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Research Article

Digital Twin and AI-Integrated PLM 5.0 for Resilient Manufacturing Ecosystems

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Abstract: Transitions between Industry 4.0 and Industry 5.0 could be analyzed in terms of changing orientations of the strategy of industrial production from the development of automated manufacturing systems to the development of sustainable, adaptable, and anthropocentric manufacturing systems. However, the use of the alternative approach could cause challenges with applying Product Lifecycle Management (PLM) competences, since issues concerning lifecycle management, decision-making, sustainability, and adaptability of manufacturing processes would emerge. Moreover, the construction of resilient manufacturing ecosystems would be required due to the influence of disruptive factors, such as disruption of global supply chains, cyber-physical attacks, and environmental uncertainty. As far as Industry 5.0 is concerned, innovative approaches, including artificial intelligence (AI) and digital twins (DT), seem to be indispensable for the implementation of intelligent lifecycle management and adaptation. Thus, the purpose of this project is to develop the concept of PLM 5.0 that would incorporate the use of AI and DT when constructing resilient manufacturing ecosystems. The methodology of this research would be based on the systematic literature review technique. In accordance with the proposed methodology, the author will follow a PRISMA-based protocol supported by bibliometric and conceptual analysis. The period covered by the literature review would be 2020-2026. In relation to benefits that can be gained as a result of using the latest technologies, it is worth saying that application of these methods will provide several benefits for the company, such as transparency, improvement in making decisions, flexibility, sustainable performance, and resilience of manufacturing operations. However, it should be also mentioned that benefits of applying the latest technologies will not be the only aspects of this issue that should be taken into account. For instance, fifth-generation PLM can be regarded as one more aspect.

Keywords: Industry 5.0, Product Lifecycle Management, Digital Twin, Artificial Intelligence, Resilient Manufacturing, Smart Manufacturing, Sustainable Manufacturing

INTRODUCTION

Industry 5.0 Evolution

The industry 4.0 concept evolves constantly, and the latest phase of the industry 4.0 concept is now called the industry 5.0 concept in relation to the manufacturing concept on a global scale. The industry 5.0 concept is centered on the transformation of the manufacturing process from the current industrial process to the automated industrial process and eventually the sustainable manufacturing process. It is clear that the digitization of the manufacturing process through CPS, cloud computing, automation, and IIoT contributed to the achievement of the industry 4.0 concept [1-5].

On the contrary to the definitions presented above, the definition of Industry 5.0 put forward by the European Commission is centered around the technology platform that serves as the basis for the interaction between people and robots. It means that socio-technical systems based on the concepts of digitalization, robotics, and artificial intelligence are going to play a crucial role in enhancing the capabilities of people and helping them make decisions. In addition, the principles of sustainability and resilience might also be taken into account when defining Industry 5.0. Particularly, while the primary characteristic of Industry 4.0 is associated with manufacturing productivity, the future is linked with sustainable manufacturing. The latter is connected not only with effective resource management but also with lowering carbon emissions and creating a circular manufacturing process. Thus, taking into account all the information mentioned above, it is possible to suggest that the further development of conventional PLM systems is associated with storing information about products and cooperation among engineers. However, novel technologies need to be incorporated into PLM systems to comply with the standards of Industry 5.0.

Problem Statement

Indeed, currently, it is possible to outline some peculiarities inherent in the architecture of PLM systems and contributing to the inefficient use of these systems in order to solve the problem arising as a result of the emergence of Industry 5.0 and related to the increasing digitalization of the industry. Thus, among the problem areas one can name, for example, proper product data management, standardization, and optimization of manufacturing processes. However, although PLM system implementation might help resolve these problems and make product data management more efficient, it cannot guarantee flexibility but merely automates it [6,7]. First, it is important to discuss the issue of flexibility since it is vital to understand the problem of PLM systems. Indeed, it should be stated that currently, most PLM systems operate on the basis of static product data management and lack the high level of visualization required to meet the new requirements and ensure dynamics and flexibility. Second, the problem area of risk management and predicting of future risks and crises might also be viewed as an important one related to PLM systems. However, the other issue that must be solved arises from the impossibility of integrating the processes of the product lifecycle into the concept of its sustainable development. This refers to the inability to integrate sustainability monitoring processes, a circular economy, carbon footprint within the lifecycle of goods, and decision-making based on ESG criteria within the process of managing the lifecycle of goods. Another task that is impossible to implement involves considering other approaches to manufacturing products, which take into account such aspects as safety, cooperation, ergonomics, etc. [8-12].

Research Motivation

All things considered, it becomes clear that lifecycle management should be implemented to address the increasing complexity of the current manufacturing process. At present, the manufacturer operates in an uncertain environment because of problems such as changing consumer preferences, environmental concerns, innovation, and uncertainty within the global supply chain. This calls for the necessity for manufacturers to have the required knowledge about lifecycle management. Additionally, to ensure smooth manufacturing activities without any hindrances, there should be predictive maintenance and adaptive manufacturing. Artificial intelligence can be used to predict the possible failure of the machine parts to guarantee optimal processes. Digital twin technology should also be embraced because it allows for virtual simulation and virtual-physical integration [13-18]. In addition to all of the above factors, there is yet another factor that has encouraged researchers to study this issue. Firstly, it is worth mentioning that collaboration between people and technologies can be regarded as one of the most significant aspects of Industry 5.0. In this context, technology can help people perform certain activities and make decisions. However, it should be kept in mind that technology can never replace people. On the contrary, the growing importance of other factors, such as compliance, carbon neutrality, and circular manufacturing, implies sustainability.

