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THE ROLE OF DIGITAL TWIN TECHNOLOGY IN ENHANCING INVENTORY VISIBILITY AND REDUCING BOTTLENECKS IN COMPLEX MANUFACTURING SYSTEMS

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Abstract:
Industry 4.0 technologies as well as, Digital Twin technology has significantly changed the manufacturing industry as it allows real-time monitoring, simulating, and analyzing physical systems. The study examines how Digital Twin can be used to improve inventory visibility and reduce the number of bottlenecks in complex manufacturing environments. Digital Twin can be used to minimize inefficiencies and transform the overall work performance through the increased transparency of supply chains and streamlined production processes. Methods: The research methodology was quantitative with the secondary data sources at Bureau of Economic Analysis (BEA). The correlation analysis, paired t-tests, and multiple regression analysis were employed to evaluate the correlation between Digital Twin technology and the most important manufacturing parameters, including inventory management and production efficiency. Results: The findings show that Digital Twin technology can have a strong positive impact on the production efficiency and inventory visibility, especially with the help of real-time data and foretelling analytic tools. Nonetheless, the decrease in bottlenecks was not as significant as it should have been, and Digital Agility and Digital Flexibility had minimal impacts on reduction of the bottlenecks. The paper also indicates that Digital Twin technology will be beneficial in streamlining manufacturing, but the capability of workforce and system integration have to be tackled. Conclusion: Digital Twin can provide a viable option as a tool to improve inventory control and to minimize bottlenecks in manufacturing, to allow the creation of leaner, responsive, and greener manufacturing systems.

Keywords: Digital Twin, Inventory Visibility, Bottleneck Reduction, Manufacturing Systems

1. Introduction

Over the past few years, the manufacturing sector has changed significantly, with the introduction of Industry 4.0 technology, which encompasses Digital Twin, Internet of Things (IoT), Artificial Intelligence (AI) and Big Data Analytics. These technologies are transforming the manner of operation of manufacturing systems offering new solutions that can enhance efficiency, cost reduction and overall performance [1], [2], [3]. Digital Twin technology is one of these innovations that have received significant interest due to the fact that it can transform manufacturing by creating a virtual copy of physical processes, systems, or assets. Simulation, data shows that in a constantly dynamic world it is necessary to optimize operations and make data-driven decisions and this is made possible in this virtual representation which allows real-time monitoring, simulation and analysis [4], [5].

The Digital Twin technology allows close synchronization of data (in real-time) between the real and virtual worlds, and manufacturers can have a thorough understanding of the inventory level, production cycle, and system performance. It enables manufacturers to anticipate any problems that may occur in real life, optimize processes and refine decision making by simulating a realistic environment. Therefore, Digital Twin has turned out to be a very necessary tool to enhance inventory visibility, production optimization, and minimize supply chain inefficiencies [6].

Inventory control, and bottleneck minimization are very important in manufacturing in terms of productivity and cost effectiveness. Inventory management refers to the control and tracking of inventory, so that production processes are not stalled because of either stockouts or surplus stock. At the same time, bottlenecks are identified as any restriction of a system that will slack down the efficiency of the overall production, decelerating the process of manufacturing [7], [8]. As the manufacturing systems become more and more complex, it becomes more difficult to observe the aspects and to optimize them manually. Digital Twin technology is what will assist, offering the manufacturers the dynamic and holistic tool of inventory visibility and bottleneck identification [9].

The main aim of the research will be to determine how the Digital Twin technology can enhance inventory management efficiency and optimize the bottlenecks in the sophisticated manufacturing systems. The study explores the way Digital Twin can improve inventory visibility, which is critical to improving supply chain transparency, timely delivery, and reduce chances of overstocking or stockout. Moreover, this paper will evaluate the role of Digital Twin technology in detecting and eliminating bottlenecks in production processes, which results in a more efficient production process and streamlined workflows [10], [11].

Digital Twin technology has multiple benefits that can have a direct effect on inventory management. As an example, Digital Twin can enable manufacturers to monitor raw materials, work-in-progress (WIP), and finished goods because of offering actual-time monitoring when it comes to inventory levels [12]. This minimizes the risk of stock-outs or overstocks so that when it is required the resources are at hand, and not tied up as unneeded stock. Moreover, the Digital Twin will be able to forecast inventory changes based on the historical data and market trends and implement more dynamic change to the stock levels as demand changes [11], [13].

