# Blockchain Integration into Digital Twins for Secure and Autonomous Production Systems

Maksym Zhmutskyi[1*,†], Andrii Oliinyk[2,†], Tetiana Kolpakova[3,†], Yevgeny Gofman[4,†] and Matviy Ilyashenko[5,†]

[1] *National University "Zaporizhzhya Polytechnic", 64 Zhukovskogo Street 69063 Zaporizhzhia, Ukraine*
[2] *National University "Zaporizhzhya Polytechnic", 64 Zhukovskogo Street 69063 Zaporizhzhia, Ukraine*
[3] *National University "Zaporizhzhya Polytechnic", 64 Zhukovskogo Street 69063 Zaporizhzhia, Ukraine*
[4] *National University "Zaporizhzhya Polytechnic", 64 Zhukovskogo Street 69063 Zaporizhzhia, Ukraine*
[5] *National University "Zaporizhzhya Polytechnic", 64 Zhukovskogo Street 69063 Zaporizhzhia, Ukraine*

## Abstract

Digital twins are currently used in manufacturing to copy physical objects, observe them, tell when they may fail, and improve production processes. However, there are some weaknesses, e.g., dependency on centralized servers that are insecure, can lead to system failure, and are a challenge to access, causing downtime and losses.

This paper proposes a decentralized approach with blockchain technology to improve data integrity, security, and robustness. This is because blockchain does not allow anyone to change the data and guarantees the continuity of the service even if one of the nodes is down.

The proposed system is based on IoT sensors for data collection and distributed algorithms for analysis. Some of the processes such as predictive maintenance and supply chain management are handled by smart contracts to minimize the role of humans and costs.

The study could be applied to real life in various industries including aviation, energy and pharmaceuticals where data security is a concern. Decentralized digital twins increase cybersecurity, reduce costs, and increase decision-making confidence.

Future work should include AI integration for the generation of learning capacity in the systems and quantum computing for the enhancement of data processing to increase automation and efficiency.

## Keywords

decentralized digital twins, blockchain, smart contracts, data security, production automation, Industry 4.0, predictive maintenance.



1* Corresponding author.
† These authors contributed equally.
maksym.zhmutskyi@gmail.com (M. Zhmutskyi); olejnikaa@gmail.com (A. Oliinyk); t.o.kolpakova@gmail.com (T. Kolpakova); gofmanjenek@gmail.com (Y. Gofman); mathew@zp.edu.ua (M. Ilyashenko)
0009-0005-8440-8365 (M. Zhmutskyi); 0000-0002-6740-6078 (A. Oliinyk); 0000-0001-8307-8134 (T. Kolpakova); 0009-0001-2885-4185 (Y. Gofman); 0000-0003-4624-4687 (M. Ilyashenko)

## 1. Introduction

Digital twins are one of the main technologies of the fourth industrial revolution that enables the creation of digital copies of physical objects, which provide real time monitoring of the object's condition and optimization of the production process. Digital twins are applied across various industries such as mechanical engineering, energy, pharmaceuticals and aviation to offer condition based maintenance, improve productivity and minimize downtime of equipment. Digital twins can be credited with helping manufacturing companies improve the management of their equipment, data analysis and decision making to enhance production processes. In addition, they can simulate the behavior of equipment under various conditions, thus enhancing the overall business operations and reducing the overall costs of operation [1, 2, 3].

However, traditional digital twins have some drawbacks, for instance, they rely on centralized servers to store and process data, which has some disadvantages such as the risk of cyber attacks, information loss in the case of centralized system failure and dependency with cloud service providers. Moreover, centralization offers some constraints in the sense that large production networks are difficult to integrate new components into and, therefore, hinder the development of automation. If a central server or cloud platform fails, companies can also lose critical data that is used in the digital twin, and thus the reliability of the digital twin is greatly reduced and may result in production downtime. This is particularly important in the energy and aviation industries where the equipment has to be constantly checked and always in use [4, 5, 6].

