



A cyber-physical production control paradigm for site waste mitigation: Synchronizing digital twin technology and lean construction principles through nanotechnology

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The construction industry continues to suffer from substantial productivity losses due to inefficient operations, wasteful use of materials, broken equipment and a lack of cohesive production management. Lean Construction is a good way to think about getting rid of waste and it remains difficult to implement because information is often delayed or not complete. Similarly, Digital Twin technology creates virtual, moving versions of construction sites, but it does not inherently offer a predictable way to reduce waste. This paper introduces a Digital Twin-Lean Management (Nano-DTLM) framework that uses nanotechnology to optimize Cyber-physical systems, Internet of Things (IoT), Digital Twin technology, Lean Construction and smart nanosensor technologies for real-time production enhancement. The proposed framework is based on edge-computing analytics, graphene-based strain sensors, nano-enabled RFID tags, nanoscale environmental sensors, and enhanced sensing for more accurate decision making, structure monitoring and foresight. To test the framework using 4D BIM, UWB positioning, RFID, telematics, and nano-enabled sensing technologies, a controlled field experiment is conducted in a 15-story commercial building project in Dubai, UAE. When tested, the experimental implementation reduced crew idle time by 29.7%, equipment downtime by 30.9%, distance that materials had to be transported by 21.9% and increased worker productivity by 21.4%. Statistics demonstrated significant improvements ($p < 0.05$; Cohen's $d = 0.82$). Nanotechnology significantly improved the sensing accuracy, reliability of data, ability to predict maintenance needs and responsiveness of cyber-physical systems. The proposed Nano-DTLM framework provides a

Keywords: Nanotechnology; Nanosensors; Digital Twin; Lean Construction.

1. INTRODUCTION

The construction industry is still a major driver of economic growth across the globe, but it still has many problems with productivity, operational efficiency and the best use of resources. A large portion of the costs of building something are things that do not add value, these are usually called waste (Muda). These things can be as high as 30% of the total project cost [1]. Such inefficiencies affect project timelines, costs, quality and long-term viability. The construction industry is increasingly adopting Lean Construction to solve these problems. This is a derivative of the Toyota Production System (TPS) that focuses on continuously delivering value while reducing operational waste in the construction process [4]. Seven types of waste are defined in Lean Construction as mistakes, overproduction, waiting, untapped talent, unnecessary transportation, excess inventory and unnecessary motion. This provides a systematic approach to improve productivity and project performance [5].

Lean Construction is strong in theory but hard to use in real life, because of the way projects are usually run. Many people use Lean tools like Last Planner System (LPS) but they use manual data collection, reporting and weekly look ahead planning which makes it difficult for them to adapt to rapidly changing site conditions [6]. This means project managers do not often see operational problems until it is too late to correct them. Delays, broken equipment, lack of materials or problems with logistics have already pushed project schedules and costs back. These problems underline the importance of intelligent production management systems, which can monitor construction work continuously and support decision making based on real-time operational data.

The rapid development of Construction 4.0 has led to the increased use of advanced digital technologies such as cyber-physical systems, the Internet of Things (IoT), Building Information Modeling (BIM), artificial intelligence (AI), cloud computing and Digital Twin (DT) technology [7]. A digital twin is a living, changing replica of a real thing or a building process, always synchronized with its real-life counterpart thanks to two-way data sharing. This allows us to watch, simulate, predict and make better decisions in real time [3]. Digital Twin technology has been very useful to track the health of the buildings, to manage the facilities, to see how things are going. But during the active construction phase it is mostly used for project tracking, for visualizing the shapes, but not for smart production control [8]. Large scale IoT deployments generate large amount of operational data that are not always exploited due to the lack of an integrated management framework capable of converting real-time data into Lean production strategies for use.

The development of carbon nanotube (CNT) composites, graphene-based strain sensors, nano-enabled RFID devices, nanoscale environmental sensors, and smart sensing materials has made intelligent building systems more intelligent with the advancement of nanotechnology. Nanosensors are more sensitive, require less power, respond faster, and are more durable in harsh construction environments than other sensing technologies. These features allow monitoring structural behavior, health of equipment, materials movement, and environmental conditions. They also enhance reliability of cyber-physical communication and predictive analytics. Thus, the combination of

nanotechnology and Digital Twin technology makes it possible to develop extremely intelligent construction management systems that can improve productivity, reduce wastage, improve worker safety, and support sustainable construction practices.