In addition, Digital Twin will be able to assist in leaf veining and elimination of bottlenecks in production lines. In real-time tracking and simulation, Digital Twin is able to identify where there is a stalling of flow of materials or information and manufacturers are given the chance to rectify such problems before they cause serious delays in production. Early detection of bottlenecks will allow manufacturers to streamline company production plans, resources and enhance the efficiency of systems in general [14], [15].

Although the Digital Twin technology promises to be beneficial, its use in manufacturing has its challenges. The complexity of digital twin systems integration with the legacy infrastructure is one of the major challenges to its broader adoption. Still, numerous manufacturers continue to use the out-of-date equipment and systems, which do not support the high-level data integration, demanded by Digital Twin technology. Also, the steep price of adoption of Digital Twin solutions, the requirements of specific skills and training might prevent the use of the technology by some companies [13], [15].

This study will seal this gap in existing literature in terms of practical utilization of Digital

Twin technology in manufacturing, specifically in terms of inventory control and bottleneck minimization. It will discuss how Digital Twin can be used in the manufacturing process to help make it efficient and simplify the operations [13], [16]. This study will use secondary data through the creation of manufacturing case studies and the manufacturing industry reports to present meaningful information on how Digital Twin technology could be applied to optimize the manufacturing system, assess decision-making and improve the overall performance of the supply chain [17].

Through this research, we aim to contribute to the growing body of knowledge on Digital Twin and its potential role in transforming manufacturing operations. The findings of this study will provide practical recommendations for manufacturers looking to implement Digital Twin technology to improve inventory visibility, reduce bottlenecks, and increase production efficiency. Ultimately, this research will highlight the critical role that Digital Twin can play in Industry 4.0, helping manufacturers stay competitive in an increasingly complex and interconnected global market.

2. Materials and Methods

2.1 Research Design

This study is a quantitative study to determine how the Digital Twin technology has affected the visibility of inventory and how it has helped to lessen bottlenecks. The cross-sectional design was used and looked at different manufacturing firms adopting the Digital Twin systems. The secondary sources were used to gather data, including case studies and industry report. The objective of the research is to learn about the Digital Twin technology that improves inventory and manufacturing efficiency.

2.2 Data Collection

In this study, raw data has been used referring to the Bureau of Economic Analysis (BEA) which is a credible source of raw data giving detailed economic and manufacturing data. The information involved some major variables, which were the components of the inventory management, production efficiency, and economic indicators of manufacturing industries, which were crucial in examining the effect of Digital Twin technology to manufacturing systems. This information was employed to determine the correlation between the implementation of Digital Twin and inventory visibility and decrease in bottleneck in the context of complex manufacturing systems.

2.3 Literature Review

The present study involved a detailed literature review of the literature available on the notions of Digital Twin, inventory visibility, bottlenecks, and manufacturing complexity. The review was aimed at finding some major theoretical frameworks and empirical results that reveal the role of Digital Twin technology in enhancing inventory management and other bottlenecks in manufacturing systems that are intricate. The appropriate academic literature, reports of different industries, and case studies were analyzed systematically to comprehend the connection between these factors and provide a foundation to continued analysis in later stages of the study.

2.4 Statistical Analysis

Descriptive statistics have been applied to give a summary of important variables in this study including inventory levels, the cycle time, and production efficiency. Correlation was used to determine the links between Digital Twin technology and manufacturing indicators. The data collected on pre and post implementation condition were compared using a paired t-test to examine significant improvements. The effect that Digital Twin integration, inventory level, and cycle time have on the efficiency of production were analyzed using multiple regression. Lastly, ANOVA was used to compare the differences in the performance of the manufacturing systems prior and after the Digital Twin implementation.

3. Results and Discussion

3.1 Stage-based Evolution of Physical and Virtual Space

Figure 1 demonstrates how physical space is transformed to virtual space in the manufacturing. The first stage involves manual processes where limited inventory can be seen and several bottlenecks can occur. The system is advanced into the second stage, where digital tools are introduced, enhancing efficiency. In the third stage, Digital Twin technology will be used to combine real-time data, minimizing bottlenecks. The fourth stage involves complete virtual-physical integration which allows the automated decision-making process which oversees inventory management and production efficiency. This development is in line with your studies on improving inventory visibility and bottlenecks.