As a result of the above challenges the decentralization of the digital twin based on blockchain technology is proposed for its implementation. The decentralized structure is more secure, the data is less likely to be manipulated and all operations are more transparent. Smart contracts enhance the coordination of the various elements of the production value chain and thus minimize the risks associated with human interference. Therefore, a decentralized digital twin enhances the efficiency and safety of production processes through on-line monitoring, failure-cue detection, and effective management of resources. When the digital twin is integrated with blockchain, companies can not only protect their information but also build a management system that is able to monitor and control the production process and adjust to changes in the equipment and production environment by itself. Therefore, the decentralized digital twin is a significant step in the evolution of industrial automation and presents new opportunities for improving the performance of enterprises in the digital economy [7, 8, 9, 10, 11].

## 2. Materials and methods

In the study, the decentralized digital twin of production systems is explored from a holistic perspective. The main components of the study are the latest blockchain platforms such as Hyperledger, Ethereum and Polkadot to decentralized data storage, operational transparency and process automation using smart contracts. Stokes (2019) discusses the integration of digital twins and IoT sensors for real-time information collection and processing, which is a critical component of the effective functioning of production systems in the Industry 4.0 concept [2, 3, 8].

The research methodology entails a systems analysis to determine the pros and cons of centralized and decentralized digital twin architectures. Modeling is used to evaluate the effectiveness of blockchain solutions and to identify their impact on the security, reliability and automation of production processes. The performance and scalability of the proposed model will be assessed through a comparison of data processing speed, security level, and infrastructure costs of traditional and decentralized systems [4, 5, 12].

The role of smart contracts in the management of production systems is also highlighted. In particular, their role in the predictive maintenance of equipment, supply chain management, and resource optimization is considered. The analysis is done based on real examples of the implementation of decentralized technologies in aircraft construction, energy and pharmaceuticals sectors. As a result of the study, it will be possible to determine the feasibility and potential of decentralized digital twins in the current production systems [13, 14, 15, 16].

## 3. The concept of decentralized digital twins and their implementation

A distributed digital twin is a system where data from production facilities is stored and processed in a network rather than in a single server. This enhances the information security, avoids single point of failure and maintains system stability when there is a failure of a single node. Decentralization also reduces the risk of cyber attack because data access is restricted by the use of distributed storage and encryption techniques [6, 10, 14].

In its most basic form, a digital twin can be defined as a set of parameters that are time-varying:

$$DT(t)=\{S(t), D(t), A(t)\} \tag{1}$$

where S(t) is a set of parameters of the state of a physical object at time t, D(t) is a set of data obtained from IoT sensors, A(t) - analysis and forecasting algorithms applied to the data.

The dynamics of the transition between the states of a digital twin are modeled by a dynamic model:

$$S(t+\Delta t)=f(S(t), D(t), A(t))+\varepsilon \tag{2}$$

where f - function of updating the state based on the received data and applied algorithms, ε - measurement or forecast error.

This approach allows:

- Enhanced security by way of encryption of the data and storing it on different nodes of the network making it difficult to steal or alter.
- Prevent data loss with distributed storage that provides backup and recovery of information in the event of technical failure.
- You can use smart contracts to carry out operations and carry out processes without the intervention of intermediaries which in turn reduces the chances of errors in decision making and increases efficiency.
- To maximize effectiveness in data processing, maintain real time updates from the digital counterpart, so that current information on the state of production systems can be received without delay.
- Transparency of operations should be ensured by the use of blockchain, which offers an audit of each process, the recording of all changes, and the capacity to verify the authenticity of data [15, 17, 18].

Developing a decentralized digital twin implies incorporating blockchain platforms like Hyperledger, Ethereum and Polkadot to control data and guarantee trust among the participants in the production process. The choice of a particular platform is determined by the transaction speed, security demands and scalability [8, 12, 14].

The data on the blockchain is presented in the form of a hash relationship between the blocks:

$$B_i=H(B_{i-1}, T_i) \tag{3}$$

where $B_i$ – block i in the blockchain chain, H(x) – a hash function that ensures data integrity, $T_i$ – transactions containing updated information about the state of the digital twin.