There have been a good number of studies researching on Lean Construction, Digital Twin, and IoT-enabled construction monitoring separately. But not many have developed an integrated cyber-physical framework that can leverage the use of these technologies with smart nanosensor systems to control production in real-time and predict the amount of waste generated. Digital Twin driven Lean production management is not much used in the field of nanotechnology so far as most of the research has been done on project visualization, progress monitoring or single sensor applications. This research bridges the gap by establishing an integrated framework encompassing cyber-physical systems, Digital Twin, Lean Construction, IoT sensing and nanotechnology. The framework establishes an intelligent production control platform with self-monitoring, future anticipation and continual improvement capabilities.

The most significant new contribution of this research is a new framework for digital twin-lean management called Nano-DTLM that creates a fully automated cyber-physical production control paradigm by integrating smart nanosensor technologies and digital twin and lean construction principles. In contrast to most Digital Twin systems for progress tracking and visualization, the proposed framework uses a closed-loop cyber-physical architecture to convert multiple IoT and nanosensor data into real-time, predictive Lean decision support. Graphene based strain sensors, carbon nanotube vibration sensors, nano-enabled RFID devices, and nanoscale environmental monitoring improve predictive maintenance, track materials and increase operational intelligence with sensing that is more accurate. The combination of various fields creates a smart construction management system that is state-of-the-art and can reduce waste in operations, increase productivity, make the best use of resources, and support sustainable Construction 4.0 practices.

The study aims to develop an algorithmic framework that can connect different types of IoT and nanosensor data with the major types of Lean construction waste. The study also aims to test and validate the proposed Nano-DTLM framework through the integration of Digital Twin technology, 4D BIM, multi-sensor data fusion and smart nanosensors on a real high-rise construction project. The study measures the effectiveness of the proposed framework on waste reduction, productivity improvement and predictive production control in comparison to traditional construction project management approaches.

Nanotechnology is one of the most important technologies for smart building and managing infrastructure. Recent inventions of graphene-based strain sensors, carbon nanotube (CNT) composites, nanoscale RFID devices, nano-enabled concrete sensors, and self-powered nanomaterial sensing systems have made cyber-physical construction environments far more accurate, durable, and able to monitor in real-time. Nanosensors are more resistant to harsh construction environments, more sensitive, consume less power and respond faster compared to traditional sensing technologies. Combining nanotechnology and Digital Twin technology allows for the collection of very precise data for the monitoring of structures' health, condition of equipment, monitoring of the environment and predictive maintenance. Combining nanotechnology with Lean Construction principles yields a smart platform that can reduce operational waste and improve safety, productivity and sustainability during the entire construction project lifecycle.

2.1. Lean construction and latency challenge

Lean Construction is a major departure from the traditional project management approach which relies on the concept of a series of discrete tasks to be performed in a particular order. It is based on a production-oriented philosophy that emphasizes the continuous flow of work, value generation and the elimination of waste during the whole construction process [1]. Lean Construction is about making processes more reliable and removing non-value-added activities to improve project performance, resource use and productivity. There are many ways to implement Lean, but one of the most popular ways to plan and control production is the Last Planner System (LPS). LPS utilizes look-ahead schedules and the Percent Plan Complete (PPC) metric as two collaborative planning tools to make workflow more reliable and reduce the impact of upstream variability on project execution [6].

LPS is widely used but has little practical use in real life, as it is based on manual data collection, paper-based documentation and regular planning cycles. Standard LPS systems often do not have the time and space resolution to track how things are changing rapidly on large, complex construction sites, especially in crowded cities [9]. Consequently, project managers and site supervisors are slow to recognize operational problems like lack of materials, broken equipment, too many workers, and logistics problems. Delays in information make it difficult to correct in a timely manner, resulting in minor operational problems that cascade through the production process and adversely affect schedule reliability, productivity and overall project performance.

The problems listed above show the importance of the need for real-time automated production control systems to monitor construction work, detect problems and assist in immediate decision-making. A good idea is to combine cyber-physical systems, Internet of Things (IoT) technologies and Digital Twin platforms to collect high-frequency operational data, which enables us to control lean production, improve workflow continuously and predictably reduce waste in modern Construction 4.0 environments.