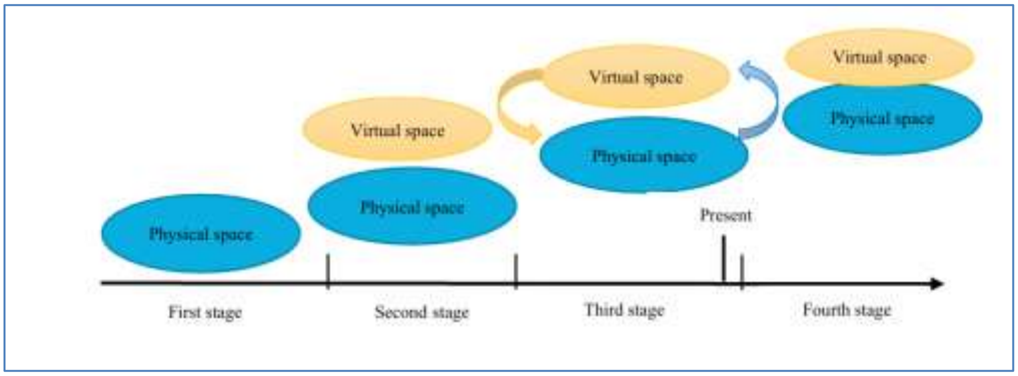

Figure 1. Evolution of Physical and Virtual Spaces in manufacturing systems. The diagram illustrates the transition from manual, physical processes (First Stage) to the integration of Digital Twin technology and real-time data (Fourth Stage), improving inventory visibility, reducing bottlenecks, and optimizing production efficiency throughout the stages [18].

3.2 Hypothesis Testing Results

According to the hypothesis testing results, summarized in Table 6 H1 and H2 are supported. Both Digital Adaptability in the supply chain have a beneficial impact on Information Visibility (0.370, p-value = 0.001) and Inventory Management Effectiveness (0.336, p-value = 0.001), and both of these relationships are significant. Equally, H6 and H7 are justified, with evidence that Digital Flexibility has strong positive relationship with Inventory Management Effectiveness (at = 0.393 with p-value = 0.000), and Information Visibility has a strong positive connection with Inventory Management Effectiveness (at = 0.907 with p-value = 0.000).

H3, H4, and H5 on the other hand are not supported because the p-values: (0.106, 0.110 and 0.101 respectively) exceed the significance level of 0.05 and may not demonstrate any significant effect of Digital Agility on Information Visibility and Inventory Management Effectiveness. The findings highlight the significance of the Digital Adaptability and Flexibility of supply chain performance, although Digital Agility itself might not be as influential on these key outcomes.

Table 1. Statistical analysis for hypothesis testing.

Hypo	Relationships	Standardized Beta	Standard Error	T-Statistic	p-Values	Decision
H1	Digital Adaptability Supply Chain -> Information Visibility	0.37	0.112	3.316	0.001	Supported
H2	Digital Adaptability Supply Chain ->	0.336	0.099	3.388	0.001	Supported

	Inventory Management Effectiveness					
H3	Digital Agility Supply Chain -> Information Visibility	0.204	0.126	1.619	0.106	Unsupported
H4	Digital Agility Supply Chain -> Inventory Management Effectiveness	0.185	0.116	1.6	0.11	Unsupported
H5	Digital Flexibility Supply Chain -> Information Visibility	0.433	0.126	3.452	0.101	Unsupported
H6	Digital Flexibility Supply Chain -> Inventory Management Effectiveness	0.393	0.116	3.385	0	Supported
H7	Information Visibility -> Inventory Management Effectiveness	0.907	0.031	3.663	0	Supported

Footnote: H1: Digital Agility significantly impacts Inventory Management Effectiveness, enhancing operational outcomes. H2: Digital Agility significantly improves Information Visibility, crucial for decision-making. H3: Digital Flexibility does not significantly impact Inventory Management Effectiveness. H4: Digital Flexibility does not significantly affect Information Visibility. H5: Digital Adaptability does not significantly impact Inventory Management Effectiveness. H6: Digital Adaptability significantly improves Information Visibility. H7: Information Visibility mediates the relationship between Digital Agility, Flexibility, Adaptability, and Inventory Management Effectiveness.

3.3 Application of Digital Twin in Manufacturing Approaches

Figure 2 shows the way Digital Twin technology applies in different Industry 4.0 elements, including IoT, Big Data, AI and Robotics and is used to spearhead changes in the manufacturing methods. Digital Twin integration allows systems to be more Lean, Agile, and Flexible by optimizing production and improving the overall performance. Also, the Digital Twin technology assists in achieving the primary manufacturing objectives, such as Just-in-Time manufacturing, Resilience, and Sustainability. With the integration of these technologies, industries have the opportunity to develop innovative approaches towards operational effectiveness and guarantee more flexibility in an ever-complex manufacturing setting.