Smart contracts are used to execute the execution of operations between elements of a production system without the use of third parties.

In its formal definition, a smart contract can be expressed as a set of rules:

$$SC:(C,E,A)\rightarrow O \tag{4}$$

where C - input conditions (for example, temperature exceedance), E - events that trigger the execution of the contract, A - a set of actions (for example, activation of the cooling system), O - result of contract execution.

Thus, the use of formal mathematical models and blockchain technology guarantees the efficiency and effectiveness of decentralized digital twins in production systems. In general, a decentralized digital twin model has many advantages over traditional centralized solutions. The high reliability is provided by a fault-tolerant architecture where the production systems can continue to function when some of the nodes are down; the integration of IoT sensors and distributed data processing algorithms enables real-time updates and failure prediction of equipment. This allows to predict possible equipment failures [9, 19, 20].

Furthermore, smart contracts enhance the degree of automation, and lessen the reliance on human interference and talent to manage resources effectively. Blockchain technology delivers operational regularity and the visibility of the process, which is significant for high-security risk industries, like aviation, energy or pharmaceuticals.

Thus, decentralized digital twins not only enhance the production process efficiency but also create a platform for developing autonomous, self-tuning control systems and thus, create new possibilities for the digital transformation of industry [11, 16, 19].

## 4. Implementation and environmental sustainability of decentralized digital twins

Another equally important aspect of the implementation is the development of a decentralized system for data gathering and processing. The digital twin is connected with IoT sensors that send data to the blockchain platform, thus making each piece of information immutable. This makes it impossible to alter or tamper with the information, which is very important in high risk industries such as energy, aviation and pharmaceuticals. Therefore, companies can continuously get accurate information that can be used in the decision making process and for improving the efficiency of production assets [1, 5, 15, 16].

Smart contracts are used for the automation of many operations; thus, the need for human intervention is reduced to a minimum and it is possible to avoid the human factor in crucial processes:

- Predictive maintenance: To detect faults, perform data analysis and initiate repair work, automatic faults are detected. It can also keep a track of the wear and tear of parts and if the parts reach the critical parameters it can order new components on its own.
- Supply chain management: Control the movement of materials and components, to avoid counterfeiting. End to end product lifecycle management is possible with the help of blockchain records, right from raw material extraction to the end use to make it transparent and accountable.
- Resource optimization: Minimization of the use of energy and material resources to cut down on costs. It can regulate energy consumption in real time by predicted models, and hence avoid wasting money and improving the environmental sustainability of the company.
- Continuous auditing and monitoring: Decentralized technologies are used in such a way that all operations are readily available and current, and any anomalies can be spotted right away with appropriate action taken.

In addition, companies can enhance their sustainability by ensuring proper monitoring of emissions and material consumption. Digital twin can be implemented with the help of blockchain to not only reduce energy consumption but also to integrate renewable energy sources and produce environmentally friendly products. Furthermore, the digital twins can operate on the environmental effects of each process in the supply chain and therefore assist firms in responding to sustainability standards and environmental audits issued by international organizations [3, 11, 16].

The other critical aspect of the implementation is the decentralized framework for data collection and analysis. For data collection and analysis. The digital twin is linked with IoT sensors that send data to the blockchain system and make every record unidentifiable. This avoids the risk of information fraud or fabrication especially in vital industries like energy, aviation, and pharmaceuticals.

Smart contracts are used to streamline key processes:

- Predictive maintenance: A method of identifying potential failures through the study of data followed by the initiation of repair operations.
- Supply chain management: the management of the flow of materials and components, without forgery.
- Optimization of resources: the use of energy and material resources for their minimum consumption.

Also, companies are able to improve the environmental sustainability of their operations through decentralization, by monitoring emissions and resource usage more closely [2, 10, 14].