2.2. Digital twins as cyber-physical infrastructure

The digital twin technology can offer more than the traditional Building Information Modeling (BIM) by establishing a continuous flow of information between the real-world construction assets and their virtual counterparts [7,10]. Unlike static 3D BIM models that mainly provide geometric and semantic data, Digital Twins are dynamic, integrating real-time operational data with virtual simulation models, enabling smart decision-making, continuous monitoring and predictive analysis throughout the entire construction lifecycle. This characteristic turns Digital Twins into the key cyber-physical infrastructure for smart construction management within the Construction 4.0 paradigm. From the point of view of the system architecture, a construction Digital Twin consists of three layers which are interconnected. The physical asset layer is the construction workers, tools, materials and infrastructure on site that continuously generate operational data. The virtual analytical layer consists of simulation engines, artificial intelligence (AI), predictive analytics, 4D and 5D BIM models and more. It receives incoming data and verifies how construction is progressing and streamlines production workflows. These two layers are connected by a middleware communication layer, which comprises various Internet of Things (IoT) communication protocols, edge-computing platforms, cloud databases and data integration services that synchronize the physical and virtual environments in real time [8]. Recent advances in Internet of Things (IoT) technologies, such as Ultra-Wideband (UWB) positioning systems, Radio Frequency Identification (RFID), computer

vision, laser scanning, and wireless sensor networks, have greatly facilitated Digital Twins in acquiring high-frequency operational data from construction sites [11]. But these technologies are still limited to a handful of specific applications in the real world. For now, most applications are single-purpose, such as monitoring worker safety, tracking equipment, or automatic identification of assets. That is why Digital Twin technology is not fully developed for integrated project-level production optimization, data-based decision-making and full Lean Construction management yet [12]. These issues require integrated cyber-physical frameworks that can combine different sensing technologies, smart data analytics, and production management strategies into one system to enable real-time decision making for humans.

2.3. Knowledge gap: the lean-digital twin convergence

Lean construction and digital twin technologies have been attracting a lot of attention, but the synergies between the two are still not clear in a single production management framework. Prior research on Lean Construction has focused primarily on the application of human-centered management techniques and the optimization of sociotechnical processes to improve organizational performance, teamwork, workflow reliability, and the creation of value over time [4]. In contrast, the majority of the research on Digital Twin technology has been limited to technical issues such as simulation algorithms, data interoperability, semantic information modeling and cyber-physical communication architecture [13]. Therefore, the two research areas have evolved largely independently of each other, with little interaction between advanced digital technologies and production management approaches. Several studies have found that Lean Construction and Digital Twin technology might be a good match. However, most current implementations are limited to progress tracking, data visualization or using digital twins for one-off decision-support tasks. There are few studies that have developed an integrated cyber-physical framework that can convert different types of real-time sensor data to automated Lean production decisions that can reduce waste and improve workflow all the time. Moreover, the integration of smart nanosensor technologies into Digital Twin-driven Lean Construction has not been much focused on, despite the potential of much more accurate sensing, much more accurate maintenance planning, and much more useful real-time operational intelligence.

As a result, a significant research gap remains in the development of a framework that combines Nanotechnology, IoT-based cyber-physical systems, Lean Construction principles, and Digital Twin technology into a unified intelligent production management platform. In this study, we propose a Nanotechnology-Enhanced Digital Twin-Lean Management (Nano-DTLM) framework to bridge this gap, which enables computers to process various real-time cyber-physical data and provide automated, predictive and actionable Lean decision support. The proposed framework integrates advanced sensing technologies, Digital Twin analytics, and Lean production principles within a closed-loop cyber-physical architecture to enable intelligent waste identification, proactive production optimization and continuous improvement of construction project performance to advance sustainable Construction 4.0 practices.

3. METHODOLOGY

The research adopted a mixed-methods research design for the development and validation of Nanotechnology-Enhanced Digital Twin-Lean Management (Nano-DTLM) framework. The research design combines qualitative framework development and quantitative empirical validation. The qualitative phase is aimed at generating ideas of the cyber-physical production control architecture

based on the combination of Lean Construction, Digital Twin technology, sensing based on Internet of Things (IoT) and smart nanosensor technologies. The proposed framework is tested and proven to work in a real-life construction setting in the quantitative phase. The framework's operational performance is judged by field measurements and statistical analysis. This two-step process allowed the development of the proposed production management framework and its rigorous testing to assess its effectiveness in improving construction productivity, operational waste reduction and real-time decision making.

3.1.Phase A: development of conceptual and algorithmic DTLM models

The first part of the study concerned the design of the Nanotechnology-Enhanced Digital Twin-Lean Management (Nano-DTLM) framework and the design of its algorithms. In this step, Lean Construction principles, Construction 4.0 technologies, Digital Twin architecture, Internet of Things (IoT)-based sensing and smart nanosensor technologies are thoughtfully put together to develop a single cyber-physical production management system. A detailed study of Lean production methods and digital construction technologies has been performed to identify functional relationships between operational data in real time, production control and waste reduction. The study provided the basis for a computer framework that translates different types of cyber-physical data into intelligent, automated actions for production management. The proposed algorithm builds a systematic approach for the collection of real-time data from IoT devices and nanosensors, synchronization of this data in the Digital Twin platform, continuous data analysis and prediction, and automatic generation of Lean decision-support strategies for resource allocation, logistics improvement, maintenance planning and operational waste reduction. The set of algorithms forms the intelligence of the proposed Nano-DTLM system, which enables continuous monitoring of the building process, real-time decision making and proactive control of production.

