OVERALL EQUIPMENT EFFICIENCY, TOTAL PRODUCTIVE MAINTENANCE AND DIGITAL TWIN TECHNOLOGIES - A LITERATURE REVIEW

Marc Philip Hermans[1], Péter Tamás[2]
[1]PhD Student, [2]Associate Professor
[1,2]Institute of Logistics, Faculty of Mechanical Engineering and Informatics
[1]marc.philip.hermans@student.uni-miskolc.hu, [2]peter.tamas@uni-miskolc.hu

ABSTRACT

This literature review investigates the integration of executable Digital Twins (xDTs) and Total Productive Maintenance (TPM) as a means to improve maintenance practices and operational efficiency. The review encompasses an in-depth analysis of existing research, focusing on the feasibility of an xDT as an advisor in TPM and the correlation between Overall Equipment Efficiency (OEE) and TPM activities. The findings highlight the potential benefits of integrating xDTs with TPM, including real-time monitoring, predictive insights, and decision support. However, further exploration is needed to fully understand the capabilities and effectiveness of xDTs in TPM. The review also emphasizes the lack of a standardized approach for calculating OEE, underscoring the necessity of developing a universal method to facilitate meaningful comparisons and evaluations across different systems. Additionally, investigating the correlation between OEE degradation and TPM activities is essential for informed TPM decision-making and resource allocation. Ultimately, the integration of xDTs and TPM has the potential to optimize maintenance strategies, maximize equipment efficiency, and enhance overall operational performance in diverse industries.

1. INTRODUCTION

In addition to the energy crisis resulting from the Russian-Ukrainian war, the ongoing climate crisis will compel all companies, regardless of their industry and operations, to seek solutions that maximize efficiency and sustainability [1]. Maintenance departments will not be exempt from this pursuit, as they will be compelled to enhance the utilization of their resources for optimal efficiency.

This review paper explores previous studies and research that have examined the integration of Industrial 4.0 solutions with existing maintenance concepts. The objective is to enable decision-making regarding the timing of maintenance activities by leveraging the benefits of Digital Twins. The utilization of Digital Twins aims to facilitate the decision-making process for maintenance teams, allowing them to determine whether to perform or postpone maintenance activities.

2. RETHINKING TPM: A NEW PERSPECTIVE ON MAINTENANCE EFFICIENCY

In Arno Koch's book, "OEE for the production team" [2], he views TPM (Total Productive Maintenance) as a time loss for maintenance activities, where machines are available for production but not utilized for that purpose. On the other hand, in numerous theses, papers and works [3-5], as well as in personal experience, TPM can be seen as a way of making unplannable events or at least the loss due to unplannable events, more or almost fully plannable. From an efficiency standpoint, these two perspectives appear contradictory. While minimizing maintenance activities can boost production efficiency, it also exposes companies to unforeseen losses.

To reconcile this dilemma, companies frequently opt to transition from preventive maintenance to predictive maintenance. While predictive maintenance proves highly

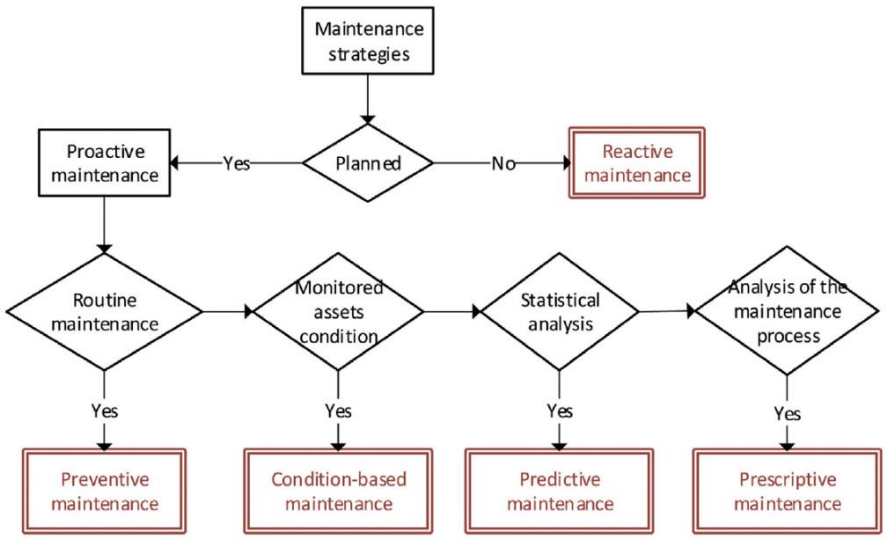


Fig. 1.
Maintenance strategies diagram [6]

effective in preventing breakdowns, it often falls short in terms of providing adequate advance notice for standby preparations, especially in scenarios involving low cycle times in serial production. As can be seen in Figure 1, predictive maintenance demands extensive data collection through sophisticated sensor systems and intricate algorithmic analysis, requiring a high level of expertise from the maintenance staff; expertise often beyond the scope of the maintenance team's interest and knowledge.

