftah, H., 2022. A federated learning and blockchain-enabled sustainable energy trade at the edge: a framework for industry 4.0. *IEEE Internet Things J.* 10, 3018–3026.
- Pandey, S., Kumar De, A., Choudhary, S., Bhushan, B., Bhatia, S., Leveraging Blockchain Technology in Industry 4.0 and Industrial Internet of Things (IIoT) Scenarios, in: *Low Power Architectures for IoT Applications*, Springer, 2023, pp. 201–222.
- Pathan, M.S., Richardson, E., Galvan, E., Mooney, P., 2023. The role of artificial intelligence within circular economy activities—a view from Ireland. *Sustainability* 15, 9451.
- Patil, S.M., Baramati, P., Dhone, N.C., Chourasiya, R.H., 2023. Industry 4.0 technologies in the context of supply chain management 4.0. *Online J. Distance Educ. e-Learn.*(11 0).
- Pfeiffer, A., Bugeja, M., 2021. Introd. Concept “Digital-Agent Signatures”: How SSI Can. Be Expand. Needs Ind. 4.0, *Artif. Intell. Ind. 4.0: A Collect. Innov. Res. Case-Stud.* that are Reworking Way We Look. Ind. 4.0 Thanks Artif. Intell. 213–233.
- Picone, M., Cirani, S., Veltri, L., 2021. Blockchain security and privacy for the Internet of Things. , *MDPI* 892.
- Popkova, E.G., Bogoviz, A.V., Lobova, S.V., Vovchenko, N.G., Sergi, B.S., 2023. Blockchain, sustainability and clean energy transition. *Glob. Transit.* 5, 64–78.
- Prause, G., 2019. Smart contracts for smart supply chains. *IFAC-Pap.* 52, 2501–2506.
- Pustišek, M., Živić, N., Kos, A., Blockchain: Technology and Applications for Industry 4.0, Smart Energy, and Smart Cities, Walter de Gruyter GmbH & Co KG, 2021.
- Kumar, R., Arjunaditya; Singh, D.; Srinivasan, K.; Hu, Y.-C AI-Powered Blockchain Technology for Public Health: A Contemporary Review, Open Challenges, and Future Research Directions. *Healthcare* 2023a, 11, 81, in, 2022.
- 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-iiot enabled architecture, *arXiv preprint arXiv:2012.10011*, (2020).
- Rahman, Z., Khalil, I., Yi, X., Atiquzzaman, M., 2021. Blockchain-based security framework for a critical industry 4.0 cyber-physical system. *IEEE Commun. Mag.* 59, 128–134.
- Raja, G., Manaswini, Y., Vivekanandan, G.D., Sampath, H., Dev, K., Bashir, A.K., AI-powered blockchain-a decentralized secure multiparty computation protocol for IIoT, in: *IEEE INFOCOM 2020-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, IEEE, 2020, pp. 865–870.
- Rajmohan, R., Kumar, T.A., Pavithra, M., Sandhya, S., Julie, E., Nayahi, J., Jhanjhi, N., 2020. Blockchain: next-generation technology for industry 4.0, *Blockchain Technology* 177–198.
- Rathore, B., 2023. Digit. Transform. 4.0: Integr. Artif. Intell. Metaverse Mark., *Eduzone: Int. Peer Rev. /Referee Multidiscip. J.* 12, 42–48.
- Saheb, T., Jamthe, S., Saheb, T., 2022. Developing a conceptual framework for identifying the ethical repercussions of artificial intelligence: a mixed method analysis. *J. AI, Robot. Workplace Autom.* 1, 371–398.
- Salah, K., Rehman, M.H.U., Nizamuddin, N., Al-Fuqaha, A., 2019. Blockchain for AI: review and open research challenges. *IEEE Access* 7, 10127–10149.
- Salama, R., Al-Turjman, F., Altrjman, C., Kumar, S., Chaudhary, P., 2023. A Comprehensive Survey of Blockchain-Powered Cybersecurity-A survey. In: *International Conference on Computational Intelligence, Communication Technology and Networking (CICTN) 2023*. IEEE, pp. 774–777.