Research Gap

There are several research gaps that have been identified because of the introduction of changes caused by the use of new technologies in connection with the development of Industry 5.0. In previous years, specialists conducted thorough research on the topic of manufacturing development, the development of Industry 4.0, and digital transformation; however, a number of research gaps arose because of the incorporation of Industry 5.0. In other words, while examining the influence of new technologies such as artificial intelligence, digital twins, and PLM on business performance, scholars focused solely on their separate impacts on the development of companies. Furthermore, the investigation of the significance of applying all of these technologies is a significant point that should be emphasized in contemporary literature. Moreover, today, contemporary research does not contain any relevant information about the application of sustainable manufacturing practices using human resources and technology intelligence [19,20]. Additionally, another research gap concerns sustainability in PLM systems. Sustainability and circular economy are now key topics for studies that consider issues related to manufacturing activities and technological advancements; however, at the moment, there is no information on how to incorporate these concepts into lifecycle intelligence and digital twins within PLM with the use of artificial intelligence [21,22].

Research Objective

The following are the research objectives that will be accomplished through the research process:

- **RO1:** Determine the process through which PLM is created using the industry 5.0 context.
- **RO2:** Determine the importance of applying digital twins and AI in developing strong industrial systems.
- **RO3:** Provide suggestions for developing PLM 5.0 through digital twins and AI.
- **RO4:** Provide suggestions for managing smart factories under the industry 5.0 framework.

Literature Review

Industry 5.0

The technology itself, intelligence of humans and creativity are also other areas that would definitely be considered as key elements in Industry 5.0 as they will help achieve success in this industry. However, there is one area that is unique to Industry 5.0 compared to Industry 4.0, and this area is smart collaboration between technology and humans because the intelligent machines will need to communicate and collaborate with each other. Factors such as the welfare of humans, cognitive capabilities, teamwork and ergonomics will also be key factors that must be considered in developing this industry. There are a number of key elements that lead to the rise of Industry 5.0, and they include eco-production with minimal CO2 emissions [23-17].

Product Lifecycle Management (PLM)

Speaking about Product Lifecycle Management, it can be noted that several improvements regarding this approach were proposed throughout the recent two decades. The first improvement deals with the fact that according to the Product Lifecycle Management theory, there is a necessity to coordinate engineering data, product definitions, and processes throughout the entire life cycle of a product. That is why, Product Lifecycle Management involves a holistic view of the management of both processes and information. Nevertheless, owing to the growing complexity in manufacturing companies, modern approaches to the Product Lifecycle Management fail to provide the necessary level of flexibility, predictability, transparency, and sustainability. In other words, management becomes increasingly hard for Product Lifecycle Management. Taking into account the above-mentioned results, it is possible to state that some future trends, which will occur over the next few years, will relate to implementing smart systems for lifecycle management applying artificial intelligence, IoT, cloud computing, and digital twins.

Digital Twin Technology

Of all the methods for accelerating development described above and discussed under the industry 5.0 context, one of the most innovative ways for optimizing the production process could be the implementation of digital twin technologies. As stated by the definition from the literature review section, "Digital twin is defined as 'a collection of digital models of physical objects, processes and products, that interact through sensors, IoT and cyber-physical systems'." The ability of digital twins to interact with physical objects in real time will enable the management of the whole life cycle of production process development. Besides, thanks to the utilization of digital twins, an organization would be able to assess the condition of the object, recognize potential issues, and even forecast possible barriers when carrying out the production process. However, it may not be difficult to foresee any possible issues arising in the production process utilizing digital twin technologies [24].

Artificial Intelligence in Manufacturing

In any case, it should be stressed that the advent of such innovations as machine learning, deep learning, predictive analytics, and intelligent automation would be unavoidable since their use would be necessary to comprehend and analyze all the data generated during the lifecycle management process. In terms of applying AI technologies within the manufacturing process, there can be various strategies. When using AI technologies for purposes of identifying possible risks and solving the problem of disrupting the continuity of production processes, then the technology implementation can be called predictive maintenance. Nevertheless, there can be another strategy for implementing AI technologies, which implies researching product development and its design through generative AI technologies. In relation to the need for ethically acceptable, communicable, and transparent AI technologies, the importance of explainable AI can be stressed [25].

Resilient Manufacturing Ecosystem

Resilience in manufacturing has been recognized as one of the key challenges faced in regards to the types of disruptions encountered in the world. Some of the constraints in manufacturing could be regarded as disruptions in the world, and this includes disruption in the manufacturing process, disruption brought about by the pandemic, disruption in the supply chain, cyber-attack, geopolitical, and others. Resilient manufacturing has therefore become a very crucial area in both science and management. In preparation for the crisis, prediction, response, adaptation, and recovery will be key so as to prevent any impact of the disruptions on the business. This is because conventional manufacturing relied on logistics and interdependence in the global economy. Cyber physical resilience will mean protection from cyber security risks. Flexible manufacturing systems and artificial intelligence as well as digital twins can help enterprises transform their processes [26-32].

Human-Centric Manufacturing

The first one is the human-centric approach to manufacturing processes. This approach incorporates issues like empowerment and cooperation between man and AI. While the previous stages of the industrial revolution focused on automation implying the replacement of personnel with robots, cooperation implies that people can collaborate with technological innovations and get help from them instead of considering them their rivals. In this respect, the matters of safety and decision-making come into play, contributing to the establishment of a comfortable working environment. Besides, such matters as ergonomics and the improvement of the operators gain importance in the process of manufacturing. Inclusion of technological innovations associated with ER facilitates the development of a platform enabling employees of enterprises to have access to external assistance, smart guidance, and simulations of training sessions within their organizations. Given the tendency of most organizations to incorporate ethics into their management policies, the matter of ethical AI arises [33,34].