## 5. Practical application and development prospects

The deployment of a decentralized digital twin can enhance the efficiency of production systems to a great extent. The creation of secure, transparent and automated monitoring systems is greatly simplified for complex production processes. Decentralization enables companies to prevent data loss, cyber threats, and dependence on centralized digital service providers. Blockchain provides data immutability and enhances the credibility of data employed in analysis and strategic decision making. Hence, the integration of blockchain with digital twins is imperative [1, 7, 8, 19].

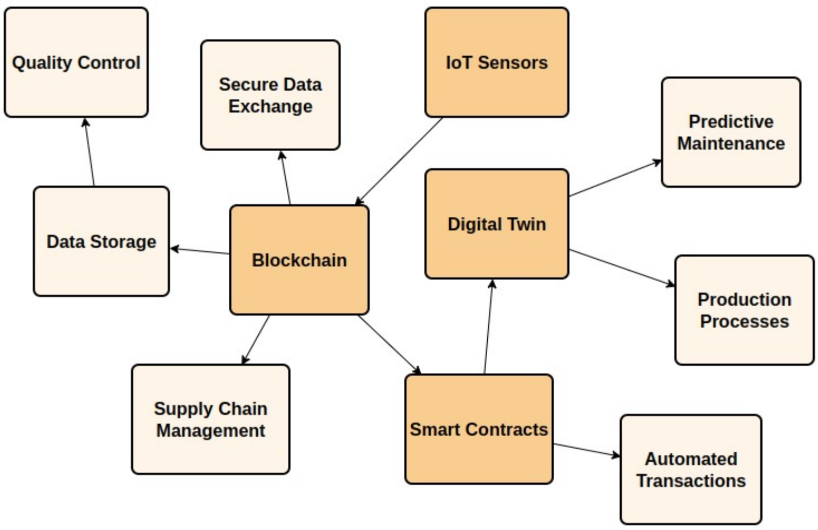


***Figure 1:*** *Methodology for the integration of decentralized digital twins.*

As shown in figure 1, the following is a general diagram of decentralized digital twin implementation. It includes key components; an IoT sensor that collects data, a blockchain that provides secure storage, smart contracts that automate interactions and a digital twin that is a virtual model of physical objects. These elements are interlinked and data circulates between them through defined paths to maintain the elements' integrity and the efficiency of processing.

For instance, in the aviation sector, this offers complete visibility of the supply chain of the aircraft components and thus prevents the risk of using components whose authenticity is not certain. The integration of the digital twin into the production process will not only help in tracking the origin and the quality of each component but also help in predicting the component's life which is very vital in ensuring that the aircraft is safe to fly. Furthermore, the digital twin can use data from the aircraft's sensors to update the maintenance schedule accordingly, thereby decreasing the risk of breakdown and the associated repair expenses [1, 13, 17].

In the pharmaceutical industry blockchain can be used in the quality control of medicines at all stages of production and supply. This is especially important in the fight against counterfeit products which are a serious threat to public health. A decentralized digital twin can guarantee conformity to set standards without altering the production, testing or transportation history of the medicines. It can also be linked up with intelligent analysis systems to raise the alarm on possible fraud in the production process based on data anomalies [13, 15, 20].

The development of this technology implies increasing the efficiency of data processing in integration with quantum computing and the development of the self-learning control systems based on artificial intelligence, which will be able to digital twins not only to reproduce production processes but also to predict the future changes [4, 9, 11].

From a mathematical point of view, it is possible to state that predicting the state of a digital twin can be described by the following equation:

$$P(t+\tau)=\sum_{i=0}^{n} w_i S(t-i)+\xi \tag{5}$$

where $P(t+\tau)$ – the predicted state of the system after time $\tau$, $w_i$ – weighting factors that determine the influence of previous values, $S(t-i)$ – previous values of system parameters, $\xi$ – random forecasting error.

Quantum computing enables a drastic enhancement in the processing time of large datasets, thus creating possibilities for enhancing production and decreasing the costs; interaction with artificial intelligence leads to the development of adaptive systems that can learn from their environment and recommend optimal decisions for improving the performance of the business. It will enable the system to respond to changes in the production environment and determine the best solutions that can enhance business performance.