3.1.1. Core of the DTLM framework

The proposed Digital Twin-Lean Management (DTLM) framework is a fully automated, multi-layered cyber-physical production control system, continuously translating various real-time telemetry data into smart Lean production decisions. A closed-loop decision-making process is developed for identification, assessment and mitigation of the major types of construction waste. It utilizes Digital Twin technology, Internet of Things (IoT) sensing, Building Information Modeling (BIM), and advanced data analytics. The system enables to keep information from the real construction site and its digital twin in sync at all times, allowing proactive production control, predictive analytics and real-time operational optimization.

The DTLM framework integrates real-time tower crane telemetry with high-frequency spatial data from Ultra-Wideband (UWB) worker positioning systems to decrease waiting waste, such as idle equipment and personnel. When the idle time reaches specific thresholds, the Digital Twin automatically identifies the bottlenecks in production, like having an excess of materials in the queue or resource conflicts, and gives recommendations to resolve the issue immediately, such as reallocating crews, scheduling equipment and optimizing work flows. These suggestions go out to mobile supervisors to get production back to normal and minimize downtime.

Transportation waste is tracked through the use of Global Positioning System (GPS) devices and Radio Frequency Identification (RFID) technologies. These technologies help to track the movement of construction materials and equipment throughout the site in real time. The DTLM framework analyses transport routes, detects deviations from optimal logistic paths, detects cases of double

handling of materials and detects congested points on construction sites. Based on these analyses, the Digital Twin recommends the best storage locations and transport routes to make logistics more efficient and reduce the need for relocation.

The framework integrates automated material tracking using RFID with the 4D BIM schedule of the project to ensure actual inventory levels are always compared against what is planned for the construction for inventory management [10]. When abnormal inventory buildup or lack of materials is detected, the system automatically makes changes to the supply chain by suggesting purchases or placing temporary limits on shipping. This prevents inventory from being overstocked and reduces waste of materials.

Dense spatial heat maps are generated from continuous UWB trajectory data of construction workers to reduce motion waste. These heat maps show where workers are over-rotating, where the workspace is congested and where workflow patterns are not working well. The DTLM framework is based on the identified inefficiencies in space and proposes the optimized placement of materials, layout of workstations and routing of the workforce to reduce unnecessary movement and improve the productivity of the worker.

The framework also addresses wasteful overproduction by combining drone-based photogrammetry with the Digital Twin environment to constantly monitor the construction progress against the planned 4D BIM schedule. If the construction process does not adhere to the approved production sequence, the system produces “stop-work” notifications and recommendations on how to modify the schedule to avoid starting work too early or out of sequence.

The use of Terrestrial Laser Scanning (TLS) together with computer vision systems based on artificial intelligence (AI) reduces defects and the waste generated by them. These systems constantly compare the conditions of the construction site with the design specifications and geometric tolerances [10]. If there are differences, it automatically creates digital inspection reports, repair tickets and spatial alerts in the Digital Twin environment, enabling issues to be resolved in a timely manner before they escalate to later construction phases.

Finally, the framework prevents the loss of unused talent by maintaining a dynamic digital skills database with information on job duties, certifications and the skills required by the workforce. This data is exploited by the DTLM framework to allocate the people to the tasks wisely considering their technical knowledge and the needs of the operation. This results in a better utilization of the work force, higher productivity and improved functioning of Lean production management.

The proposed DTLM framework establishes a cyber-physical production control architecture that transforms different types of sensing data into smart, predictive and automated Lean decision support in real-time. The framework controls all the main types of construction waste at the same time. This enables real-time optimization of production, better utilization of resources, better construction quality and higher operational efficiency throughout the lifecycle of the project.

3.1.2. Nanotechnology-enabled sensing infrastructure

To further improve the sensing and prediction capability of the proposed Digital Twin-Lean Management (DTLM) framework, a nanotechnology-enabled sensing infrastructure is embedded into the cyber-physical system. Graphene-based strain sensors are placed in important structural parts to monitor the health of the structure all the time. Carbon nanotube (CNT)-based vibration sensors are

placed on construction equipment to allow for planned maintenance. Building materials are tagged with nano-enabled RFID tags to simplify inventory and logistics tracking, and nanoscale environmental sensors constantly monitored temperature, humidity, airborne particulate matter and dangerous gases. These smart nanosensors produced high-resolution data in real time and transmitted it using IoT gateways and edge computing modules. The data is introduced in synchronization with the Digital Twin platform to help smart analytics and Lean decision making. The overall cyber-physical architecture of the nanotechnology-enhanced Digital Twin is shown in Figure 1, which illustrates how smart nanosensors, edge computing, IoT communication, Digital Twin technology, AI, and Lean Construction principles can all be integrated into a closed-loop production management framework. Table 1 presents the smart nanotechnology parts of the proposed Nano-DTLM framework, their uses, and their operational benefits.

