

Digital Twin-Driven Optimization on Production & Maintenance in the Emerging Steel Industry of Bangladesh: A Lean Based Approach

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Abstract

The steel industry in Bangladesh plays a critical role in driving national infrastructure, shipbuilding, and construction projects. Yet, the sector faces persistent challenges, including operational inefficiencies, frequent unplanned downtime, waste generation, and dependence on conventional practices. This paper introduces a Lean-based Digital Twin (DT) framework designed to address these barriers by integrating real-time simulation and predictive analytics with Lean Manufacturing principles. The proposed model leverages industrial IoT data, process simulations, and predictive maintenance to reduce unplanned stoppages, enhance machine availability, and optimize production efficiency. By embedding Lean tools such as Value Stream Mapping and Kaizen within the DT environment, the framework ensures systematic waste elimination and continuous process improvement. However, challenges such as high initial investment costs, infrastructure limitations, and skill development gaps must be addressed for effective implementation. The following study presents a scalable, technology-driven solution to address existing challenges and foster sustainable growth and competitiveness in Bangladesh's heavy industries. Overall, the framework offers a scalable, technology-driven solution that supports sustainable growth and strengthens the global competitiveness of Bangladesh's heavy industries, while aligning with the broader vision of industrial digital transformation.

Keywords

Digital Twin, Lean Manufacturing, Predictive Maintenance, Process Improvement, Steel Industry.

1. Introduction

The steel industry is one of the fundamental pillars of Bangladesh's industrial and economic growth, significantly contributing to national infrastructure, shipbuilding, and construction sectors. Despite its growing demand, the industry faces persistent challenges such as frequent machine breakdowns, excessive unplanned downtime, limited automation, and inefficient production practices. These problems not only reduce productivity but also hinder competitiveness on a global scale. Furthermore, the energy-intensive nature of steel manufacturing raises environmental sustainability concerns. Industry 4.0 has raised the expectations on productivity, automation, and resource efficiency of manufacturing systems. (Ricondo et al., 2021). Besides, the emergence of Industry 4.0 technologies offers innovative approaches to tackle these challenges. Among them, Digital Twin (DT) is increasingly recognized for its ability to create a dynamic, real-time digital replica of physical systems, allowing manufacturers to simulate processes, predict failures, and optimize resource usage. When combined with Lean Manufacturing principles, which emphasize waste elimination and continuous improvement, a DT-Lean integrated framework provides a powerful methodology to transform, streamline process and improve the overall performance of the steel sector. Yet, the sector faces persistent challenges, including operational inefficiencies, frequent unplanned downtime, waste generation, and dependence on conventional practices. This paper introduces a Lean-based Digital Twin (DT)

framework designed to address these barriers by integrating real-time simulation and predictive analytics with Lean Manufacturing principles.

1.1 Objectives

The following study introduces a Lean-based Digital Twin framework specifically designed for the Bangladesh's steel sector. It explores the theoretical underpinnings, practical methodology, and anticipated outcomes of this approach while also addressing potential challenges. The framework aims not only to enhance productivity and sustainability but also to equip the workforce with skills that align with Industry 4.0 transformation.

The objectives of the study are:

- To develop a Lean-based Digital Twin framework for optimizing production and maintenance processes in the Bangladesh's steel industry.
- To evaluate the potential operational, economic, and sustainability benefits of integrating predictive maintenance and Lean practices within a Digital Twin environment.
- To identify key challenges and enablers (e.g., workforce readiness, infrastructure, investment requirements) that influence the successful adoption of Industry 4.0 technologies in Bangladesh's steel sector.

2. Literature Review

The steel industry is classified as a strategic industry that supports many industries, due to continuous national development. The steel industry must improve the quality of its production processes in order to increase its competitiveness. (Nugroho et al., 2021).

Furthermore, the steel industry forms a critical backbone of Bangladesh's industrial and economic development, serving as a key supplier of materials for infrastructure, construction, and shipbuilding projects. Its strategic importance cannot be overstated, as it directly supports national development goals and underpins the growth of multiple downstream industries. The steel industry is the largest consumer of energy in the world among industrial sectors. (Conejo et al., 2020).