Instead of merely transitioning from preventive maintenance to predictive maintenance, our aim is to introduce a concept that shifts preventive maintenance towards a predictive approach. This is where the concept of the executable digital twin can play a significant role. By utilizing the digital twin as a real-time monitoring tool rather than just a simulation or planning tool, we can achieve this objective [7]. To realize this concept, three main areas need to be investigated:

1. Development of a Comprehensive OEE Calculator: The first focus is on creating an OEE calculator that provides a comprehensive framework for measuring overall equipment effectiveness and identifying areas for improvement.
2. Mapping Maintenance Tasks to OEE Factors: The second area involves mapping maintenance tasks to the three factors of OEE (Availability, Performance, and Quality). This mapping enables a deeper understanding of how maintenance activities impact overall equipment effectiveness.
3. Implementation of an Executable Digital Twin for Maintenance Advice: The final aspect centers around implementing an executable digital twin that leverages advanced technologies to offer guidance and recommendations for maintenance tasks. This digital counterpart enhances decision-making processes related to maintenance activities, leading to more informed and efficient maintenance planning.

Through an in-depth exploration of this approach, we can highlight its distinctive contributions. What sets this framework apart is its integration of multiple elements, including a comprehensive analysis of OEE calculation methods, strategic mapping of maintenance tasks, and the utilization of digital twin technologies for maintenance

guidance. This synthesis of methodologies allows for the alignment of preventive and predictive maintenance, harnessing the capabilities of an executable digital twin. The novelty lies in the framework's capacity to optimize maintenance efficiency and effectiveness through a comprehensive and innovative approach that brings together these essential components.

3. METHODICAL APPROACH

This literature review starts by exploring the available Literature on ScienceDirect on the topics of Overall Equipment Efficiency (OEE), Total Productive Maintenance (TPM), and Digital Twin Technologies, highlighting their unique contributions and drawing insights from relevant research studies.

The decision to rely solely on ScienceDirect as the sole platform for articles on Digital Twin, OEE, and TPM, aligns with the specific research interests and objectives of this review. The following three points give a more elaborated explanation to the decision:

1. Quality over Quantity: Emphasis is placed on prioritizing the quality of the sources rather than the quantity of available literature. ScienceDirect's extensive collection of peer-reviewed journals and reputable publications is well-regarded. By focusing on high-quality sources, the reliability and trustworthiness of the gathered information are ensured.
2. Broad Timespan: Recognizing the importance of exploring the historical development and evolution of OEE, TPM, and the Digital Twin concept, it was deemed significant to consider a wide range of time. ScienceDirect's comprehensive coverage facilitates the examination of the progression of these topics from their early stages to their current state.
3. Language Preference: The decision to avoid incorporating a third language into the research influenced the selection of English articles only. While SpringerLink offers a substantial number of English articles, it also contains a notable presence of German articles. To maintain a focus exclusively on English-language publications, ScienceDirect was chosen as it predominantly features articles in English.

By selecting a platform that accommodates language preferences and offers the desired level of comprehensiveness, the gathered articles are tailored and focused according to the objectives of the review.

To further enhance the relevance of the search results and align them with the specific research scope, subject area filters including Engineering, Decision Sciences, Mathematics, and Computer Science were applied. This approach enabled a more targeted exploration of articles within the domains most relevant to the research. The search was conducted using the following three keywords, ensuring a comprehensive coverage of the desired topics.

1. Overall Equipment Efficiency (OEE) [8-10]: OEE is a widely used performance metric that assesses equipment utilization in manufacturing. Various aspects of OEE have been investigated in the literature, including calculation methods, application in different industries, and improvement strategies. Studies have proposed different OEE models and frameworks, such as the Six Big Losses model, to enhance equipment performance. The impact of

factors like maintenance practices, production planning, and organizational culture on OEE has also been examined.