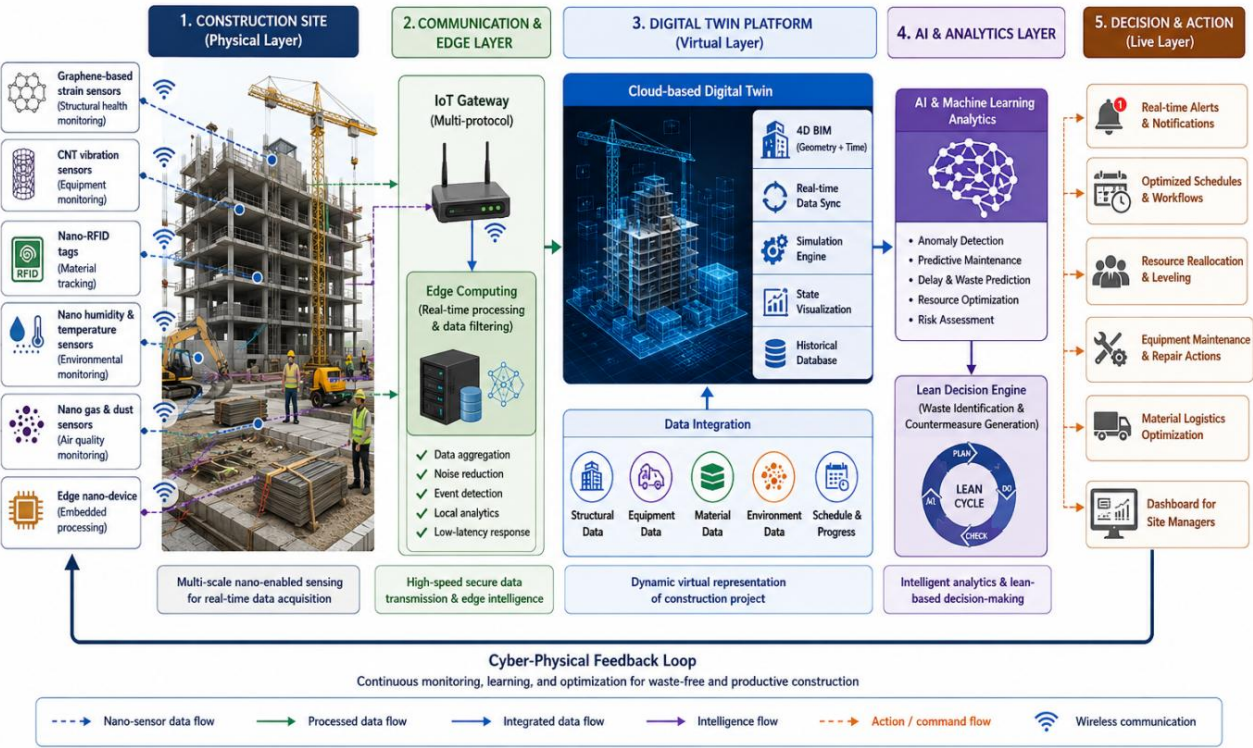


Figure 1 Nanotechnology-enhanced Digital Twin cyber-physical architecture for intelligent construction management.

Table 1 Smart nanotechnology components integrated into the DTLM framework.

Nanotechnology	Application	Benefit
Graphene strain sensors	Structural monitoring	High sensitivity
CNT vibration sensors	Equipment monitoring	Predictive maintenance
Nano-RFID tags	Material tracking	Improved logistics
Nano humidity sensors	Environmental monitoring	Real-time sensing
Nano gas sensors	Air quality monitoring	Worker safety
Nano edge devices	Data acquisition	Low power consumption

3.2. Phase B: field deployment pilot

In the second part of this study, the proposed Nanotechnology-Enhanced Digital Twin-Lean Management (Nano-DTLM) framework is implemented in the field at large-scale and validated in the structural construction phase of a 15-story commercial building in Dubai, United Arab Emirates (UAE). The aim of this phase is to test the effectiveness of the proposed cyber-physical production control system in real construction environments and not only in simulations. The project is divided into two operational phases to allow for direct comparison of performance. Floors 1-4 are used as the control group by the conventional method of managing construction projects. The proposed Nano-DTLM framework is fully implemented on Floors 5-10 and observed for a period of four months. Such an experimental design would provide a good idea of how the proposed framework would affect the logistics, operational efficiency and the quality of the construction. The cyber-physical infrastructure of the proposed framework is composed of three operational layers working in conjunction: IoT sensing layer, Digital Twin computing layer, and data analytics layer.