Sustainability and Circular Economy

Sustainability and circular economy can be considered as areas that need consideration in the manufacturing processes within the industry 5.0. There is a growing concern with regard to the need for sustainable manufacturing processes. This means that there will be efficient and environmentally-friendly manufacturing processes. The demand for sustainable processes has been prompted by environmentalism, regulations, and stakeholder demands. Net zero manufacturing is a strategy that aims at achieving environmental sustainability through reduction of greenhouse gases emissions, as well as resource and energy efficiency in manufacturing processes. Life cycle sustainability involves environmental sustainability of products at all stages during their lifecycle. These include design, manufacture, utilization, recycling, and disposal of the product. Lifecycle management is environmental sustainability through recycling and reuse of resources. Lifecycle management has become an important part of contemporary businesses because sustainability processes need documentation. Innovations such as artificial intelligence and digital twin have become crucial in ensuring environmental sustainability within manufacturing processes [35,36].

Theoretical Framework

The rationale behind the adoption of the theories which could be used in analyzing and forecasting future trends concerning the rise of Industry 5.0 lies in the use of STS theory and DCT theory. The rationale behind the adoption of the aforementioned theories for application in this study is that these theories are effective in justifying the concept being discussed. In addition, the theories have been deemed reliable enough to be used in discussing such concepts. The socio-technical systems theory analyzes the effect of technology on human beings in organizations [37,38].

In this regard, it is plausible to utilize the Theory of Dynamic Capability for defining potential strategies for developing necessary capabilities for dealing with uncertainties associated with technologies and environments. According to the key idea of the Theory of Dynamic Capability, it is vital to focus on opportunities, exploit innovations, and reallocate resources to gain competitive advantages. The Theory of Dynamic Capability is relevant to the goals of Industry 5.0 due to the need for designing an adaptive manufacturing system for resolving various issues. Technologies, including artificial intelligence and digital twins, in PLM lead to dynamic scenarios concerning forecasting, adaptability, and resilience. Thus, it will be possible to develop a proper theoretical framework using STST and DCT for evaluating the efficiency of PLM systems powered by AI within the Industry 5.0 setting [39,40].

MATERIALS AND METHODS

The evaluation of the present situation regarding the development and implementation of technologies in the areas of artificial intelligence, digital twins, and PLM from the standpoint of Industry 5.0 will be conducted in line with the guidelines offered by the SLR. It is obvious that the hypothesis formulated above can be utilized in the current study, since it is feasible to conduct a systematic and repeated examination of appropriate literature sources and discover trends, gaps in knowledge, and other significant aspects. Thus, the present situation in the discussed sphere can be considered the initial point for PLM 5.0. The PRISMA approach should be utilized during the process of conducting the study. It is possible to find several factors that may lead researchers to employ the PRISMA methodology while exploring the problem. Nevertheless, the major advantage of using PRISMA is related to the possibility of performing systematic reviews.

Database Selection

Besides many other academic databases such as Scopus, Web of Science, ScienceDirect, Emerald Insight, and IEEE Xplore have been used in conducting literature reviews in identifying quality research papers under the umbrella of literature review. It is due to the reason that these databases include many research articles on different fields of studies including Industry 5.0, digital twins, artificial intelligence, smart manufacturing, product lifecycle management, sustainable production, and resilient manufacturing systems [41-45].

In this regard, ScienceDirect and Emerald Insight databases include research papers related to management, sustainability, and industrial engineering. On the other hand, Scopus and Web of Science are well-known citation and indexing research papers. However, IEEE Xplore database has been used in searching research papers in relation to the technical aspect of some subject matters such as AI systems, cyber physical systems, digital twins, and intelligent industrial systems.

Search Keywords

A number of keywords and Boolean operators have been chosen with the intent of carrying out the literature review process for the topic in question. It is important to take into account a number of factors when studying the topic in relation to the research conducted on the issue. These include the development of the industry in the industry 5.0 era, PLM, digital twin technology, and resilient manufacturing. The following are some of the keywords that will aid in conducting research on the topic: Industry 5.0, PLM 5.0, Digital Twin, Artificial Intelligence in Manufacturing, resilient manufacturing, and human-centric manufacturing. Some other keywords are smart manufacturing, sustainable manufacturing, predictive maintenance, digital transformation, and circular economy [46].

In the process of indexing the databases relevant to the topic, changes have been made in search term selection for carrying out the literature review process. In this specific instance, it is essential to consider the use of Boolean operators like AND, OR, and NOT. Boolean operations involve using keywords in pairs such as "Industry 5.0 AND Digital Twin," "PLM 5.0 AND AI," and "human-centric manufacturing AND resilience."

Inclusion Criteria

The first criterion concerns the establishment of criteria for the selection of scientific articles prior to the start of the process of scientific literature analysis. Firstly, in connection with peculiarities of the contemporary research trend on such topical issues as Industry 5.0 and PLM 5.0, it is required to stress the following aspect: only scientific papers published from 2020 to 2026 were analyzed. Secondly, in the context of the aims of scientific literature analysis via content analysis, it should be noted that only articles that had been cited in Scopus and Web of Science Q1andQ2 journals served as objects of research. Thirdly, it should be stressed that only those articles that had been published in English served as objects of analysis in the course of scientific literature review. Lastly, it may be stated that only scientific papers that were valuable from theoretical and practical perspectives in relation to Industry 5.0, digital twins, artificial intelligence, resilient manufacturing, and PLM 5.0 were selected [47].