2. Total Productive Maintenance (TPM) [11-13]: TPM is a comprehensive maintenance approach aimed at maximizing equipment effectiveness. Literature on TPM covers implementation methodologies, tools, and the benefits of TPM adoption. Different TPM pillars, including autonomous maintenance, planned maintenance, and focused improvement, have been explored. The relationship between TPM and performance measures like OEE and equipment downtime reduction has also been investigated.

3. Digital Twin Technologies (DT): Digital Twin Technologies involve creating virtual replicas of physical systems or products for simulation and optimization. Research on digital twins spans various industries, including manufacturing, aerospace, healthcare, and transportation. The benefits of digital twins, such as improved asset management and operational efficiency, have been highlighted [7]. Topics covered include data integration, real-time analytics, and predictive maintenance [8]. Integration of digital twins with other technologies like IoT and AI has also been studied [9].

The identified literature is expected to provide significant insights into the importance of OEE, TPM, and digital twin technologies in optimizing equipment efficiency, maintenance practices, and operational performance. These studies offer valuable contributions to the theoretical foundations, implementation methodologies, and practical implications of these concepts across various industrial contexts.

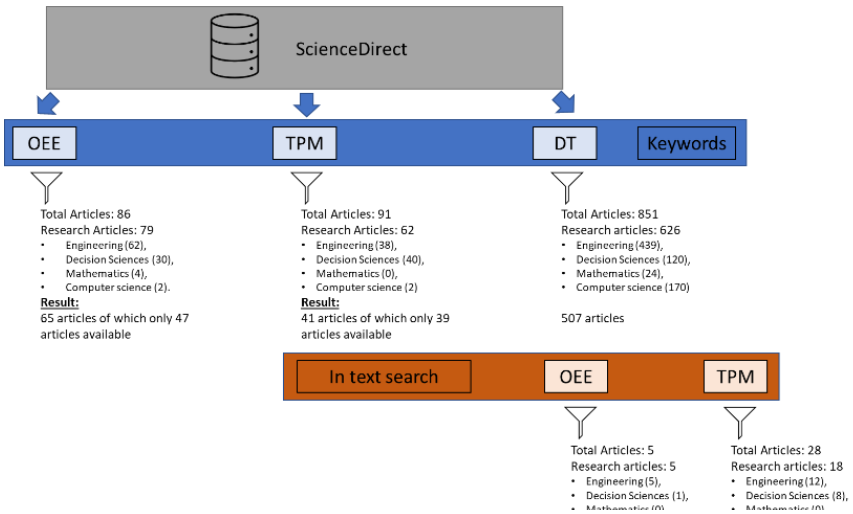


Fig. 2.
Filtering of articles [Own]

Based on the selected keywords and applied filters, shown in Figure 2, the findings include:

- Overall Equipment Effectiveness (OEE): A total of 86 articles were found, with 79 being research articles. Out of these, 47 articles were available and downloaded for further analysis.
- Total Productive Maintenance (TPM): A total of 91 articles were found, with 62 being research articles. Among them, 39 articles were available and downloaded for further examination.

- Digital Twin Technology (DT): A total of 851 articles were identified, with 626 being research articles. Due to the large number, additional filtering was necessary.

To refine the search, specific filters were applied to focus on OEE and TPM. The results of this refinement include:

- OEE: A total of 5 articles were found, all of which were research articles, and all 5 articles were available and downloaded for further investigation.
- TPM: Out of the 28 articles found, 18 were research articles, and 14 articles were available and downloaded.

The remaining 101 research articles where in a next step categorized and weighted. Utilizing a systematic methodology, the articles were meticulously categorized and ranked based on the information extracted from their abstracts and additional keywords. The categorization involved classifying the articles into distinct thematic categories, while the ranking process assigned importance and relevance scores to gauge their alignment with the research objectives. This rigorous categorization and ranking approach facilitated the organization of articles and prioritization of those deemed most pertinent for the literature review.

The scoring system in Figure 3 was utilized to assign weights or grades to the 101 selected articles, considering their relevance to the research topics. Those articles that directly addressed the calculation of OEE, the grouping of maintenance activities within TPM, and referenced executable Digital Twin concepts were assigned a score of 3. Articles that made direct references to the other keywords received a score of 2, while those with vague references to the remaining keywords obtained a score of 1. This scoring mechanism not only facilitated a systematic evaluation of the articles but also helped to manage the quantity by narrowing down the selection to the most pertinent ones aligned with the research objectives.