The IoT sensing layer consists of 45 active Ultra-Wideband (UWB) anchors and wearable tags, which allow real-time location of workers and construction equipment with a precision of approximately 10 cm. Some 1,200 passive Radio Frequency Identification (RFID) tags are also affixed to precast concrete members, reinforcing steel bars and building materials to facilitate automated inventory management and material tracking. Three smart tower cranes equipped with integrated telematics monitored constantly the working conditions of the equipment, the number of lifts, the rate of utilization and the time when it is not in use. Some building parts and tools are integrated with the following sensors in order to enhance cyber-physical monitoring: graphene-based strain sensors, carbon nanotube (CNT)-based vibration sensors, and nano-enabled environmental sensors. These sensors can accurately report structural response, condition of the tools, temperature, humidity, and environmental factors.

The Digital Twin computational layer is built using the Autodesk Revit 4D BIM model, synchronized with the Siemens Teamcenter® Digital Twin platform through data exchange back and forth [8]. This virtual environment tracked construction progress, worker distribution, equipment use, material movement and structural conditions in real time. This allowed the continuous visualization, simulation and prediction of how construction operations would proceed.

The data analytics layer consisted of Python-based algorithms that are specifically designed to process the different types of data streams received from the IoT devices and smart nanosensors. The analytical framework delivered real-time analysis of space and time, enabling anomaly detection, predictive maintenance evaluation, logistics optimization and automatic Lean decisions. The machine-assisted analytics constantly identified operational inefficiencies, forecasted potential workflow disruptions, and provided recommendations to solve issues with staffing, equipment scheduling, material logistics, and waste reduction. The decisions taken are then automatically synchronized with the Digital Twin platform and sent to site supervisors to create a closed-loop cyber-physical production management system able to support smart, predictive and data-driven construction operations.

The overall working of the proposed Nano-DTLM framework is shown in Figure 2. The unified cyber-physical production management system is composed of smart nanosensors, IoT communication, Edge computing, Digital Twin technology, artificial intelligence and Lean decision support. Edge-computing gateways process sensing data from the construction site in real-time,

synchronize it with the Digital Twin platform and analyze it using AI-driven algorithms to develop predictive Lean countermeasures for reducing waste and increasing productivity.