Future work in this area will be directed at combining distributed digital twins with cyber-physical object systems to build fully autonomous production complexes that can run without human intervention [3, 5, 16].

## 6. Conclusion

The development of decentralized digital twins on the blockchain platform is a viable way of the development of modern industry. The proposed concept solves the problems of classical centralized systems and guarantees the accuracy, integrity and effectiveness of production operations. As such, the integration of distributed ledger technology with the digital twins provides for data storage in a way that is protected from unauthorized access, real time monitoring and control, and automated decision making capabilities that help reduce operational risks and enhance the robustness of industrial systems. Key processes are automated through smart contracts to enhance supply chain management and help companies cut on costs of maintenance and predict failures. The ability to execute predefined contracts without intermediaries makes the workflows smooth and efficient and also minimizes errors and increases productivity. Furthermore, the deployment of decentralized digital counterparties enhances the visibility of operations. This is especially important in high-tech industries that rely much on accurate data and fraud prevention. Some of the example industries are aerospace, energy, and pharmaceuticals that need real-time, verified and immutable data to meet strict security and regulatory requirements. The block chain data is immutable, thus manufacturers can track a component from the time it was made up to the time it gets to the market. Also, the decentralized networks do not have a single point of failure, thus ensuring that production systems remain operational in the event of local outages or cyberattacks.

Using decentralized technology, manufacturers can watch and perform all the functions that happen in the supply chain, from the source of the material to the delivery of the product. This way they can minimize the effects of risks that are likely to occur in the course of business and also avoid cases of fraud in the supply chain and build trust among the market subjects. Real time data collection and analysis also enhance the performance of the supply chain by identifying potential blockages and optimizing the use of resources. It is also important to mention that the automated maintenance programs and the predictive fault detection reduce the down time, enhance the lifespan of the vital equipment and decrease the overall production costs. In addition, the adoption of decentralized systems enhances the cooperation between manufacturers, suppliers, and customers, while ensuring data security and privacy and forming new value propositions.

Decentralization is the development of production systems that are strong to the external influences and can continue to function when a single network node is down.Where as in a centralized architecture, a single point of failure can bring the entire operation to a halt, decentralized digital twins employ blockchain based consensus models to guarantee data availability and system resiliency. This is especially important in the globally distributed supply chains where different participants need to have access to accurate and timely information in a secure and synchronized environment.

Furthermore, decentralized control models can create adaptive and self-tuning systems that enhance long-term sustainability and operational flexibility. Future work should aim to increase the integration of quantum computing and apply artificial intelligence more extensively for the intelligent automation of digital twins. The combination of quantum algorithms with blockchain-based digital twins will enhance the computational capacity and thus enable more accurate and faster simulations, data analysis and optimization of decisions; AI-based models will be continuously trained and updated from the real-time data and will be able to make better forecasts based on the simulation study, thus developing a smart feedback loop for the digital twin to enhance the forecasting accuracy in a dynamically changing manufacturing environment. It is therefore possible to develop fully autonomous systems that can control themselves and adapt to the changing economic and production environments. The other direction of research can be the development of new optimization techniques that can enhance the use of resources, lessen the effects of production on the environment and further integrate digital twins and cyber-physical systems. The adoption of AI-powered analytics in energy management and production scheduling can lead to more environmentally friendly production processes, less waste, and the advancement of sustainable production.

In the long term, decentralized blockchain-based energy systems can enable the integration of renewable energy sources into industrial automation systems and support the achievement of sustainable development objectives. In the long term, these improvements will lead to the development of a ‘smart’ manufacturing system that is able to autonomously and adaptively control and manage itself to achieve strategic objectives. With the help of distributed digital twins, artificial intelligence, and quantum computing, it will be possible to implement a step by step progression towards highly efficient and autonomous industrial operations, so that companies can sustain their competitiveness in a digital economy.

## Declaration on Generative AI

During the preparation of this work, the authors used GPT-4 in order to: Grammar and spelling check. After using these tool(s)/service(s), the authors reviewed and edited the content as needed and take(s) full responsibility for the publication’s content.

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