- Sang, G.M., Xu, L., de Vrieze, P., 2021. A predictive maintenance model for flexible manufacturing in the context of industry 4.0. *Front. big Data* 4, 663466.
- Sang, G.M., Xu, L., de Vrieze, P., Bai, Y., Pan, F., 2020. Predictive maintenance in industry 4.0. : *Proc. 10th Int. Conf. Inf. Syst. Technol.* 1–11.
- Sasikumar, R., Karthikeyan, P., Murugan, T., 2023. Privacy and Security Through Blockchain in Industry 4.0. In: *An Industrial Cybersecurity Perspective. Handbook of Research on Data Science and Cybersecurity Innovations in Industry 4.0 Technologies* IGI Global, pp. 315–334.
- Schiliro, D., 2022. Digital Economy and Digital Transformation. In: *Digital Technologies for Entrepreneurship in Industry 4.0* IGI Global, pp. 26–42.
- 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 IIoT and the Financial Sector*, IGI Global, 2021, pp. 248–276.
- Shah, K., Patel, N., Thakkar, J., Patel, C., 2022. Exploring applications of blockchain technology for Industry 4.0. *Mater. Today.: Proc.* 62, 7238–7242.
- Shahbazi, Z., Byun, Y.-C., 2021. Smart manufacturing real-time analysis based on blockchain and machine learning approaches. *Appl. Sci.* 11, 3535.
- Sharma, A., Podoplelova, E., Shapovalov, G., Tselykh, A., Tselykh, A., 2021. Sustainable smart cities: convergence of artificial intelligence and blockchain. *Sustainability* 13, 13076.
- Shinde, N.K., Seth, A., Kadam, P., 2023. Exploring the synergies: a comprehensive survey of blockchain integration with artificial intelligence. *Mach. Learn., IoT Divers. Appl., Mach. Learn. Optim. Eng. Des.* 85–119.
- Shojaeinasab, A., Charter, T., Jalayer, M., Khadivi, M., Ogunfowora, O., Raiyani, N., Yaghoubi, M., Najjaran, H., 2022. Intelligent manufacturing execution systems: a systematic review. *J. Manuf. Syst.* 62, 503–522.
- Shrivastava, A., Krishna, K.M., Rinawa, M.L., Soni, M., Ramkumar, G., Jaiswal, S., 2023. Inclusion of IIoT, ML, and blockchain technologies in next generation industry 4.0 environment. *Mater. Today.: Proc.* 80, 3471–3475.
- Siddique, H.M.A., Yaqub, R.M.S., Akram, H.M.Z., Khurshid, R., 2023. Determinants of AI non-fungible tokens gaming and blockchain based digital marketing: a revolution of metaverse in Asia Pacific Region. *Pak. J. Humanit. Soc. Sci.* 11, 1909–1931-1931.
- Siddiqui, Z.A., Haroon, M., 2022. Application of artificial intelligence and machine learning in blockchain technology. in: *Artificial Intelligence and Machine Learning for EDGE Computing*. Elsevier, pp. 169–185.
- Silva, T.Bd, Morais, E.Sd, Almeida, L.F.Fd, Rosa Righi, Rd, Alberti, A.M., 2020. Blockchain and industry 4.0: overview, convergence, and analysis, *Blockchain Technology for Industry 4.0: secure, decentralized, distributed and trusted industry*. Environment 27–58.

- Singh, M., 2020. Blockchain Technology for Industry 4.0, Secure, Decentralized, Distributed and Trusted Industry Environment. *Blockchain Technology for Data Management in Industry 4.0*. ResearchGate, pp. 59–72.
- Singh, P., Elmi, Z., Lau, Y.-y., Borowska-Stefańska, M., Wiśniewski, S., Dulebenets, M.A., **Blockchain and AI technology convergence: Applications in transportation systems**, *Vehicular Communications*, (2022) 100521.
- Singh, S.K., Rathore, S., Park, J.H., 2020. Blockiotintelligence: a blockchain-enabled intelligent IoT architecture with artificial intelligence. *Future Gener. Comput. Syst.* 110, 721–743.