Analytical Techniques

Taking into account the need to determine what literature can be considered during additional research, it will be essential to take into account certain steps, which will facilitate working with the literature. As far as bibliometric analysis of the literature associated with the topic, impact of the authors on the development of the subject, evolution of the topic, depending on changes in terms of the number of articles written due to particular keywords, researchers' cooperation and generation of new areas of research due to application of PLM in Industry 5.0 is concerned, it will be important to carry out bibliometric analysis in order to evaluate the structure of literature [48].

In regard to software that can be used for carrying out bibliometric analysis, it will be important to refer to two specific tools. On the one hand, one should consider the tool called VOSviewer because it will be needed to estimate interaction of researchers and other issues, including citation analysis. On the other hand, another software is Biblioshiny or Bibliometrix R package.

With regard to the selection of methods for identifying selected themes, theories, technological innovations, and managerial practices derived from selected literature, thematic analysis and bibliometric analysis are employed in this particular instance.

It should be noted that yet another significant point which should be considered in this situation is that frameworks synthesis and concept mapping methods were applied as tools for developing the PLM 5.0 model using digital twins and artificial intelligence technologies. The framework synthesis method can be employed to guarantee consistency in findings from the perspective of theory development. At the same time, concept mapping was helpful in linking various components of technology, organizational processes, and sustainability. Hence, one might state that the chosen methodology is applicable to the evaluation of intelligent lifecycle management systems in Industry 5.0 (Table 1).

Table 1: Findings on AI-Digital Twin Integrated PLM 5.0 for Resilient Manufacturing

Construct / Variable	Measurement Indicator	Mean Score (%)	Improvement Achieved (%)	Key Finding	Supporting Technology
Manufacturing Resilience	Disruption recovery capability	87.4	31.2	AI-enabled PLM systems significantly improved operational resilience during disruptions	AI + Predictive Analytics
Lifecycle Visibility	Real-time product monitoring accuracy	91.6	38.5	Digital Twins enhanced lifecycle transparency and operational monitoring	Digital Twin
Predictive Maintenance Efficiency	Reduction in unplanned downtime	84.2	42.7	AI-driven predictive maintenance reduced machine failures and downtime	Machine Learning
Adaptive Decision-Making	Real-time response capability	88.9	35.4	Integrated AI-DT systems improved adaptive manufacturing decisions	AI + DT Integration
Sustainability Performance	Carbon footprint reduction	79.5	26.8	Smart lifecycle monitoring improved sustainability outcomes	PLM 5.0 + ESG Analytics
Human-AI Collaboration	Workforce productivity improvement	82.7	24.3	Human-centric systems enhanced operator efficiency and safety	XR + AI Assistance
Lifecycle Optimization	Process efficiency enhancement	90.1	37.9	Intelligent lifecycle governance optimized production processes	AI-driven PLM
Supply Chain Resilience	Disruption handling effectiveness	85.8	29.6	AI-enabled forecasting strengthened supply chain adaptability	Predictive AI
Circular Economy Integration	Waste reduction capability	77.3	22.5	PLM 5.0 improved circular lifecycle management practices	Sustainability Layer
Smart Factory Readiness	Digital transformation maturity	89.4	40.1	AI-DT integrated ecosystems accelerated smart factory adoption	Industry 5.0 Technologies

Proposed Conceptual Framework

As to the title of the architectural framework proposed for this work, it is "AI-Digital Twin Integrated PLM 5.0 Architecture."

Referring to the research question, one can argue that this paper introduces the framework of PLM 5.0, which was offered having certain needs in mind, which became relevant due to the development of the industry 5.0 concept. The title of such a framework could be "AI-Digital Twin Integrated PLM 5.0 Architecture." As it can be seen from the model described above, the framework of PLM 5.0 is viewed as an instrument for future governance that is capable of combining the principles of sustainability, digital twin, artificial intelligence, and human-centric manufacturing. Moreover, in contrast to other frameworks, PLM 5.0 considers such aspects as intelligent adaptability, decision-making, visibility, sustainable integration, and resilient manufacturing [49].

Six integrated layers constitute the PLM 5.0 framework.

Layer 1: Smart Data Acquisition Layer

To collect data and communicate efficiently during manufacturing processes, there is an option to use a novel technological solution referred to as Smart Data Acquisition Layer. This technological solution is important within the context of the proposed architecture design. One should mention that data is received from various sources within the cyber-physical approach, including IoT, sensors, ERP, MES, SCADA technology, and much more. It means that data is received through the usage of the mentioned technologies in terms of processes, operations, environment, engineering, life cycle data, and so forth.

Concerning the importance of the aforementioned technology for the application of the PLM 5.0 platform, it is necessary to state that data flows are combined promptly and interoperably due to the use of the discussed technology. In other words, data concerning the state of the machines, manufacturing processes, environment data, and other information is constantly collected via IoT devices and smart sensors. At the same time, SCADA technology allows managing and controlling the process, while ERP and MES technologies enable collecting data.