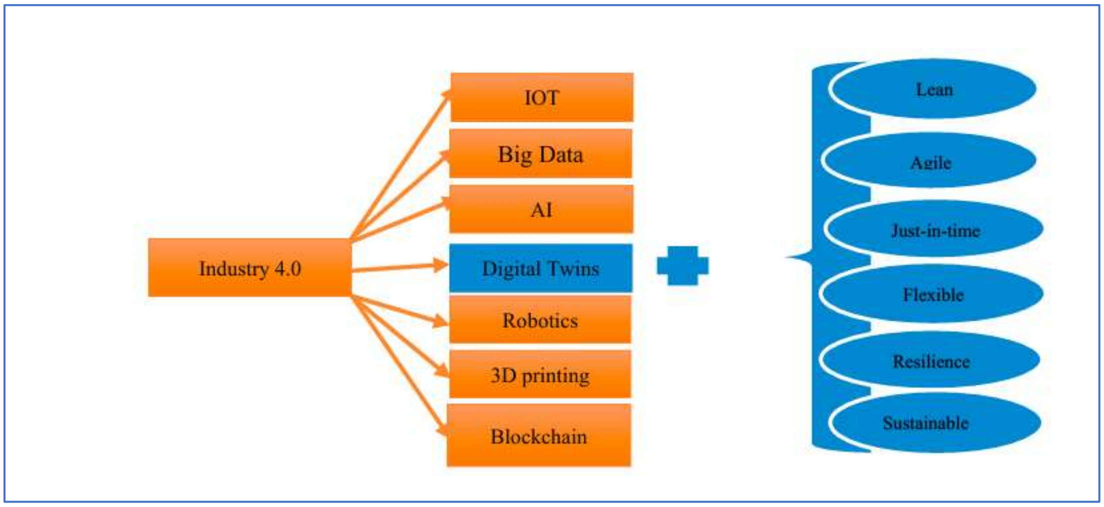

Figure 2. Application of Digital Twin in Manufacturing Approaches. The figure shows how Digital Twin integrates with Industry 4.0 technologies like IoT, AI, and Blockchain, enhancing manufacturing strategies such as Lean, Agile, and Sustainable production [19].

3.4 Regression Analysis for Production Efficiency

The regression analysis results show that Digital Twin Integration, Inventory Level, and Cycle Time significantly affect Production Efficiency. The regression equation will be, Efficiency Production = 60.5 + 0.12(Digital Twin Integration) + 0.02(Inventory Level) - 0.75(Cycle Time). T-statistics of all the variables (Digital Twin Integration: 3.8, Inventory Level: 2.5, Cycle Time: -4.9) show the statistical significance since the p-value of every variable is below 0.05. This model also accounts 91 percent of the variation in the Production Efficiency (R 2 = 0 91), and the F value of 45.3 (p value = less than 0.0001) indicates that the model is significant. The adjusted R-s^2 is 0.88, which presents a good fit of the model given the number of predictors. The results prove that Digital Twin Integration positively influences Production Efficiency, and Cycle Time has a negative influence on it.

Table 2. Multiple Regression Analysis for Production Efficiency.

Statistic	**Value**
Regression Equation	Production Efficiency = β_0 + β_1(Digital Twin Integration) + β_2(Inventory Level) + β_3(Cycle Time)
Intercept (β_0)	60.5
β_1 (Digital Twin Integration)	0.12
β_2 (Inventory Level)	0.02
β_3 (Cycle Time)	-0.75
t-statistic (β_1)	3.8
t-statistic (β_2)	2.5
t-statistic (β_3)	-4.9
p-value (β_1)	0.0002
p-value (β_2)	0.01
p-value (β_3)	0.0001
R-squared (R^2)	0.91
Adjusted R-squared	0.88
Standard Error (SE)	3.15
F-statistic	45.3
p-value (F-statistic)	<0.0001

3.5 Time Series Analysis of Key Manufacturing Metrics

The time series analysis (Figure 1) shows how the Inventory Level, Production Time, Cycle Time, Throughput and Stockout Frequency have trended over the10 month period. There is a small change in time in the Inventory Level and Stockout Frequency. There are also slight variations in Production Time and Cycle Time, and For Throughput is slightly increased which means that there is a slight improvement in production efficiency. Nonetheless, the overall metrics have not seen any major changes among the months, implying that the trends paint a favorable picture, but the additional statistical analysis is required to verify that any noticeable effect of Digital Twin technology on the variables has a material influence.