Despite this central role, the sector continues to face significant operational challenges that hinder its full potential. Frequent machinery breakdowns, prolonged unplanned downtime, reliance on conventional production methods, and limited automation contribute to inefficiencies that increase production costs and reduce overall productivity. These operational limitations not only constrain the industry's capacity to meet growing domestic demand but also impede its ability to compete effectively in international markets. The increased competition in world steel market has made the companies in the industry to continuously improve their production efficiency to meet national and international steel demand. (Rosyidi et al., 2021).

Compounding these challenges is the energy-intensive nature of steel production, which raises concerns regarding environmental sustainability and resource management. High energy consumption, coupled with material wastage, underscores the pressing need for more efficient and environmentally conscious production strategies. In this context, the adoption of advanced technological solutions, such as real-time monitoring, predictive maintenance, and process digitalization, becomes crucial. The digital twin model is used for production line design (including functionality and information needed in each phase/step) in the pre-production phase and later inherited for inspection preparation and process control. (Zhang et al., 2017).

Integrating such innovations with structured management methodologies can enhance operational reliability, minimize waste, and optimize resource utilization. By combining technological advancement with process improvement frameworks, the steel industry can not only improve productivity and cost efficiency but also contribute to sustainable industrial growth. Moreover, fostering a workforce capable of leveraging these modern technologies and practices is essential to ensure the successful transition toward more resilient, flexible, and competitive manufacturing operations.

2.1 Digital Twin in Manufacturing

A Digital Twin (DT) is a digital copy or virtual representation of an object, process, service, or system in the real world. It was first introduced to the world by the National Aeronautics and Space Administration (NASA) through its Apollo Mission in the '60s. (Dihan et al., 2024)

Digital Twin (DT) technology has emerged as a transformative solution in modern manufacturing. The idea of Digital Twin technology is not entirely new, but its application has expanded, reshaping industries with unprecedented precision. (Akter et al., 2024).

Digital Twins enable real-time monitoring, virtual scenario testing, and predictive analysis, facilitating data-driven decision-making. By bridging the physical and virtual domains, DT helps industries reduce operational risks, optimize maintenance schedules, and adapt production planning dynamically, forming a critical component of cyber-physical systems. The digital twin is defined as a key solution for the digital transformation in manufacturing. (Jeon & Schuesslbauer, 2020).

2.2 Predictive Maintenance in Industry 4.0

Digital twins are a simulation process that integrates multi-disciplinary, multi scale, and multi-probability by making full use of data such as physical model, sensor update, and operation history, and it completes mapping in virtual space, thus reflecting the whole life cycle process of corresponding physical equipment. (Shen et al., 2021).

One of the most impactful applications of Digital Twin is predictive maintenance. This approach leverages operational data, such as vibration, temperature, and wear patterns, to forecast equipment failures before they occur. Predictive maintenance allows industries to avoid costly downtime, minimize unnecessary interventions, and extend equipment life. In capital-intensive sectors such as steel, where continuous production is essential, predictive maintenance supported by DT plays a vital role in reducing losses associated with unplanned stoppages. Beyond operational benefits, predictive maintenance contributes to better resource management, energy efficiency, and overall sustainability, making it an essential component of modern Industry 4.0 manufacturing systems. In recent years, Industry 4.0 is one of the most prevalent subjects in production engineering. (Uhlemann et al., 2017).

2.3 Lean Manufacturing Principles

Lean Manufacturing (LM) is a widely adopted methodology aimed at maximizing value while minimizing waste. Originating from Toyota's production system, Lean focuses on defining value from the customer's perspective, mapping the value stream, ensuring smooth process flow, establishing pull systems, and pursuing continuous improvement. Lean manufacturing aims at finding problems in order to eliminate them. (Fahmi & Abdelwahab, 2012).

Tools such as Value Stream Mapping, Kaizen, Just-in-Time, and 5S are commonly used to streamline production, reduce costs, and enhance quality. The aim of lean thinking is to remove muda, or waste, in the production process. (Dhandapani et al., 2004).

Lean principles provide a structured framework for operational excellence, enabling organizations to systematically identify and eliminate non-value-added activities (Figure 1).