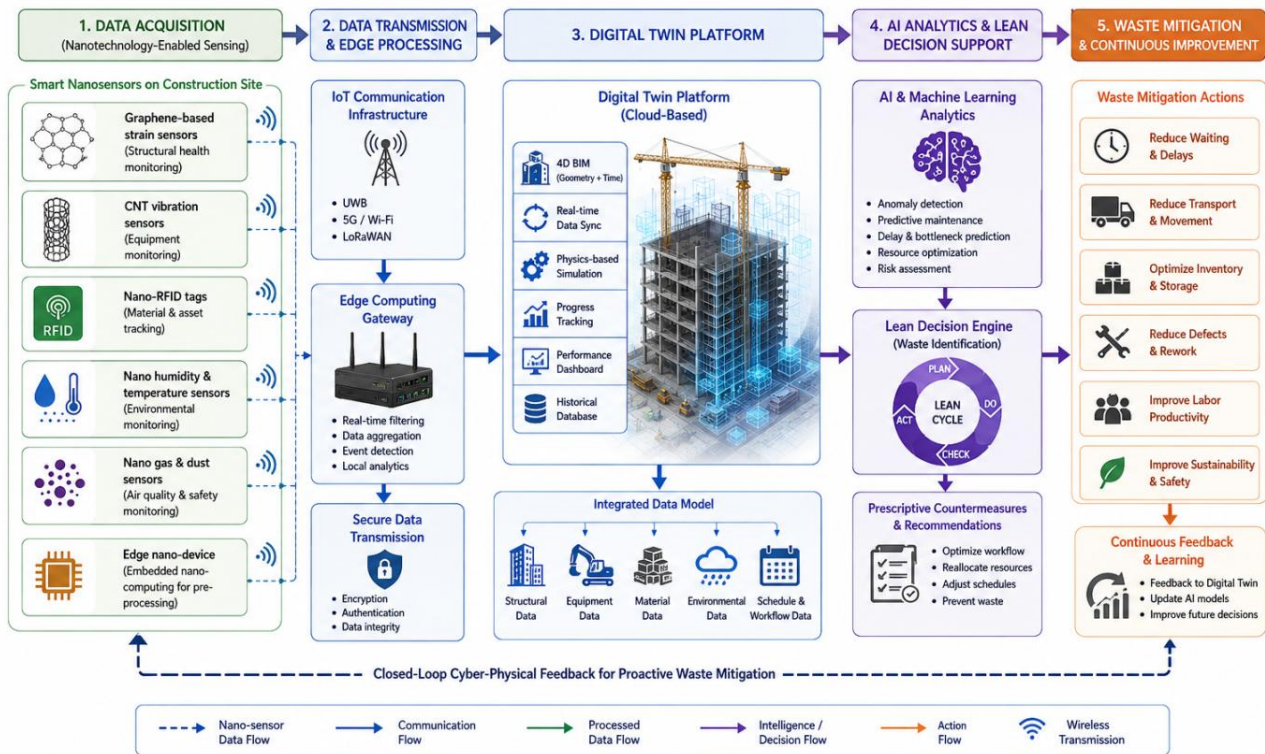


Figure 2 Integration of smart nanosensors within the digital twin-lean management (Nano-DTLM) framework.

4. RESULTS AND ANALYSIS

4.1. Field implementation measures

This section presents the results of the application of the proposed Digital Twin-Lean Management (DTLM) framework in a real case. To evaluate the effectiveness of the DTLM system on the construction site, the key indicators of the operation are compared before and after the introduction of this system. The study explores the shift from the traditional approach to management of construction projects to the cyber-physical DTLM paradigm and studies its effects on the utilization of workers, equipment performance, flow of materials, productivity, quality of work, and efficiency of operations. The results indicate that the combination of Digital Twin technology, IoT-based sensing, and Lean Construction principles enables real-time monitoring, predictive analytics, and data-driven decision-making that can reduce operational waste and improve project performance.

4.1.1. Field performance data synthesis

The four-month field implementation demonstrated that the proposed Digital Twin-Lean Management (DTLM) framework resulted in significant and consistent improvements in all performance indicators relative to the conventional approach to managing construction projects.

Real-time cyber-physical monitoring, Digital Twin synchronization and Lean decision support optimized continuously construction workflows to minimize operational waste and maximize project efficiency. The most evident improvement is the utilization of the workforce. The implementation of the DTLM framework resulted in a 29.7% decrease in crew idle time, from 15.8% in the baseline construction management approach to 11.1% with real-time tracking. Predictive operational management and constant monitoring of construction equipment also significantly increased the use of equipment, reducing heavy equipment downtime from 12.3% to 8.5%, which translates to a 30.9% increase in operational efficiency. The results indicate that the DTLM framework can be utilized to improve resource coordination, reduce unnecessary delays, and optimize overall production efficiency through real time monitoring and data driven decision making. The proposed Digital Twin-Lean Management (DTLM) framework is compared with the traditional way of managing construction projects in Figure 3. The numbers represent the extent of performance improvement. The graph illustrates percentage gains in several key Lean performance indicators following the implementation of Digital Twin technology, cyber-physical systems, IoT-based monitoring and real-time production control. It is observed that the structural defects, rework costs, heavy equipment downtime, crew idle time and material transportation are significantly decreased and the labor productivity is significantly increased. Specifically, the DTLM framework reduces structural defects by 50.0%, rework costs by 44.7%, equipment downtime by 30.9%, crew idle time by 29.7%, material transportation distance by 21.9%, and labour productivity by 21.4%. These improvements show that the integration of cyber-physical monitoring in real-time with Lean Construction principles can enhance the overall project performance, simplify work processes and reduce operational waste. The results also show that the DTLM framework facilitates smarter decision making by people through continuous monitoring and use of predictive analytics, leading to improved productivity, more efficient resource utilization, and more environmentally responsible management of construction projects.