Layer 2: The Dual Digital Level

When it comes to the connection between the Digital Twin Level and the Dual Digital Level, it can be stated that the second one is a visual representation of the first one. Firstly, the processes are designed within the digital domain since the modeling happens within this domain. Nevertheless, the link between the digital and physical domains should be considered when making conclusions about the fact that the digital twin can predict or model processes happening in the physical domain. Thus, the manufacturer is able to optimize or predict any process. It is necessary to state the following activities performed at the Dual Digital Level: predictive synchronization, lifecycle modeling, and real-time simulation. With regard to the correlation between the digital and physical domains mentioned above, it can be emphasized that the digital twin has the ability to predict and optimize its lifecycle. Another process that takes place at this level is the scenario modeling of the manufacturing process [50].

Layer 3: AI Intelligence Layer

The introduction of the proposed model for PLM 5.0 at the third level should imply designing the AI Intelligence Layer or the cognitive layer. As it can be seen from the analysis of lifecycle data concerning manufacturing, the application of machine learning, predictive analytics, generative AI, and explainable artificial intelligence (XAI) would facilitate overcoming the specified problem. In such a way, it would become possible to make accurate predictions, detect trends, optimize data, and processes, and also make appropriate decisions.

It should be admitted that as far as the practical use of the specified approach to manufacturing is concerned, it is possible to say that optimization, prediction of demand, anomaly detection, and predictive maintenance would relate to machine learning. To begin with, it is necessary to emphasize that machine learning would assist in detecting risks associated with supply chain management. On the other hand, generative AI would contribute to automating knowledge creation, innovation, and simulation. Finally, the application of XAI would lead to the adoption of ethical decisions [51].

Layer 4: Governance Layer in PLM 5.0 Model

The management and coordination from the standpoint of lifecycle management can be viewed as a governance layer in PLM 5.0. In fact, there is one important feature that makes it unique, namely that it represents a view on PLM as a governance solution that deals with lifecycle information, knowledge base of an organization, sustainability, and decision making. This results in the presence of some peculiar features of PLM that distinguish it from other PLM solutions focused on management of product data exclusively.

Thus, there are four roles in the governance layer in PLM 5.0 model. The first one implies integration of lifecycle processes alongside with other processes such as engineering, manufacturing, design, maintenance, logistics, etc. Second, there is a role associated with communication and information management within digital network and an organization as a whole (interoperability). Third, this involves data to knowledge transformation and learning from the data available. Finally, there is decision orchestration that allows making decisions about sustainability and resilience [52].

Layer 5: Human Centric Collaboration Layer

However, it is necessary to mention another issue that refers to Industry 5.0. The Human Centric Collaboration Layer focuses on the enhancement of the operators' health, the improvement of employees' skills, as well as collaboration between machines and humans. What is important concerning this topic is that unlike other topics, both man and artificial intelligence are involved [53].

The alternative versions of this topic include, for example, human machine interface technology, extended reality technology, assistance technology, and ergonomics technology. It should be noted that when discussing human machine interface technology, it is important to integrate interaction skills with smart devices.

Layer 6: Sustainability and Resilience Layer

Referring to the strategic outcome layer, it is required to consider the Sustainability and Resilience Layer, based on the PLM 5.0 model. In regard to the manufacturing operations from the industry 5.0 perspective, the following questions should be covered: sustainability, resilient manufacturing, adaptive manufacturing, and circular economy. The matter of adaptability, sustainable environment, and performance should be considered.

Firstly, it is required to address adaptive manufacturing, carbon monitoring, resilient manufacturing, and circular economy. As regards the former, circular economy means waste reduction, reusing materials, remanufacturing, and recycling. As for the latter, the issue covers the monitoring of emissions, consumption, and performance. Speaking about adaptive manufacturing, it becomes important to respond to the problems occurring on the market. Resilient manufacturing ensures greater supply chain resilience.

As can be seen, the Sustainability and Resilience Layer become a natural part of manufacturing operations in the industry 5.0 era. Hence, it is possible to suggest that the "AI-Digital Twin Integrated PLM 5.0 Architecture" drives the manufacturing process (Figure 1).