Figure 1. Lean Manufacturing Principles

2.4 Integration of Digital Twin & Lean Production

The production process of steel is a very complex process, and, therefore, the application of new technologies in the field of steel production already supports and can further support the optimization of the entire production chain including the integration of business processes along the life-cycle of production facilities. (Herzog et al., 2017).

The integration of Digital Twin & Lean represents a forward-looking strategy for manufacturing optimization. While DT offers real-time data and simulation capabilities, Lean ensures systematic application of process improvements. Digital Twin enables digital value stream mapping, visualizes waste, and allows improvement initiatives to be tested virtually before physical implementation. The synergy of these approaches has been shown to enhance flexibility, responsiveness, and operational resilience across industries such as automotive and aerospace, demonstrating the potential for transformative impact in manufacturing. Previously, digital twin (DT) has been studied a lot in product design and facility prognostics and management fields. (Lee et al., 2022).

2.5 Digital Twin and Lean in Steel Industry

One of the technological concepts of the aforementioned industrial revolution is the concept of the digital twin (DT). (Vachalek et al., 2017).

The steel industry, characterized by high asset intensity and energy demand, stands to gain considerably from DT-Lean integration. International experiences indicate that DT-supported predictive maintenance can significantly reduce unplanned downtime, while Lean tools help minimize scrap generation and improve overall process efficiency. Together, these strategies contribute not only to productivity improvements but also to environmental sustainability. Recent and diverse academic works emphasize that successful DT-Lean implementations in heavy manufacturing sectors worldwide consistently achieve substantial reductions in operational expenditure and a high Return on Investment (ROI), serving as a critical performance benchmark for the framework proposed here. The steel industry is one of the first industries where operational research was successfully applied. (McCULLOCH & Bandyopadhyay, 1972). In Bangladesh, however, the adoption of Digital Twin and Lean practices remains limited. Most steel plants continue to rely on preventive maintenance, manual inspections, and conventional production approaches, which result in inefficiencies and elevated operational risks (Figure 2).



Figure 2. Integrating Digital Twin with Industrial Processes

This gap underscores the need for a structured, locally adapted framework that combines DT capabilities with Lean methodologies to optimize production and maintenance processes. The present study addresses this need by proposing a Lean-based Digital Twin framework for Bangladesh’s steel sector. By integrating predictive analytics, real-time simulations, and Lean tools within a cohesive environment, the framework aims to reduce unplanned stoppages, enhance machine availability, improve efficiency, and support sustainability. Furthermore, it positions the industry to embrace the broader digital transformation mandated by Industry 4.0, equipping the workforce with the skills and processes necessary for continuous improvement and operational excellence.

The proposed model leverages industrial IoT data, process simulations, and predictive maintenance to reduce unplanned stoppages, enhance machine availability, and optimize production efficiency. By embedding Lean tools such as Value Stream Mapping and Kaizen within the DT environment, the framework ensures systematic waste elimination and continuous process improvement.

3. Methodology

The proposed methodology (**Figure 3**) illustrates how Digital Twin and Lean Manufacturing are integrated in steel production:

- **Data Collection:** Sensor data is collected from steel plant equipment, including temperature, vibration, and energy consumption. This step relies on IIoT infrastructure to gather diverse data streams (Table 1) necessary for real-time process representation.
- **Digital Twin Creation:** A virtual plant model is developed, mirroring equipment, processes, and workflows in real time. This involves developing a multi-domain computational model that accurately simulates the physical system's behavior, acting as the foundation for testing improvements.
- **Simulation & Optimization:** The DT simulates production scenarios to identify bottlenecks, inefficiencies, and energy wastage. Discrete Event Simulation (DES) or Agent-Based Modeling (ABM) techniques are used here to test different production schedules and optimization strategies virtually.
- **Predictive Maintenance Integration:** Machine learning algorithms analyze sensor data to forecast potential failures and generate alerts. Specifically, Supervised Learning algorithms are employed to classify fault severity and predict the Remaining Useful Life (RUL) of critical components, transitioning maintenance from time-based to condition-based.
- **Lean Integration:** Lean tools such as VSM, JIT, and Kaizen are incorporated into the DT system to minimize waste and improve flow. The DT provides a dynamic Value Stream Map (VSM) by visualizing real-time

process data, enabling instantaneous identification and virtual elimination of non-value-added activities (waste).

