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THE AI-DRIVEN BLUE OCEAN: REIMAGINING INNOVATION

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Abstract:

Lean concept and Total Productive Maintenance (TPM) are modern strategies for managing industrial processes. These strategies largely rely on reliable and consistent data records, which are essential for monitoring and managing Overall Equipment Effectiveness (OEE). Support for TPM principles can be considered through the potential application of blockchain technology in the digital record-keeping domain.

We used Python to simulate the maintenance activities in the production of sintered parts. The created model integrates daily aggregated TPM losses across all six standard categories into a structure of linked records supported by blockchain. Each record contains key maintenance indicators and process performance metrics.

The simulation results indicate a statistically significant improvement in OEE performance with a reduction in process variability and convergence toward World Class Manufacturing (WCM) reference values. In this way, we preserved the data integrity within the simulation model.

Recording of TPM activities supported by blockchain provides a single, reliable source of truth (SSOT) for multifunctional teams, while enabling systematic tracking of TPM losses. In this paper, we highlighted challenges related to integration with enterprise resource planning (ERP), as well as practical implementations of blockchain for the TPM records in the transformation of Lean systems within the Industry 4.0 framework.

Keywords:

Blockchain Technology, Lean Concept, Total Productive Maintenance, Overall Equipment Effectiveness.

INTRODUCTION

In the context of Industry 4.0, the optimization of industrial processes increasingly relies on the integration of organizational principles and digital technologies. An effective approach can be observed through improvements in efficiency, flexibility, and reliability of production systems. The Lean concept and Total Productive Maintenance (TPM) represent key strategies in modern industrial process management, aimed at eliminating waste, reducing variability, and maximizing resource utilization. As a performance indicator that combines availability, performance, and quality, Overall Equipment Effectiveness (OEE) is commonly applied [1] [2].

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The concept of World Class Manufacturing (WCM) further extends Lean and TPM principles through the integration of maintenance, quality, logistics, workplace organization, and human resources. Recent approaches emphasize the need for digital support and reference models for assessing organizational maturity in achieving sustainable performance in industrial systems [3] [4].

Despite the widespread use of TPM in industrial practice, limitations of traditional implementations are evident, particularly in terms of the reliability and consistency of maintenance records. Conventional TPM systems largely rely on manual entries, paper documentation, or uncoordinated digital tools. The associated risks include logging errors, data inconsistencies, and limited transparency across multifunctional teams [5]. These limitations directly affect the accuracy of OEE calculation. Decision making based on data analysis becomes especially challenging in complex computer integrated manufacturing (CIM) environments characteristic of Industry 4.0 [6] [2] [7].

Alongside the development of analytics and distributed information systems, new opportunities are emerging for improving maintenance systems and industrial resource management. Immutability of records, transparency, and distributed consensus are key characteristics of blockchain technology that make it suitable for ensuring data integrity in industrial environments [8] [9]. Existing literature shows that industrial applications of blockchain are mainly focused on supply chain traceability, data security, and system interoperability. Applications in the domain of TPM and operational maintenance management remain limited and insufficiently explored in empirical studies [10] [11]. This indicates a need for experimental models that critically examine the actual contribution of blockchain technology in the context of industrial maintenance.

In this paper, we examined the potential for improving the reliability of TPM activity records and the stability of OEE metrics in an industrial production process through the application of blockchain technology. A prototype of a TPM system supported by blockchain was developed in Python, and its impact on OEE performance was analyzed. The simulation of maintenance activities was implemented for sintered production over a defined period of twenty working days. The study examines whether an immutable and transparent record of TPM activities, covering all six standard types of TPM losses, can contribute to improved OEE values and reduced process variability compared to traditional recording approaches. In addition, the implications of the proposed approach are considered in relation to WCM objectives, as well as challenges related to its scalability and integration with existing industrial information systems within the Industry 4.0 framework [10].

2. MATERIALS AND METHODS

This study was conducted through a controlled simulation experiment that models the application of TPM processes in a CIM environment. The experimental setting includes two sintering machines operating under identical planned conditions over a period of twenty consecutive working days, with an eight hour working schedule per day. The first machine (Machine A) represents a control system in which maintenance activities are recorded using traditional methods, while the second machine (Machine B) represents an experimental system in which a TPM prototype supported by blockchain is applied.

The process modelling is based on the standard TPM framework, which includes six primary types of losses: breakdowns, setup and adjustment losses, startup losses, idling and minor stoppages, reduced speed, and defect losses. These losses are generated on a daily basis using models that reflect typical real variations in industrial processes. For the control and experimental systems, different distributions and levels of variability are defined, representing the expected effects of more consistent TPM practices and more reliable data recording.