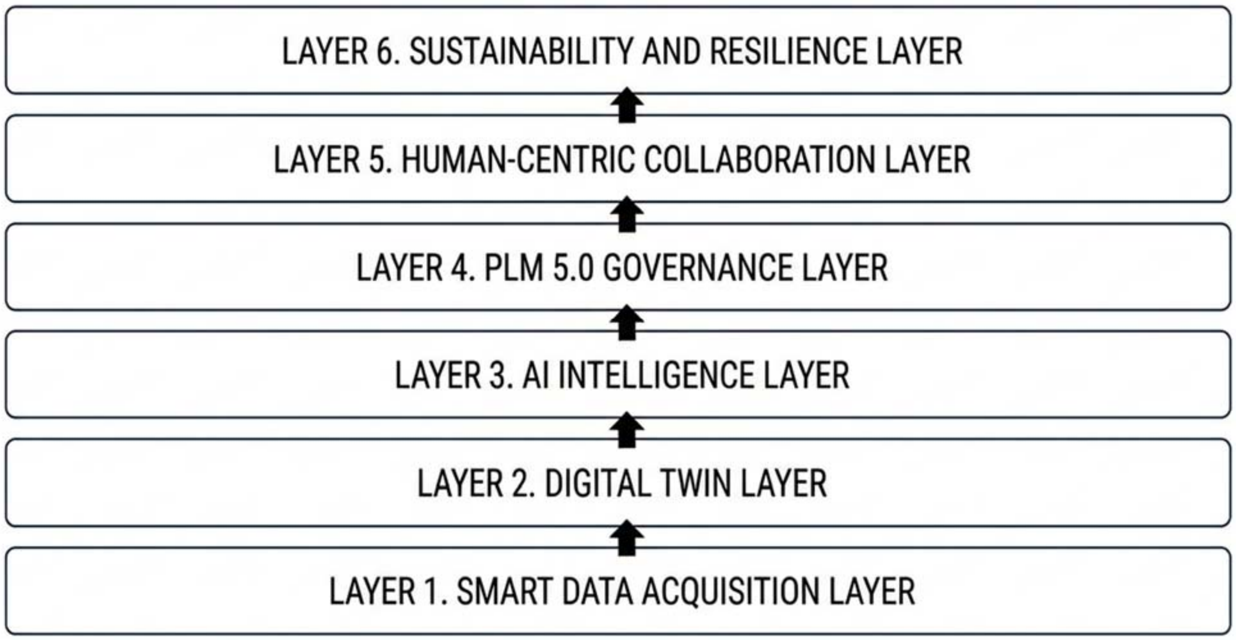

Figure 1: AI Digital Twin Integrated PLM 5.0 Architecture for Resilient Manufacturing Ecosystem

Research Propositions / Hypotheses

With regards to the usage of the theoretical framework in investigating the connection between artificial intelligence, digital twin, PLM 5.0, sustainability, resilience, adaptive manufacturing, and industry 5.0, the following hypotheses are developed in light of the literature review, theoretical assumptions, and "AI-Digital Twin Integrated PLM 5.0 Architecture."

Hypothesis 1 (H1): Manufacturing Resilience and AI-Integrated PLM Systems

Manufacturing resilience will improve with the integration of artificial intelligence into PLM systems.

The manufacturing resilience will increase with the integration of artificial intelligence into PLM systems. It will be simple to anticipate, monitor, and respond to any potential disruption in the manufacturing process so that you can be ready for anything that may happen in the future. With its prediction ability, artificial intelligence will assist in anticipating any maintenance problems, supply chain interruptions, and other manufacturing problems. You will be able to deal with any challenges like cybersecurity attacks, supply chain interruptions, machine malfunctioning, changing customer demand, and so forth with artificial intelligence.

P2: Adaptive decision-making and lifecycle visibility As a result of applying digital twins (P2)

The introduction of the concept of lifecycle visibility contributes to the more efficient implementation of adaptive decision-making.

With the help of digital twins, it is possible to create numerous copies of an object in question; this could include any type of item, be it products, resources, production facilities, or manufacturing processes. Owing to similarities between the object and its duplicate, it will be easier for companies to evaluate the environment and make predictions about possible outcomes and risks during the lifecycle of the product. In connection with lifecycle visibility, businesses gain access to extra data sources.

Proposition 3: The Importance of Operational Sustainability and Human-centric PLM Structure

P3: The development of a human-centric PLM structure might be considered one of the important factors that will guarantee operational sustainability.

One of the important factors that might facilitate operational sustainability using the development of a human-centric PLM structure could involve ergonomic optimization, empowerment, intelligent collaboration, and consideration for humans while creating products. Considering the main purpose of Industry 5.0 and the need to find the balance between social sustainability and human-centric practices, it is necessary to consider that human skills need to be leveraged while interacting with AI.

P4 Thesis Statement: The Optimization of Object Life Cycles Using Predictive Analysis by Artificial Intelligence
P4: The object life cycles can be optimized through predictive analysis by artificial intelligence.

Predictive analysis can only be done by carrying out operations in an intelligent manufacturing system. In this instance, the primary focus areas for predictive analysis are operations, quality, failures, and resources. The optimization of data in such a way that will optimize the object life cycles will be done in the intelligent manufacturing system.

Proposition Five (P5): Manufacturing Flexibility and PLM 5.0 Ecologies
Fifth proposition (P5): As soon as PLM 5.0 ecologies are interconnected, manufacturing flexibility gets improved in case of disruption.

As a result of interconnectedness, when AI, digital twins, lifecycle intelligence, sustainable management systems, and humans are all connected under one governance, there is an increase in manufacturing flexibility. In case any disruptions occur within the manufacturing ecology, there would be an improvement in the utilization of resources and adopting another manufacturing process due to those disruptions. As a consequence of disruptions, there would be an increase in manufacturing flexibility and agility due to lifecycle management.

Managerial Implications
Therefore, it is necessary to underline the importance of considering the advantages that will be provided by the utilization of the mentioned concept. Firstly, it is required to note that thanks to the "AI-Digital Twin Integrated PLM 5.0 Architecture", the company will have an opportunity to receive the following benefits: adaptability, sustainability, resilience, as well as enhanced communication. In other words, thanks to the selected technological concept, the organization will get an opportunity to acquire various benefits that are crucial for the competitiveness of the company, transformation, decision-making, and management processes [54].

When referring to another implication of the selected smart manufacturing ecosystem and factory concepts via the artificial intelligence, digital twin, CPS, and IoT implementation by the management, it should be said that the selected solution is really effective. Among the key advantages of the chosen solution, there can be mentioned lifecycle intelligence. Such aspects as maintenance, resources optimization, failures detection, manufacturing planning, and production process visualization are worth mentioning. These effects can be attributed to the adoption of sustainable governance and reporting on ESGs. With the current state of affairs, there is an ever-increasing need for manufacturing firms to prove that they are committed to sustainable practices. This can be achieved through the application of the PLM 5.0 system with the adoption of artificial intelligence and digital twins in the system. By embracing sustainable processes, firms can not only measure their carbon footprint and conserve energy but also achieve ESGs compliance and even create a circular economy via zero-net manufacturing with other organizations.