Keyword	Catagory	Nr of articles	Ranking
OEE	Calculating OEE	14	3
	OEE and Fuzzy	1	2
	OEE, TPM	3	2
	OEE and DES	1	1
	OEE and maintenance manufacturing	1	1
	OEE and maintenance status	1	1
	case study	12	0
	Digital Dashboard	1	0
	improve the effectiveness	2	0
	Ind 4.0 and Improvement	1	0
	OEE and AM	1	0
	OEE and CO2 Emissions	1	0
	OEE and cyber security	1	0
	OEE and Energy	1	0
	OEE and flexibility	1	0
	OEE and FMEA	1	0
	OEE and Scheduling	1	0
	OEE and time margins	1	0
	Performance increase	1	0
	Transfer of knowledge	1	0
Total		47	21

Keyword	Catagory	Nr of articles	Ranking
DT & OEE	DT and Bottleneck analyses	1	0
	case study	2	0
	DT and 5G	1	0
	DT and ICT	1	0
Total		5	0

Keyword	Catagory	Nr of articles	Ranking
TPM	TPM standardizing	4	3
	TPM History	1	1
	TPM management	1	1
	Calculating OEE	1	0
	case study	12	0
	Implementing TPM	1	0
	Key_OEE	10	0
	TPM and CO2emissions	2	0
	TPM and I4.0	1	0
	TPM and Tele maintenance	1	0
	TPM and TQM	4	0
	TPM problem identification	1	0
	TPM, SPC, TPM standardizing	1	0
Total		40	6

Keyword	Catagory	Nr of articles	Ranking
DT & TPM	DT and maintenance	2	1
	case study	4	0
	DT and benefits	1	0
	DT and Jobshop	1	0
	DT and Sustainability	1	0
	DT Challenges	1	0
	DT cyber security	1	0
	DT Digital Thread	1	0
	DT general	1	0
	DT review	1	0
Total		14	2

Fig. 3.
Grading Mechanism [Own]

4. MAIN FINDINGS

After scoring the 101 articles, a total of 29 articles were selected for further analysis. Figure 4 shows how each article underwent a thorough critical reading and was subsequently grouped. The following are the key findings obtained from the 21 articles that focused on the topic of Overall Equipment Effectiveness (OEE):

1. Overall Equipment Effectiveness (OEE) and Total Productive Maintenance (TPM) Concepts:
    a. Total Productive Maintenance (TPM) plays a crucial role in ensuring uninterrupted production flow and involves the participation of all members within the organization.
    b. OEE serves as a fundamental measure for assessing the tangible benefits derived from implementing TPM.
    c. Mathematical decision models have the potential to enhance the OEE indicator and overall performance of manufacturing lines.
2. OEE Evaluation and Analysis:
    a. OEE is widely utilized for evaluating the effectiveness of manufacturing systems.
    b. Different methodologies employed for evaluating OEE can yield varying results.
    c. Analyzing OEE assists in identifying areas for improvement and optimizing production processes.

3. OEE and Performance Measurement:
    a. OEE is a valuable tool for measuring the performance of production systems.
    b. Automation can contribute to increased OEE by reducing downtime and enhancing production speed.
    c. Simulation techniques, such as Discrete Event Simulation (DES), can be employed to evaluate OEE and optimize production processes.
4. OEE in Logistics and Material Supply:
    a. OEE analysis can be applied to commissioning and logistics processes.
    b. The identification of losses through OEE analysis leads to improved efficiency in logistics processes.
    c. OEE analysis aids in determining value-added shares in material supply.
5. OEE and Decision-Making:
    a. Fuzzy Associative Memory (FAM) models enable the assessment of maintenance status for production equipment.
    b. Association Rule Mining (ARM) techniques can analyze and model OEE values to support decision-making.
    c. OEE estimation methods that consider uncertainty contribute to accurate decision-making.
6. OEE Implementation and Optimization:
    a. Implementing TPM and enhancing maintenance systems result in improved OEE.
    b. Industry-specific OEE models assist in identifying significant time losses and enhancing operational excellence.
    c. Digitization, data transparency, and clarity contribute to improving TPM indicators and work efficiency.
7. Capacity Optimization and Costing Models:
    a. Mathematical and costing models support capacity optimization and operational efficiency.
    b. Balancing capacity maximization with operational efficiency is crucial.
    c. Capacity optimization should not overlook operational inefficiencies.
8. Global Efficiency Assessment and Manufacturing System Optimization
    a. OEE and Overall Throughput Effectiveness (OTE) serve as essential indicators for assessing the effectiveness of production systems.
    b. Analysis, design, and decision-making methodologies incorporate formal languages and modelling/simulation tools.
    c. The integration of lean methods, manufacturing process objectives, and fuzzy logic controllers facilitates the optimization of manufacturing processes.