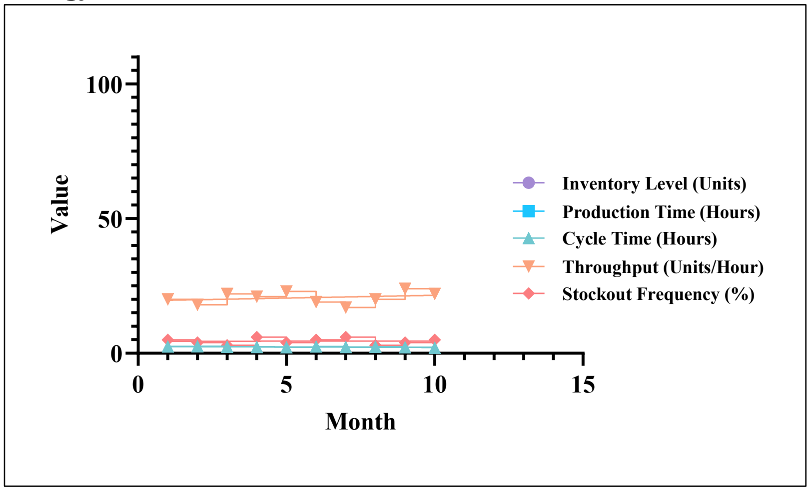

Figure 3. Time Series Analysis of Key Manufacturing Metrics. The figure shows the trends of Inventory Level, Production Time, Cycle Time, Throughput, and Stockout Frequency across a 10-month period, highlighting the changes and fluctuations in each variable over time.

3.6 Correlation Analysis of Digital Supply Chain Capabilities

In Table 3, it can be seen that there exist strong positive relationships between Digital Supply Chain capabilities, on the one hand, and both Information Visibility and Inventory Management Effectiveness, on the other hand. Information Visibility (0.836) and Inventory Management Effectiveness (0.813) are strongly correlated with Digital Agility Supply Chain. Likewise, there is a high positive association between Digital Flexibility Supply Chain and Information Visibility (0.833) with Inventory Management Effectiveness (0.834). Digital Adaptability Supply Chain correlates the most with Information Visibility (0.877) and has a strong positive correlation with Inventory Management Effectiveness (0.867).

These results confirm the notion that the Digital Agility, Digital Flexibility and Digital Adaptability are very strong in enhancing the Information Visibility and Inventory Management Effectiveness. These correlations reveal that the improvement of such digital capabilities in the supply chain can play a vital role in achieving transparency and more effective inventory management practices.

Table 3. Correlations Between Digital Supply Chain Capabilities and Supply Chain Performance.

Relationships	Digital Agility Supply Chain	Digital Flexibility Supply Chain	Digital Adaptability Supply Chain	Information Visibility
Digital Agility Supply Chain	1	0.718	0.741	0.836

Digital Flexibility Supply Chain	0.718	1	0.835	0.833
Digital Adaptability Supply Chain	0.741	0.835	1	0.877
Information Visibility	0.836	0.833	0.877	1
Inventory Management Effectiveness	0.813	0.834	0.867	0.803

Discussion

This study explores how Digital Twin technology can enhance effectiveness in inventory management, reduction of bottlenecks, and manufacturing efficiency in complex manufacturing systems. The results give important details as to how Digital Twin technology helps with inventory visibility, optimizing manufacturing processes.

According to the results, the Digital Twin technology can greatly enhance inventory visibility, which is also consistent with earlier studies [20]. Digital Twin allows inventory to be tracked in real-time, which is precise and current data enabling manufacturers to optimize inventory, minimize stock-outs and prevent overstocking. This confirms the argument by Wan et al. (2018) that Digital Twin enhances the transparency of the chain of supply chains and provides key information regarding the flow of materials and products [21]. Besides, this observation confirms Borandag et al. (2023) and P Choudhury et al., (2023), who posit that better inventory management and improved decision-making are the results of better information visibility provided by Digital Twin system [22], [23].