In this study, the Overall Equipment Effectiveness (OEE) metric is calculated as the product of three components: availability, performance, and quality.

$$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality}$$

Availability is defined as the ratio of operating time to planned production time, where operating time is obtained by subtracting downtime losses from the total planned time:

$$\text{Availability} = \frac{\text{Operating Time}}{\text{Planned Production Time}}$$

Performance reflects the relationship between the actual production output and the ideal production rate, where net run time is calculated as operating time reduced by idling and minor stoppages:

$$\text{Performance} = \frac{\text{Ideal Cycle Time} \times \text{Total Count}}{\text{Net Run Time}}$$

Quality represents the proportion of good units in total production:

$$\text{Quality} = \frac{\text{Good Count}}{\text{Total Count}}$$

These definitions are consistent with standard TPM methodology [1].

For Machine B, we defined a structure of immutable digital records of daily aggregated TPM losses and corresponding performance indicators, inspired by blockchain technology. The records are implemented as a linear chain of blocks connected through cryptographic hash functions. Each block contains aggregated daily TPM losses, machine identification, a timestamp, and calculated values of availability, performance, quality, and OEE. The first block represents the initial block, while each subsequent block includes a reference to the hash of the previous block. In this way, traceability and data integrity are ensured within the observed model.

The integrity of the blockchain chain is verified by validating the linkage between all blocks through comparison of hash values. This confirms the consistency and immutability of the records within the implemented model. Such a structure enables the establishment of a single reliable source of data for monitoring TPM activities and process performance. In this way, reliance on manual documentation systems is reduced.

Based on daily calculated OEE values for both machines, a statistical analysis was conducted with the aim of comparing the performance of the control and experimental machines. The study is based on the assumption that the application of TPM records based on blockchain may lead to an increase in the average OEE value, as well as a reduction in performance variability. To test the differences between the observed machines, a paired t-test was applied to daily OEE values, with a significance level of α = 0.05. This approach was selected because the comparison is performed between two machines over the same working days, thereby eliminating the influence of temporal variations. In this way, both the statistical significance and the magnitude of the observed differences between the analyzed scenarios are evaluated. The null hypothesis H0 is defined as the absence of a difference in average daily OEE values between Machine A and Machine B, while the alternative hypothesis H1 assumes the presence of a statistically significant difference between the observed machines. The effect size was assessed using Cohen's d coefficient [12].

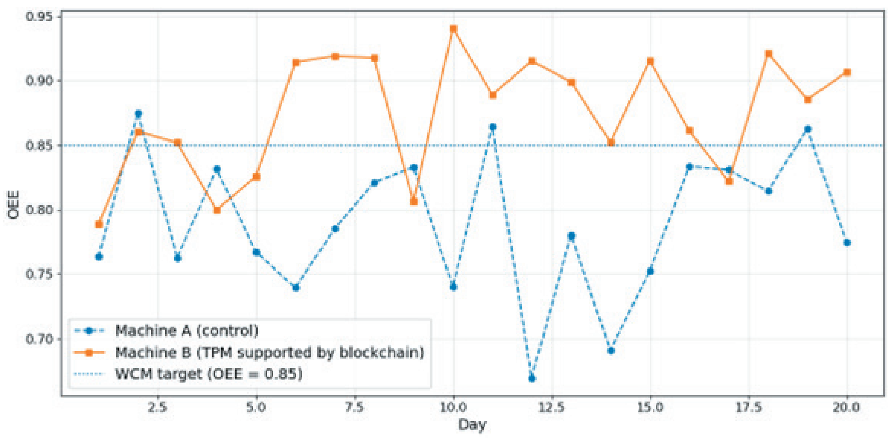

Figure 1. Comparison of OEE performance over twenty days

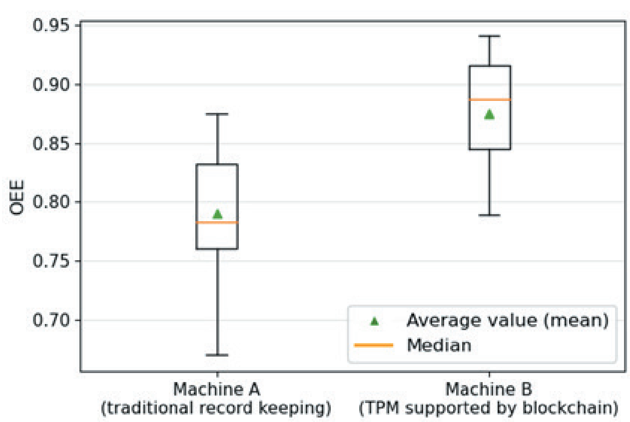

Figure 2. Boxplot of daily OEE value distribution for Machine A and Machine B

3. RESULTS

The simulation results over twenty working days indicate an improvement in OEE performance for the machine with TPM records based on blockchain compared to the reference machine with traditional maintenance records. Average OEE values and the corresponding variability indicate a higher level of overall equipment effectiveness for Machine B compared to Machine A. The relative improvement in the average OEE value of Machine B compared to Machine A is 10.9 percent.