The 6 remaining research articles on TPM, can be grouped as follows:

1. Maintenance Operation Improvement and Planning:

a. A novel approach to improve maintenance operations.
b. The development of a computer-aided maintenance resources planning (CAMRP) system for multiple CNC machining centers.

2. TPM Implementation and Availability Improvement:
   a. The implementation of Total Productive Maintenance (TPM) supported by 5S to enhance the availability of an automotive production line.
3. Maintenance Strategy and Management:
   a. The improvement of preventive maintenance management in an energy solutions company.
4. Predictive Maintenance and Failure Rate Prediction:
   a. Introduction to an ensemble-learning model for predicting the failure rate of equipment under different operating conditions.
5. Lean Management and Operational Efficiency:
   a. The application of lean management principles, including data transfer, knowledge transfer, and establishing causal linkages between activities and performance.

Findings of the last 2 papers on digital twin technologies, each paper represents a single group with the following findings:

6. "Subsystem selection for digital twin development: A case study on an unmanned underwater vehicle":
   a. A generic process was established to determine a priority-based set of system components for digital twin development, specifically for condition-based maintenance purposes.
   b. The identified "triage" set of components represents the subset that, when monitored through a digital twin, leads to the greatest increase in total system reliability at minimal cost.
   c. The process can be applied to any system aiming to leverage digital twin technology while considering cost and reliability estimates.
7. "Text mining techniques for the management of predictive maintenance":
   a. A scheme for the classification of maintenance approaches is proposed to support the management of predictive maintenance.
   b. An algorithm based on text mining technology is integrated into a cyber-physical system model to enable predictive maintenance.
   c. The implemented tool assists maintenance managers in making appropriate decisions regarding the scheduling of maintenance activities when there is an alert about a possible machine failure.

5. RESULTS AND DISCUSSION

The findings in the articles with the keyword set to OEE, indicate that the definition and classification of losses have a significant impact on the calculation of OEE. Different methodologies and approaches can lead to variations in calculated values, and accurately identifying and categorizing losses is crucial for improving the effectiveness of operations [17-19].