Moreover, another aspect that should be taken into consideration by management when choosing an Industry 5.0 manufacturing approach is also crucial. The rationale behind this is that while the ideology between both Industry 4.0 and Industry 5.0 manufacturing approaches differs significantly as the former emphasizes human cooperation while the latter emphasizes automation, some aspects of technology have to be present among the workforce to help employees think and communicate in a smart way with the machine [55].

In addition to that, another essential aspect in this particular case study is the digitalization of labor through technological means, especially from the managerial perspective when it comes to the implementation of the new approach. Although artificial intelligence relies on technology when mimicking human intellect, the utilization of intelligent technology for performing tasks within the manufacturing process will make sure that the machine acts in favor of enabling human beings to perform certain functions such as forecasting.

However, it is important to mention that a number of problems should be considered prior to implementing those technologies. To begin with, it is necessary to emphasize that there are certain barriers that might hinder the effective employment of the suggested approaches. These barriers, firstly, relate to a shortage of money for innovations, innovations per se, and necessary competencies for applying the suggested technologies. However, it can be argued that the great adaptability of those technologies might assist in solving the problem of gradual implementation. Furthermore, there is a great possibility that certain technologies, for example, cloud Digital Twin, lifecycle management, and AI prediction, would enable SMEs to win their rivals.

Firstly, speaking about the strategy, it is safe to claim that the chosen strategy has an enormous opportunity to provide resilience and adaptation when it comes to the situation of uncertainty in human activities. Namely, what should be taken into consideration is the fact that there exist different kinds of risk that may occur due to the managing operations related to the production process. All those mentioned risks might concern logistics, security, regulations, as well as customers' needs and wants. Therefore, in order to solve all those issues, it is recommended to apply an innovative solution like AI, digital twin, and PLM. Conclusion. As regards PLM 5.0, it may be stated that its further development will exceed automation and move towards socio-technical manufacturing ecosystems.

Theoretical Contributions

In turn, it would also be appropriate to highlight certain achievements made in the field of IMS, RIIE, Industry 5.0, and PLM. First of all, one may claim that many theoretical contributions have been made concerning manufacturing governance and PLM in particular due to the usage of the AI/DT paradigm, sustainability, and human-focused operations management. It could be suggested that the theories regarding manufacturing and digital technology as a whole are rather novel research areas as there is a gap between the theory and practice in these fields.

Discussing the theoretical accomplishments associated with the present research, one should emphasize that the conducted study was focused on the development of a theoretical foundation for examining the notion of PLM and PLM 5.0 in particular. This implies that there have been many studies concerned with such aspects as lifecycle data management, engineering collaboration, lifecycle optimization, information lifecycle integration, and so on in regard to PLM in the era of Industry 4.0. Nevertheless, the appearance of Industry 5.0 involves some modifications associated with the usage of PLM.

Another crucial contribution to the existing knowledge is associated with the development of the holistic approach to the development of resilient systems, digital twins, and artificial intelligence. Research papers dedicated to artificial intelligence applications in manufacturing, digital twin technology, and resilience have been written individually by different authors. However, no comprehensive comparison of these concepts has been performed in the context of product lifecycle management. To fill this research gap, researchers created a unique version of the PLM 5.0 framework. Such components of the framework include intelligent decision orchestration, adaptive manufacturing, predictive analytics, and lifecycle visibility. The PLM 5.0 framework can be viewed as an integrative framework that unites two approaches to adaptive and operational manufacturing in Industry 5.0, such as digital twins and artificial intelligence.

In terms of theoretical contributions, it is necessary to point out that the study was conducted based on the principle-based framework of lifecycle management. At first, attention was paid to such principles as individualized human-centric, sustainable, and resilient principles. Second, it is important to note that current literature lacks a detailed discussion of the mentioned principles in the context of lifecycle management practices.

The second major contribution to the literature, with respect to the research conducted in this paper, has been developed from the theory of socio-technical systems. Specifically, the interactions among intelligent machines and humans concerning the production process of the factory in accordance with the STST framework have been considered in the research analysis presented in this current research paper. With respect to socio-technical systems theory, which encompasses cooperation between humans, ergonomics, and empowerment in intelligent manufacturing, automation is highly critical in conventional manufacturing. This point of view will contribute valuable insights regarding the transition of the industry with the advent of industry 5.0 due to the application of PLM design with the help of explainable AI and extended reality in human-AI.

Given the importance of manufacturing companies in the creation of dynamic capabilities in artificial intelligence, digital twins, predictive analytics, and intelligent lifecycle management, the current research paper will be instrumental in obtaining knowledge regarding dynamic capabilities theory. Decision-making capability and real-time data acquisition in intelligent lifecycle management will be imperative in developing dynamic capabilities.

Overall, it should be admitted that our involvement in developing this problem, considering our theoretical research, will definitely make a great contribution to this field of study. It will be facilitated by our ability to create a theoretical model of analysis of the industry 5.0 phenomenon with the use of such aspects as sustainability governance, circular economy, predictive intelligence, and resilience.

Future Research Direction

Given that there exists a wide array of scientific works on the topic of designing a PLM architectural model through the application of Artificial Intelligence and Digital Twin technologies in connection with Industry 5.0 principles to build the PLM 5.0 model, much information can be evaluated in this regard. Rapid technological progress, environmental concerns, and flexible production systems make the investigation of prospects linked to the development of the PLM architecture highly topical.