Machine B achieved an average OEE of 0.875 with a standard deviation of 0.046, while Machine A reached an average value of 0.789 with a standard deviation of 0.054. During most of the simulation period, Machine B achieved OEE values above the 0.85 threshold, while Machine A reached such values only occasionally.

The dynamics of OEE value changes during the simulation period are shown in Figure 1. While the OEE values of Machine A show pronounced daily fluctuations, Machine B achieves a higher level of OEE with lower daily variability during most of the simulation period.

Differences in the variability of daily OEE values between the observed machines were examined using the analysis of data distribution. The distribution of daily OEE values for both machines, shown in Figure 2, illustrates differences in performance dispersion between Machine A and Machine B.

The results indicate that Machine B has a narrower interquartile range and lower overall dispersion of OEE values compared to Machine A, reflecting lower performance variability during the simulation period. The observed differences in the level and variability of OEE values were further examined using appropriate statistical tests in order to determine their statistical significance.

To statistically verify the observed differences in daily OEE values between the observed machines, a paired t-test was applied. The analysis was conducted using OEE values for the same working days, ensuring a comparison of performance under identical time conditions. The test results indicate a statistically significant difference in average OEE values between the two machines, leading to the rejection of the null hypothesis.

The results of the paired t-test show a t-value of 4.848 and a p-value of 0.000112 at a significance level of 0.05. This confirms a statistically significant difference between the machines. The effect size, measured by Cohen's d, is 1.08, indicating a strong effect.

The obtained p-value is lower than the selected significance level, confirming the statistical significance of the difference in average OEE values between the observed machines. The effect size, estimated using Cohen's d, indicates a large difference between Machine A and Machine B.

In addition to the analysis of production performance, a validation of the implemented TPM record structure based on blockchain was conducted using the same approach. During the simulation, a blockchain chain was generated consisting of one initial block and twenty daily blocks corresponding to aggregated TPM data recorded. Each block contains a timestamp, machine identification, daily totals of TPM losses by category, corresponding OEE components, and total OEE value, as well as the cryptographic hash of the previous block.

The integrity check of the blockchain chain showed that all previous hash links are consistent, with no detected irregularities. This confirms the consistency and immutability of the records within the implemented digital structure. Based on this verification, it can be concluded that the structure supported by blockchain enables reliable recording of daily aggregated TPM data within the observed simulation model.

Such technological validation of the implemented digital structure provides a basis for further considerations, which are addressed in the discussion of the potential application of the TPM approach supported by blockchain.

4. DISCUSSION

The obtained results enable a comprehensive analysis of the impact of digital records of TPM activities supported by blockchain on the performance and stability of the industrial production process. The discussion is structured by linking the observed results with the theoretical foundations of Lean and TPM approaches, relevant findings from existing literature, and by considering practical implications within the context of the Industry 4.0 concept.

The primary objective of TPM is the elimination of the six standard categories of losses through systematic and disciplined recording of maintenance activities, along with continuous monitoring of overall equipment effectiveness [1]. The simulation results indicate that the machine supported by blockchain achieved an average OEE improvement of 10.9% compared to the control machine, while simultaneously approaching and maintaining OEE values around the WCM threshold of 85%.

This finding is consistent with contemporary interpretations of TPM, which emphasize that the full benefits of the methodology can only be realized when maintenance data are reliable, consistent, and accessible to all relevant stakeholders [5]. While traditional TPM literature treats record keeping as a supporting element, more recent studies suggest that data quality has become a critical limiting factor in digitalized production systems [2].

In this context, the recording of TPM activities supported by blockchain does not represent a replacement for the TPM methodology, but rather its digital structural backbone [13]). This enables a more consistent application of Lean principles and systematic monitoring of continuous improvement in modern industrial environments [14] [15].

Within the conducted simulation, a reduction in the variability of OEE values was observed for the machine with TPM records supported by blockchain. This pattern indicates more stable and predictable process behavior compared to a system based on traditional maintenance records.

Contemporary maintenance literature suggests that average KPI values alone are not sufficient for reliable decision making, and that process stability represents a prerequisite for systematic performance improvement [6]. In this context, lower variability of OEE values reduces the risk of misinterpreting performance and enables more accurate planning of preventive and predictive interventions.