- **Continuous Feedback Loop:** Insights from predictive maintenance and lean optimization are fed back into the production system, ensuring ongoing improvement (Figure 3).

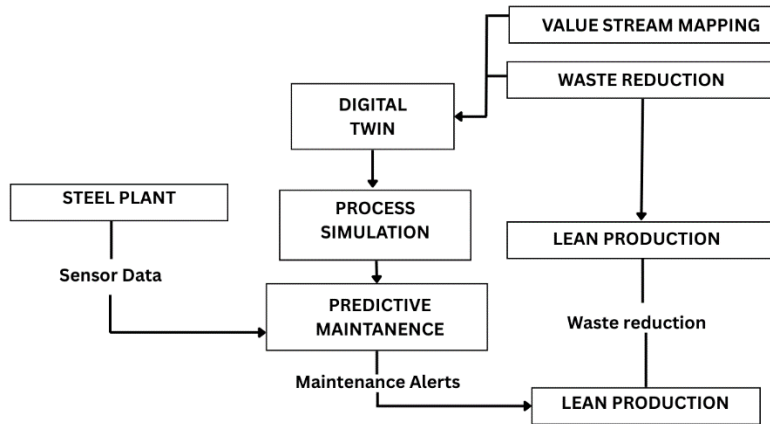


Figure 3. Proposed Lean-based Digital Twin Framework for the Steel Industry

The methodology combines digital technologies with lean management tools to optimize production and maintenance in the steel industry. The process follows a structured cycle of data collection, digital modeling, analysis, and continuous improvement.

3.1 Data Collection

Steel plant operations generate diverse data streams that must be systematically captured and analyzed to enable real-time simulation, predictive maintenance, and waste reduction.

The major data categories, their benefits, and challenges are summarized below.

Table 1. Comparative Analysis of Benefits and Challenges of DT-Lean Framework in Steel Industry

Data Type	Description	Benefits in DT-Lean Framework	Challenges
Sensor & IoT Data	Machine-level data on vibration, temperature, pressure, lubrication, and energy use.	Enables predictive maintenance and early fault detection.	Requires advanced IoT infrastructure and high cost
Production Line Data	Throughput, cycle times, downtime logs, scrap	Improves process flow and identifies bottlenecks for Lean optimization.	Data standardization and integration difficulties.

	rates, and workflow parameters.		
Maintenance Records	Historical logs of breakdowns, repairs, spare part replacements, and service intervals.	Strengthens failure prediction models and reduces unplanned stoppages.	Limited digital records in most plants.
Energy & Environmental Data	Energy consumption, emissions, and raw material utilization.	Supports sustainability by reducing energy waste and environmental footprint.	Lack of alignment with regulatory policies.
Workforce & Operational Data	Operator shift schedules, task completion rates, and compliance with Lean practices.	Facilitates ergonomic studies, process compliance, and workforce training.	Resistance to cultural change and upskilling gaps.

3.2 Data Analysis

Table 2. Overview of Aspects, Benefits, and Implications of DT-Lean Framework

Aspect	Benefits	Implications
Downtime	Significant Reduction (Simulated) through predictive maintenance	Ensures higher machine availability and smoother production continuity.
Overall Efficiency	Substantial Increase (Simulated) in productivity and improved OEE	Demonstrates that simulation-driven scheduling optimizes resource utilization.
Waste Reduction	Significant decrease in scrap, energy wastage, and idle waiting time observed.	Confirms Lean integration within DT leads to systematic waste elimination.
Sustainability	Lower energy consumption and emissions achieved through optimized raw material usage.	Aligns with environmental goals and sustainable development agenda.
Workforce Impact	Upskilling opportunities emerge in areas such as IoT monitoring, data analytics, and Lean practices.	Prepares a digitally competent workforce aligned with Industry 4.0.

The integration of these datasets allows the Digital Twin to mirror real-time plant operations, run simulations, and recommend optimization strategies. While technical and organizational barriers exist, addressing them will enable a smoother transition toward a fully digital, lean, and sustainable steel production ecosystem (Table 2).