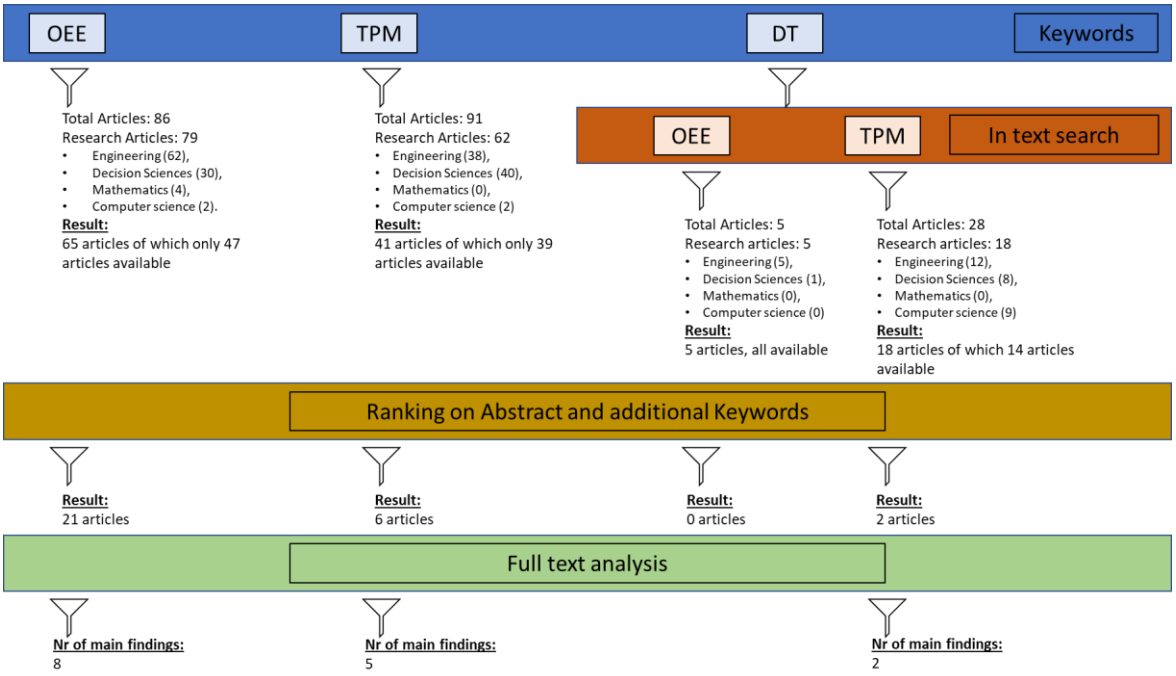


Fig. 4.
Abstraction process from articles to main findings [Own]

Taking this though one step further, it can be said that consistency in the method and definitions for calculating OEE between a real-world system and its' digital twin is crucial for comparability, accuracy of insights, validation, and seamless integration. It ensures that both systems align in their assessment of equipment performance, enabling maintenance teams to make informed decisions and drive improvements effectively. A few key reasons to support this statement:

1. Comparability: When the same method and definitions are used for calculating OEE in both the real-world system and the digital twin, it enables direct comparisons between the two. This comparability allows maintenance teams to assess the performance of the physical system and its virtual representation accurately. It also facilitates identifying any gaps or discrepancies between the real-world data and the digital twin's simulation results.

2. Accuracy of Insights: Consistency in the calculation method and definitions ensures that the OEE values obtained from both the real-world system and the digital twin are accurate and meaningful. It enables maintenance teams to make reliable data-driven decisions based on a shared understanding of equipment performance. Inaccurate or inconsistent OEE calculations can lead to misleading insights and hinder effective maintenance planning and optimization efforts.

3. Validation and Verification: Having the same method and definitions for calculating OEE in both the real-world system and the digital twin allows for validation and verification of the digital twin's accuracy and reliability. By comparing the OEE values obtained from the physical system with those generated by the digital twin, maintenance teams can assess the fidelity of the virtual representation. Consistency in the calculations enhances confidence in the digital twin's ability to replicate and predict real-world OEE performance.

4. Seamless Integration: When the real-world system and the digital twin share the same method and definitions for calculating OEE, it facilitates seamless integration of the two. Data and insights can be easily exchanged and applied between the physical system and the digital twin, enabling continuous monitoring, analysis, and optimization of equipment performance. This integration supports a more cohesive and effective maintenance strategy.

None of the papers do directly correlate OEE with TPM in the context of using OEE degradation to advise on TPM in a Digital Twin. Still a broader interpretation of certain papers can be relevant to this correlation. Few key points from the examined papers:

- Overall Equipment Effectiveness (OEE) is the key measure of the tangible benefits obtainable from the TPM strategy. [20]
- The authors of "Mathematical Decision Model to Improve TPM Indicator" propose a decision aid method based on a mathematical model to improve the OEE indicator and the overall performance of the manufacturing line.
- OEE can be used to measure the performance of a production system. [21]
- OEE can be used to identify areas of improvement in production systems. [21]
- In "An application of association rule mining in total productive maintenance strategy: an analysis and modeling in wooden door manufacturing industry", the authors used Association Rule Mining (ARM) to analyze and model the Overall Equipment Effectiveness (OEE) value obtained from a manufacturing industry. [22] These ARM generated dynamic rules accelerated the decision-making process and improved the response and efficiency of time and costs and facilitated the process of decision-making by related stakeholders and enabled the company to establish an appropriate TPM management strategy.

These findings indicate the close relationship between OEE and TPM. OEE serves as a key indicator to assess the effectiveness and performance of TPM implementation. By monitoring OEE degradation through a Digital Twin, it can potentially provide insights and advice on TPM-related improvements or maintenance actions to maintain or improve the overall equipment effectiveness. While the specific correlation between OEE degradation and TPM advice in a Digital Twin may not be directly addressed in the provided papers, the broader understanding of the relationship between OEE and TPM can be valuable for integrating them in a Digital Twin system.

A digital twin is a virtual representation or model of a physical object, process, or system that combines the physical and digital aspects to create a dynamic simulation mirroring its real-world counterpart. It is created by integrating data from various sources, including sensors, IoT devices, and historical records.