The statistical validation of the obtained results further supports the interpretation of the observed differences in process stability. The fact that differences in OEE performance are not the result of random variation indicates the reliability of the conclusions obtained from the simulation. The observed effects can therefore be interpreted as systematic rather than as a consequence of short-term deviations.

In existing TPM research, statistical analysis is often limited to a descriptive level, without the explicit application of formal hypothesis testing and effect size estimation [5] [6]. Such an approach makes it more difficult to clearly evaluate the stability and reliability of the observed improvements.

A comparison of the obtained results with contemporary research indicates that the observed improvement in overall equipment effectiveness is consistent with findings from previous studies examining digitally supported TPM and maintenance systems. Variations in the reported effects are largely influenced by the industrial context, measurement methodology, and the level of digital system implementation [6]. Empirical studies show that digitally supported maintenance frameworks can lead to measurable improvements in OEE performance [7].

Within the context of Industry 4.0, blockchain technology is most often discussed at a conceptual level or in relation to transparency, traceability in supply chains, and data management [9] [11] [10]. Empirical applications in the domain of operational maintenance and direct management of OEE metrics remain relatively limited [10].

In contrast to such approaches, this study implements a digital record structure based on linking records through hash functions, enabling the preservation of data integrity related to TPM activities and performance within the simulation model. The results of this research indicate the possibility of simultaneously improving OEE performance, reducing process variability, and preserving data integrity within a unified and methodologically controlled experimental framework.

During the simulation, the machine supported by blockchain achieved an average OEE value above 85%, which is commonly used in WCM literature as a reference threshold. The WCM methodology does not focus solely on achieving high performance levels. It is also based on establishing reliable, standardized, and transparent measurement mechanisms that serve as a foundation for continuous process improvement and data driven decision making [3].

In industrial systems characterized by high downtime costs and strict quality requirements, such as sintered production [16], the need for reliable maintenance records is particularly pronounced. Inadequate recording of maintenance activities can lead to significant operational and economic consequences. The results of the conducted simulation suggest that a TPM approach supported by blockchain can contribute to reducing this risk. In this way, a reliable and consistent set of data on the causes of downtime, process performance, and product quality is ensured.

Accordingly, the proposed approach provides an operational basis for the systematic monitoring of WCM objectives in complex, CIM environments characteristic of Industry 4.0.

Despite the positive results, it is important to consider the limitations of the conducted study. The results are based on a simulation model that includes a limited number of observed machines, and the findings cannot be directly generalized to complex industrial systems with a larger number of production resources.

In addition to these limitations, the implemented model of digital records supported by blockchain does not fully address issues of scalability, latency, and integration with existing information systems for production and maintenance management, such as ERP and MES platforms. These requirements represent an important prerequisite for the application of similar solutions in real industrial environments.

The broader implementation of blockchain technology within Industry 4.0 is constrained by challenges such as scalability and interoperability. Different architectural models and approaches to integration with existing digital systems are being considered as potential solutions to overcome these limitations [10].

Experimental validation of the proposed approach in real production conditions represents an important direction for future research. Possible extensions of the model include integration with predictive maintenance, digital twins, and advanced process analytics. In addition, extending the existing structure of digital records toward a distributed environment with multiple participants, along with the introduction of appropriate consensus mechanisms and data access management, represents a further avenue for future work.

5. CONCLUSION

The potential application of digital records supported by blockchain in the context of TPM was examined through a simulation model of a sintering process. The analysis focused on the reliability of TPM activity records and the stability of the OEE metric, as key performance indicators in Lean and WCM environments.

The simulation results over a period of 20 working days indicate that the machine with TPM records supported by blockchain achieves a higher level of overall equipment effectiveness compared to the reference machine based on a traditional maintenance recording approach. The observed improvement in OEE is accompanied by a reduction in the variability of daily values, indicating more stable process behavior and greater reliability of performance over the observed period.

The achieved OEE values for the machine with records supported by blockchain reach and maintain a level that is often identified in the literature as the threshold of WCM. This finding is consistent with Lean and TPM principles, which recognize process stability and data reliability as the foundation for sustainable improvements and effective management of production systems.

The technological contribution of this study is reflected in the definition and validation of a digital record structure based on linking daily records of TPM losses and associated performance indicators within a chain of records. This demonstrates the possibility of preserving data integrity and traceability within the simulation model, without relying on manual or inconsistent recording systems.

Although the obtained results indicate the potential of a TPM approach supported by blockchain, the study has certain limitations. The analysis is based on a simulation model with a limited number of machines and does not address issues of scalability, latency, and integration with existing information systems for production and maintenance management. Future research may focus on experimental validation in real production environments, as well as on extending the model toward integration with contemporary industrial digitalization concepts within Industry 4.0.

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