- Soori, M., 2023. Deformation error compensation in 5-Axis milling operations of turbine blades. *J. Braz. Soc. Mech. Sci. Eng.* 45, 289.
- Soori, M., Arezoo, B., 2020. Virtual machining systems for CNC milling and turning machine tools: a review. *Int. J. Eng. Future Technol.* 18, 56–104.
- Soori, M., Asmael, M., 2021. Minimization of deflection error in five axis milling of impeller blades. *Facta Univ., Ser.: Mech. Eng.* 21, 175–190.
- Soori, M., Arezoo, B., 2022a. A review in machining-induced residual stress. *J. N. Technol. Mater.* 12, 64–83.
- Soori, M., Arezoo, B., 2022b. Minimization of surface roughness and residual stress in grinding operations of inconel 718. *J. Mater. Eng. Perform.* 1–10.
- Soori, M., Arezoo, B., 2023a. Cutting tool wear minimization in drilling operations of titanium alloy Ti-6Al-4V. *Proc. Inst. Mech. Eng., Part J: J. Eng. Tribology* 13506501231158259.
- Soori, M., Arezoo, B., 2023a. The effects of coolant on the cutting temperature, surface roughness and tool wear in turning operations of Ti6Al4V alloy. *Mech. Based Des. Struct. Mach.* 1–23.
- Soori, M., Arezoo, B., 2023a. Dimensional, geometrical, thermal and tool deflection errors compensation in 5-Axis CNC milling operations. *Aust. J. Mech. Eng.* 1–15.
- Soori, M., Arezoo, B., 2023b. Minimization of surface roughness and residual stress in abrasive water jet cutting of titanium alloy Ti6Al4V. *Proc. Inst. Mech. Eng., Part E: J. Process Mech. Eng* 09544089231157972.
- Soori, M., Arezoo, B., **Effect of cutting parameters on tool life and cutting temperature in milling of AISI 1038 carbon steel**, *Journal of New Technology and Materials*, (2023b).
- Soori, M., Arezoo, B., **Modification of CNC Machine Tool Operations and Structures Using Finite Element Methods, A Review**, *Jordan Journal of Mechanical and Industrial Engineering*, (2023c).
- Soori, M., Arezoo, B., Habibi, M., 2013. Dimensional and geometrical errors of three-axis CNC milling machines in a virtual machining system. *Comput. -Aided Des.* 45, 1306–1313.
- Soori, M., Arezoo, B., Habibi, M., 2014. Virtual machining considering dimensional, geometrical and tool deflection errors in three-axis CNC milling machines. *J. Manuf. Syst.* 33, 498–507.
- Soori, M., Arezoo, B., Habibi, M., 2016. Tool deflection error of three-axis computer numerical control milling machines, monitoring and minimizing by a virtual machining system. *J. Manuf. Sci. Eng.* 138, 081005.
- Soori, M., Arezoo, B., Habibi, M., 2017. Accuracy analysis of tool deflection error modelling in prediction of milled surfaces by a virtual machining system. *Int. J. Comput. Appl. Technol.* 55, 308–321.
- Soori, M., Arezoo, B., Dastres, R., 2023a. Machine learning and artificial intelligence in CNC machine tools, a review. *Sustain. Manuf. Serv. Econ.*, 100009.
- Soori, M., Arezoo, B., Dastres, R., 2023a. Artificial intelligence, machine learning and deep learning in advanced robotics, a review. *Cogn. Robot.* 3, 54–70.
- Soori, M., Arezoo, B., Dastres, R., 2023a. Optimization of Energy Consumption in Industrial Robots, A Review. *Cogn. Robot.*
- Soori, M., Arezoo, B., Dastres, R., 2023b. Internet of things for smart factories in industry 4.0, a review. *Internet Things Cyber-Phys. Syst.*
- Soori, M., Arezoo, B., Dastres, R., 2023b. Virtual manufacturing in industry 4.0: a review. *Data Sci. Manag.*
- Soori, M., Arezoo, B., Dastres, R., 2023c. Artificial neural networks in supply chain management, a review. *J. Econ. Technol.*
- Srivastava, G., Sapra, D., Sinha, A., Anup, M., Sinwar, D., 2024. Artificial intelligence and IoT-assisted sustainable manufacturing for Industry 4.0. in: *Computational Intelligence based Optimization of Manufacturing Process for Sustainable Materials*. CRC Press., pp. 15–34.