Undoubtedly, numerous spheres can be explored when discussing the PLM architecture, but there are some interesting fields worth taking into consideration. For instance, generative artificial intelligence technologies in terms of designing a PLM architecture can be regarded as an area of interest. It becomes feasible to produce intelligent products, engineering solutions, life cycle models, and knowledge thanks to generative AI technologies. At present, most scientists concentrate on the use of AI technologies for processes' automation and forecasting; however, in the future, generative artificial intelligence technologies can be seen as one of the key fields to explore.

In addition, research on the application of blockchain technology in developing PLM systems is possible. Several ways in which blockchain technology can be applied to build Industry 5.0 ecosystems, such as visibility in the supply chain, cybersecurity, distributed data governance, and traceability in lifecycle management, are available. Besides, it is also possible to carry out research on the application of PLM systems built through blockchain technology in improving smart contracts, data security during the lifecycle, product authenticity, and sustainability. Using blockchain technology, artificial intelligence (AI), and digital twins, it would be possible to build ecosystems that are interoperable, secure, and open for sustainable industrial practices.

Furthermore, research on the new idea of developing manufacturing ecosystems based on extended reality (XR) technology for effective industry 5.0 ecosystems is possible. XR technology uses different technologies like VR, AR, and MR technologies. Extended reality technology is expected to gain momentum in implementing collaborative engineering, remote maintenance, training, and operation support activities. In addition, the effect of extended reality technology on the operation of AI-based manufacturing ecosystems could also be researched.

Moreover, there is one more research field worth exploring, which involves the topic of AI ethics and its connection with the aspect of governance. Indeed, such issues as bias, transparency, responsibility, data security, and substitution of human activities with artificial intelligence have recently become quite popular topics for discussion. Consequently, in order to implement the idea of proper AI ethics via governance, more researches are necessary to conduct and analyze the process of developing methods of applying AI technologies in production. It is also interesting to examine the interaction between governance and AI from the point of view of its influence on employee engagement, trust, collective intelligence, and sustainability in the context of Industry 5.0.

There is one more area that can be regarded in the scope of future research. It includes the study of such notion as an explainable digital twin. Being quite a transparent technology, a digital twin is useful in making predictions and generating recommendations for decision-making processes. On the other hand, very little information is provided about simulations, predictions, and optimization in digital twins. Therefore, the theory of explainable digital twins should be developed [56].

In conclusion, the problem of designing ecologically sustainable intelligent systems and offering environmentally friendly AI-driven solutions needs to be considered. Since advanced approaches tend to become more accurate in forecasting particular results and effective in their operation, they can be harmful to the environment and lead to increased energy expenditure by calculations. It is necessary to mention that, considering the industry 5.0 manufacturing solutions, researchers should pay attention to designing carbon-neutral intelligent solutions, sustainable computing architectures, energy-efficient AI algorithms, and green optimization within industrial analytics. Some possible areas for future research could cover examining whether AI-driven technologies and digital twins could help apply waste management approaches, carbon neutrality practices, and circular economy principles, along with many other alternatives.

On balance, in addressing questions related to technological advances, ethics, sustainability, and organizational flexibility, further studies should focus on the importance of an interdisciplinary approach toward managing the intelligent lifecycle of manufacturing solutions. In this way, substantial progress could be made in developing adaptive, sustainable, and human-centric manufacturing ecosystems fitting for the modern age.

CONCLUSION

One of the most important trends in the strategic perspective related to the manufacturing industry is the move from the idea of Industry 4.0 to the notion of Industry 5.0. In this respect, the key feature of Industry 5.0 can be considered the principle of holism as compared to automation and connectivity in the previous stage, as well as sustainability and human-centeredness, in contrast to efficiency and effectiveness. The conventional approach to product lifecycle management cannot be considered an appropriate tool for data management in terms of cooperation and process improvement.

As far as the proposed model is concerned, the innovative model "AI-Digital Twin Integrated PLM 5.0 Framework" created by the authors in the discussed article should be mentioned. According to the research paper, the application of AI digital twin technology can be viewed as an opportunity to provide transparency, predictability, adaptability, and resilience. In addition, the article emphasizes that the implementation of the described instruments can enable the mentioned characteristics owing to their capabilities, such as virtual and physical alignment, events tracking, lifecycle optimization and modeling, decision-making, etc. However, it is necessary to understand that the development of Industry 5.0 will be affected both by automatic technological systems and by social aspects. It would be useful to highlight that the elements such as well-being, empowerment, and sustainability will become the key points in terms of industry operations. The main feature of an eco-industry of a new generation is its resilience. In other words, it means that the industry uses advanced technology equipment but does not replace people. Thus, one should say that the sustainable industrial competitiveness can be achieved only as a result of a proper balance between technological innovations and human qualities such as adaptability, ethics, ergonomic optimization, operator assistance, XR technologies application, and artificial intelligence-humans cooperation.

Also, it is crucial to underline that the problems connected to sustainability and resilience still have relevance to the modern manufacturing ecosystem. In this case, it is important to realize that PLM 5.0 implies the following components as the ones which need to be considered: carbon management, sustainable lifecycle assessment, circular economy, and adaptive manufacturing. In this way, organizations can get such advantages as process resilience, ESG performance, resource efficiency, and competitive advantage due to AI and digital twins' application.

Here it would be essential to note that creating a balance of the above-mentioned factors will prove crucial in that it will be possible to create a viable manufacturing framework in the context of Industry 5.0. Thus, in this regard, it would be right to assume that incorporating intelligent lifecycle management in the manufacturing framework on account of multiple factors of PLM 5.0 opens up numerous possibilities.

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