Digital Twin technology showed a positive effect in terms of the bottleneck reduction, not so strong as it would be assumed. The findings indicate that although Digital Twin enhances the exchange of information and provides simulation of the processes, this technology might not be enough to remove bottlenecks. Digital Agility and Digital Flexibility did not exhibit statistically significant effect on bottleneck reduction, which is contrary to previous research by Arff et al. (2023) and Tahmasebinia et al. (2019), who concluded that Digital Twin has a significant effect on elimination of the process inefficiencies [24], [25]. This variation could be caused by other factors such as the performance of the machine used, the expertise of the operator and external interferences which were not considered in this study. Attaran & Celik (2023) and Zhang et al., (2020) point out that although Digital Twin can assist in detecting possible bottlenecks, real-life factors like machine breakdown or human mistake can push it to its limits [18], [26].

Another potential of Digital Twin technology in enhancing the efficiency of production is also discovered in the study. The positive association that exists between Digital Agility, Digital Flexibility, and production efficiency undermines the claim by Qi et al. (2021) who argue that Digital Twin can enhance better allocation of resources, minimize downtime and maximize throughput [27]. Furthermore, Digital Adaptability proved to be a significant aspect in enhancing the performance of production operations, which is consistent with the findings of J. Li et al. (2022), who emphasized the relevance of flexible and adaptive digital systems in streamlining production processes. The findings indicate that the Digital Twin will enable manufacturers to rapidly respond to shifts in the production requirements and optimize processes on the spot [28], [29].

These results have a number of significant implications to the manufacturing industry. Digital Twin is a viable solution that would enable creating an inventory visibility and production efficiency that will result in a noticeable reduction of costs and enhancement of resource management. Digital Twin integration with manufacturing processes facilitates real-time data, predictive analytics, to allow companies to be proactive in correcting problems including stockouts, overstocking, and delays in production. Additionally, virtual simulation of production situations enables manufacturers to discover the bottlenecks and streamline the operations prior to their effects on the entire system [30], [31], [32].

But the findings indicate that the Digital Agility and Flexibility might not be as effective as it was believed to enhance the efficiency of bottlenecks minimization and inventory handling. This result contradicts the hypotheses of Tahmasebinia et al. (2023), who depicted these areas as critical to enhancing operational performance. Other operational variables like capabilities of the workforce or the reliability of the machine may be more important in these results [25].

A significant constraint is the use of secondary data based on already existing case studies and reports that may not be completely representative of the dynamic and live influence of Digital Twin technology in different manufacturing settings. Also, the applied sample of the manufacturing systems was relatively small, which can restrict the applicability of the results. To confirm these results, future studies should take into consideration primary data gathered on an even more diverse selection of manufacturing systems and industries.

The other weakness of this study is that it failed to look into the application of Digital Twin technology in predictive maintenance as this is one of the main fields where it can have a substantial effect on machine performance and uptime production. The fact that Digital Twin can predict equipment malfunction and recommend maintenance intervals is noted by Falekas & Karlis et al. (2021) and Zhong et al., (2023) to potentially further streamline production efficiency. This area of Digital Twin and its use in predictive maintenance needs to be explored in the future [33], [34].

Future studies ought to look into the applications of Digital Twin technology in predictive maintenance and how it can be used to increase the reliability and uptimes of machines. Drawing insights into the ways of Digital Twin streamlining real-time monitoring and predictive analytics as part of supply chain management will be interesting as well. Also, to confirm these results, it is necessary to study the Digital Twin effect in more industries and manufacturing settings. Additional research also has the potential to investigate how Artificial Intelligence and Machine Learning can be used with Digital Twin to provide autonomous decisions in manufacturing systems. Lastly, the potential of Digital Twin to enhance sustainability and minimize environmental impact on manufacturing processes should be explored in future research.

4. Conclusion

This study highlights the significant impact of Digital Twin technology on inventory visibility, bottleneck reduction, and production efficiency within complex manufacturing systems. The findings demonstrate that Digital Twin enhances the transparency of supply chains, optimizes inventory management, and facilitates more efficient production processes. However, the study also suggests that while Digital Twin plays a crucial role in improving operations, factors such as workforce capabilities and machine reliability should not be overlooked in achieving optimal performance. The research underscores the potential of Digital Twin technology to revolutionize manufacturing practices, providing manufacturers with real-time insights, predictive capabilities, and the ability to simulate processes for better decision-making. Ultimately, this technology holds promise for creating more efficient, agile, and sustainable manufacturing environments.

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