On the other hand, an executable digital twin is an advanced version of a digital twin that operates as an application or software. It goes beyond a static model and possesses interactive functionality. An executable digital twin can simulate real-time behavior, interact with its environment, and function as a sensor, collecting data and providing feedback to the overall system. It extends its capabilities by operating as a standalone application or software, contributing to the monitoring, control, and optimization of the physical system it represents.

In the context of developing an executable digital twin, the first paper on digital twins [13] can serve as a guide for selecting the critical system components to be included in the digital twin. The identified "triage" set from the paper helps prioritize the components that have the greatest impact on system reliability and cost when monitored

through the digital twin. By focusing on these components, the executable digital twin can provide real-time insights and monitoring capabilities, leading to improved system reliability and cost-effective maintenance practices.

Furthermore, the algorithm proposed in the second paper [14], which integrates text mining technology into a cyber-physical system model, can be incorporated into the executable digital twin. By utilizing text mining techniques, the executable digital twin can analyze textual data related to maintenance activities and machine failures. This analysis enables the digital twin to support predictive maintenance decision-making by alerting maintenance managers about potential machine failures based on the extracted information. It facilitates more appropriate scheduling of maintenance activities and proactive measures to address maintenance needs.

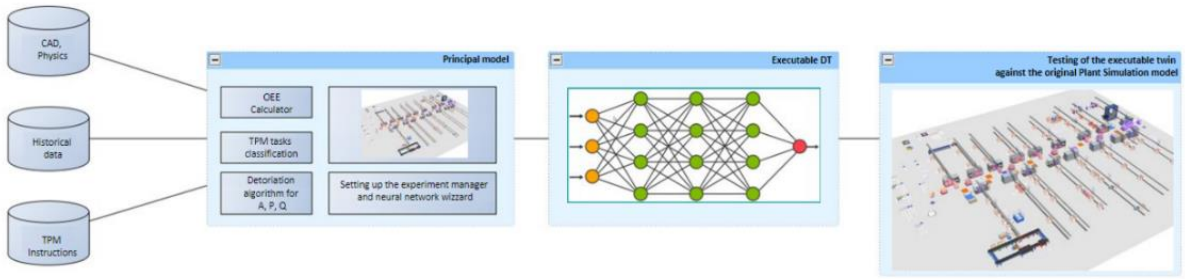


Fig. 5.
Solution proposed in "Improving the efficiency of maintenance processes in manufacturing systems using industry 4.0 tools" [Own]

6. CONCLUSION

Based on the above literature review, it can be concluded that the in Figure 5 sketched concept of an executable digital twin as an advisor in Total Productive Maintenance (TPM) is a feasible concept, although it appears to be an area that has not yet been extensively researched. The existing literature on digital twins and TPM emphasizes the potential benefits of integrating these technologies, such as real-time monitoring, predictive insights, and decision support for maintenance activities. However, there is a lack of specific studies focusing on the implementation and effectiveness of an executable digital twin as an advisor in TPM.

The reviewed papers highlight the absence of a standardized approach for calculating Overall Equipment Efficiency (OEE) and the need for a general method in order to compare and evaluate OEE across the real system and its' digital twins. This suggests that developing a consistent and universally applicable OEE calculation method is crucial. Moreover, the papers suggest that further research is needed to explore the correlation between OEE degradation and TPM activities. Understanding how changes in OEE can be used as indicators to guide TPM decision-making and resource allocation would be valuable for optimizing maintenance strategies and maximizing equipment performance.

While the concept of an executable digital twin holds promise, there is a need for additional research to investigate its potential application in TPM. Future studies could explore the development and implementation of executable digital twins that serve as advisors for TPM activities. This research could focus on identifying the critical components and processes to be included in the executable digital twin, as well as

integrating advanced analytics and predictive algorithms to enhance its capabilities. Furthermore, examining the impact of an executable digital twin on TPM effectiveness, cost-efficiency, and overall operational performance would provide valuable insights for both researchers and industry practitioners.

In conclusion, the concept of an executable digital twin as an advisor in TPM shows promise, but it is an area that requires further research and exploration. The existing literature highlights the need for standardized methods for calculating OEE and the potential benefits of incorporating an executable digital twin in TPM activities. However, specific studies focusing on the implementation and effectiveness of an executable digital twin as an advisor in TPM are limited. Further investigation in this area can provide valuable insights into developing and utilizing executable digital twins for optimized TPM practices and improved maintenance decision-making.

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