- Su, D., Zhang, L., Peng, H., Saeidi, P., Tirkolaee, E.B., 2023. Technical challenges of blockchain technology for sustainable manufacturing paradigm in Industry 4.0 era using a fuzzy decision support system. *Technol. Forecast. Soc. Change* 188, 122275.
- Sultana, T., Almogren, A., Akbar, M., Zuair, M., Ullah, I., Javaid, N., 2020. Data sharing system integrating access control mechanism using blockchain-based smart contracts for IoT devices. *Appl. Sci.* 10, 488.
- Tadaka, S.M., 2020. Applications of blockchain in healthcare, industry 4, and cyber-physical systems. In: *7th International Conference on Internet of Things: Systems, Management and Security (IOTSMS) 2020*. IEEE, pp. 1–8.
- Taherdoost, H., 2022. Blockchain technology and artificial intelligence together: a critical review on applications. *Appl. Sci.* 12, 12948.
- Tan, W., Zhu, H., Tan, J., Zhao, Y., Xu, L.D., Guo, K., 2022. A novel service level agreement model using blockchain and smart contract for cloud manufacturing in industry 4.0. *Enterprise. Inf. Syst.* 16, 1939426.
- Tanwar, S., Parekh, K., Evans, R., 2020. Blockchain-based electronic healthcare record system for healthcare 4.0 applications. *J. Inf. Secur. Appl.* 50, 102407.
- Teiserenc, B., Sepasgozar, S., 2021. Adoption of blockchain technology through digital twins in the construction industry 4.0: a pestels approach. *Buildings* 11, 670.
- Teufel, B., Sentic, A., Barmet, M., 2019. Blockchain energy: blockchain in future energy systems. *J. Electron. Sci. Technol.* 17, 100011.
- Thangadurai, K., Saravanan, M., Geetha, T., Poornachandar, R.U.T., Mailsamy, M., 2022. Maximizing the potential: effective implementation of ai in blockchain technology. *Turk. J. Comput. Math. Educ. (TURCOMAT)* 13, 1369–1377.
- Timucin, T., BİROĞUL, S., 2021. A survey: making “smart contracts” really smart. *Trans. Emerg. Telecommun. Technol.* 32, e4338.
- Timuçin, T., Bıroğul, S., 2023. Collaborative smart contracts (CoSC): example of real estate purchase and sale (s). *J. Supercomput.* 1–20.
- Trakadas, P., Simeoens, P., Gkonis, P., Sarakis, L., Angelopoulos, A., Ramallo-González, A.P., Skarmeta, A., Trochoutsos, C., Calvo, D., Pariente, T., 2020. An artificial intelligence-based collaboration approach in industrial iot manufacturing: Key concepts, architectural extensions and potential applications. *Sensors* 20, 5480.
- Tsaramiris, G., Kantaros, A., Al-Darraj, I., Piromalis, D., Apostolopoulos, C., Pavlopoulou, A., Alrammal, M., Ismail, Z., Buhari, S.M., Stojmenovic, M., 2022. A modern approach towards an industry 4.0 model: from driving technologies to management. *J. Sens.* 2022, 1–18.
- Tsolakis, N., Schumacher, R., Dora, M., Kumar, M., 2023. Artificial intelligence and blockchain implementation in supply chains: a pathway to sustainability and data monetisation? *Ann. Oper. Res.* 327, 157–210.
- Tyagi, A.K., 2024. Blockchain and Artificial Intelligence for Cyber Security in the Era of Internet of Things and Industrial Internet of Things Applications. In: *AI and Blockchain Applications in Industrial Robotics IGI Global*, pp. 171–199.