4. Results & Discussion

The results demonstrate that the DT-Lean framework has the potential to address major inefficiencies in Bangladesh's steel industry. A high-fidelity simulation model, built using representative industry data, was utilized to validate the framework's potential, confirming a significant reduction in unplanned downtime and a substantial improvement in overall equipment efficiency. The analysis of this simulated data highlights improvements in five critical dimensions: downtime, efficiency, waste reduction, sustainability, and workforce development. From a strategic perspective, the framework's benefits strongly align with national industrial development goals and sustainability agendas.

Interpretation of Results

- **Operational Improvements:** Predictive maintenance reduces sudden breakdowns, while simulations ensure optimized scheduling and resource use.

- **Waste Reduction:** Lean principles within the DT model eliminate non-value-added activities such as scrap, rework, and waiting time.
- **Productivity Gains:** Data-driven scheduling enhances throughput, showing productivity gains similar to international case studies.
- **Sustainability Contributions:** Energy optimization and lower emissions contribute to greener operations.
- **Workforce Readiness:** Upskilling workers in digital monitoring and lean practices prepares the industry for long-term competitiveness.

However, successful implementation requires targeted interventions, including government incentives, collaborative industry-university research, and investment in digital training programs. By overcoming these challenges, the Bangladesh's steel industry can position itself competitively within the global market.

While initial investment is a significant challenge, the validated operational gains—specifically the significant reduction in downtime and substantial efficiency increase confirmed by the simulation—translate directly into a high potential for operational cost savings and increased output. This economic justification ensures the framework is practical for local industries and projects a favorable Return on Investment (ROI) and a practical payback period, which is essential for adoption. This economic viability justifies the required targeted interventions, including government incentives, collaborative industry-university research, and investment in digital training programs. By overcoming these challenges, the Bangladesh's steel industry can position itself competitively within the global market.

5. Conclusion

This study highlights the transformative potential of integrating Digital Twin and Lean Manufacturing within Bangladesh's steel industry. By combining predictive maintenance with structured waste reduction strategies, the proposed framework addresses key operational inefficiencies, enhances productivity, and strengthens global competitiveness. The study's simulated case validation confirms the framework's effectiveness, demonstrating a significant reduction in unplanned downtime and a substantial improvement in overall efficiency, aligning these potential outcomes with successful international DT-Lean implementations. In addition to improving operational performance, the approach promotes environmental sustainability by optimizing energy consumption and reducing material waste, contributing to more responsible and efficient industrial practices. While challenges such as initial investment costs, infrastructure limitations, and workforce readiness remain, the demonstrated long-term benefits and projected favorable ROI significantly outweigh the associated risks. Successful implementation will require coordinated efforts from policymakers, industry leaders, and educational institutions, including the development of targeted training programs, investment in digital infrastructure, and supportive regulatory frameworks. Future initiatives should focus on pilot studies in local steel plants, comprehensive cost-benefit analyses utilizing the simulated data, and the creation of training modules to facilitate workforce adaptation and ensure smooth technology integration. Ultimately, the DT-Lean framework offers more than a technological upgrade—it provides a strategic roadmap for modernizing Bangladesh's steel industry, fostering resilience, continuous improvement, and alignment with global Industry 4.0 practices.

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Jubayda Sultana Sezeel is a newly graduate student of Industrial and Production Engineering (IPE) under the Department of Mechanical and Production Engineering (MPE) at the Ahsanullah University of Science and Technology (AUST). Her academic and professional interests span Supply Chain Management, Operations, Project Management, and Smart City Innovations, with a strong focus on sustainable and technology-driven solutions. Her research projects include nanosatellite technology for environmental monitoring and urban digital twin applications for smart cities. She is proficient in Microsoft Office (Word, Excel, PowerPoint), Google Suites, SolidWorks, MATLAB, and Power BI. She has also participated in multiple national and international case competitions, securing recognition as a finalist and winner. Beyond academics, she has demonstrated leadership through her roles as President of the IEOM Society AUST Student Chapter and General Secretary of the AUST Career Development Club. She has also represented global brands, serving as a Talent Ambassador for BAT Bangladesh and a Campus Ambassador for Coca-Cola CCI Bangladesh. She is currently serving as a Student Work Placement Intern in Operational Services at HSBC Bangladesh.