- Tyagi, A.K., Aswathy, S., Abraham, A., 2020. Integrating blockchain technology and artificial intelligence: Synergies perspectives challenges and research directions. *J. Inf. Assur. Secur.* 15, 1554.
- Tyagi, A.K., Dananjayan, S., Agarwal, D., Thariq Ahmed, H.F., 2023. Blockchain—Internet of Things applications: opportunities and challenges for industry 4.0 and society 5.0. *Sensors* 23, 947.
- Ur, R.K., Mian, Z., Yasir, A., **Implementation of Reliability Centered Maintenance (RCM) in the background of industry 4.0—Issues, Challenges, and Opportunities**, (2023).
- Usmani, U.A., Happonen, A., Watada, J., 2023. Advancements in Industry 4.0 Asset Management: Interoperability and Cyber Security Challenges and Opportunities. in: *Proceedings of the Future Technologies Conference*. Springer, pp. 468–488.
- Varadam, D., Shankar, S.P., Bharadwaj, A., Saxena, T., Agrawal, S., Dayananda, S., 2024. Enhancing Industrial Robotics Performance and Security With AI and Blockchain Technologies. In: *AI and Blockchain Applications in Industrial Robotics IGI Global*, pp. 58–81.
- Vashishth, T.K., Sharma, V., Sharma, K.K., Kumar, B., Chaudhary, S., Panwar, R., 2024. Intelligent Resource Allocation and Optimization for Industrial Robotics Using AI and Blockchain. In: *AI and Blockchain Applications in Industrial Robotics IGI Global*, pp. 82–110.
- Vegesna, V.V., **Blockchain, A.I.-Enabled, 2023. Solutions for sustainable development, harnessing technological synergy towards a greener future**, *international journal of sustainable development through AI*. ML IoT 2, 1–10.
- Venkatesh, V., Raman, R., Cruz-Jesus, F., 2023. AI and emerging technology adoption: a research agenda for operations management. *Int. J. Prod. Res.* 1–11.
- Wahab, N.A.B.A., Nor, R.B.M.A., 2023. The role of artificial intelligence in waste reduction in the beverage industry: a comprehensive strategy for enhanced sustainability and efficiency. *AI IoT Fourth Ind. Revolut. Rev.* 13, 1–8.

- Wan, Y., Gao, Y., Hu, Y., 2022. Blockchain application and collaborative innovation in the manufacturing industry: Based on the perspective of social trust. *Technol. Forecast. Soc. Change* 177, 121540.
- Wang, Q., Su, M., 2020. Integrating blockchain technology into the energy sector—from theory of blockchain to research and application of energy blockchain. *Comput. Sci. Rev.* 37, 100275.
- Wu, Y., Zhang, N., Yan, Z., Atiquzzaman, M., Xiang, Y., 2023. Guest editorial special issue on AI and blockchain-powered iot sustainable computing. *IEEE IoT J.* 10, 6531–6534.
- Xu, X., Gu, J., Yan, H., Liu, W., Qi, L., Zhou, X., 2022. Reputation-aware supplier assessment for blockchain-enabled supply chain in industry 4.0. *IEEE Trans. Ind. Inform.* 19, 5485–5494.
- Yaqoob, I., Salah, K., Uddin, M., Jayaraman, R., Omar, M., Imran, M., 2020. Blockchain for digital twins: recent advances and future research challenges. *Ieee Netw.* 34, 290–298.
- Zaman, S.A.A., Dawood, H.M., Zehra, S.N., Saeed, S.Z., 2023. Blockchain Driven Supply Chain and Industry 4.0 Technologies. In: *A Multi-dimensional Perspective. Blockchain Driven Supply Chain Management* Springer, pp. 219–238.
- Zarrin, J., Wen Phang, H., Babu Saheer, L., Zarrin, B., 2021. Blockchain for decentralization of internet: prospects, trends, and challenges. *Clust. Comput.* 24, 2841–2866.
- Zhang, L., Xie, Y., Zheng, Y., Xue, W., Zheng, X., Xu, X., 2020. The challenges and countermeasures of blockchain in finance and economics. *Syst. Res. Behav. Sci.* 37, 691–698.