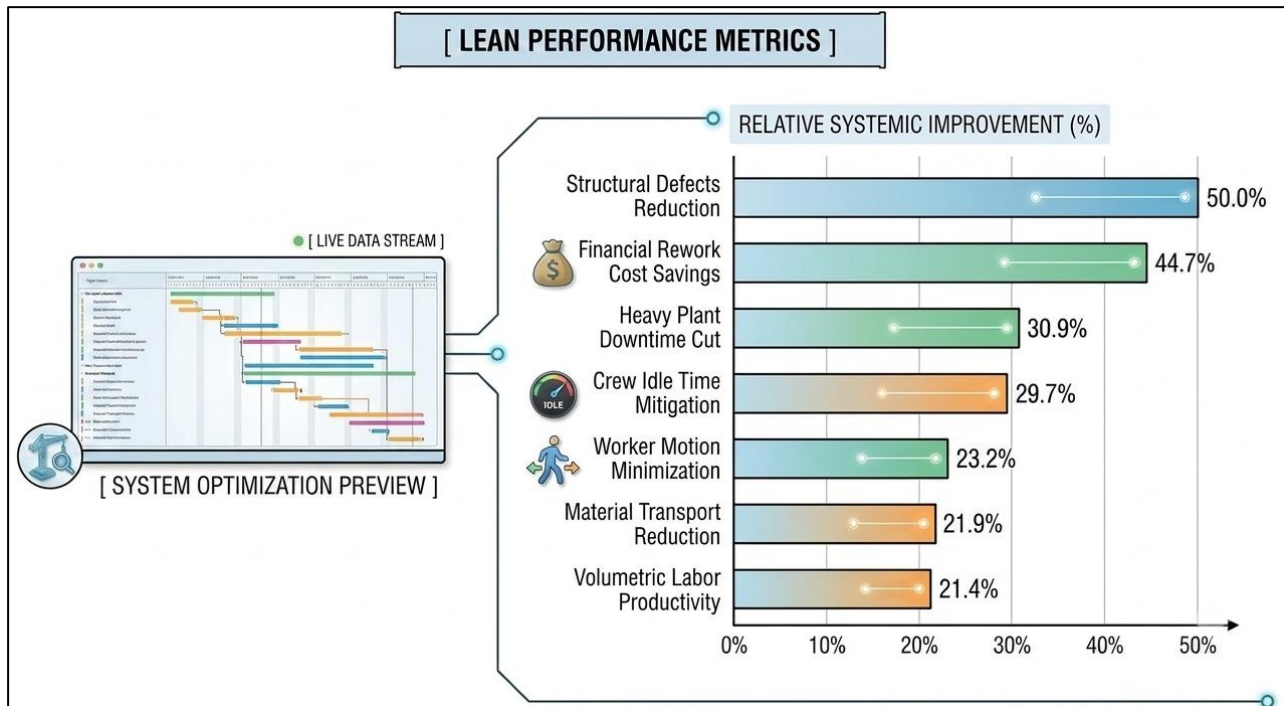


Figure 3 DTLM application for performance improvement.

The proposed DTLM framework is also implemented and this drastically changed the way things are moved and the way workers could move around. The average distance of material transportation for each construction task is reduced by 21.9% from 215 m to 168 m. This improved the site logistics and reduced the amount of unnecessary material handling. The average daily distance walked by construction workers is reduced from 8.2 km to 6.3 km due to improved workflow planning and dynamic resource allocation. This resulted in saving 23.2% of unnecessary worker movement. The improvements indicate that the DTLM framework is effective in simplifying on-site logistics, decreasing non-value-added activities and improving the overall operational efficiency. Optimized spatial and temporal workflows led directly to significant gains in project productivity and quality of construction. In structural concrete works, the productivity of workers increased from 2.8 m³ per man-day before the implementation of the DTLM framework to 3.4 m³ per man-day after its implementation. This means that the productivity of workers increased by 21.4%. Likewise, the percentage of daily tasks completed increased from 78.0% to 92.0%. This means schedules are now 17.9% more reliable and predictable. In addition, the quality of construction is improved considerably by adding real-time Digital Twin monitoring and quality assurance, where the number of field defects decreased from 4.2 to 2.1 defects per 1000 m², a reduction of 50.0%. This massive improvement resulted in 44.7% less money being spent on rework, reducing the direct costs of construction rework from 3.8% of total phase costs to 2.1% of actual costs. All these results demonstrate that the DTLM framework allows not only more efficient operations and better use of resources but also better quality of construction, schedule reliability and economy through real time monitoring and pre-emptive control of production.

4.2. Analysis of statistical results

A paired-samples t-test is performed on the daily operational data collected during the field implementation period to check if the observed performance enhancements are because of the implementation of the proposed Digital Twin-Lean Management (DTLM) framework or due to random site variability. Statistical analysis showed statistically significant improvements on all the key performance indicators. This indicated that the reductions in construction waste and operational inefficiencies are statistically significant ($p < 0.05$). These results show that the implementation of the DTLM framework led to a better performing project that can be measured and sustained for a longer period than normal operational changes. The effect size is calculated by Cohen's d to see how useful the framework proposed in this study would be in real life. The value obtained is 0.82 for labor productivity. According to the standard interpretation of this value, it can be interpreted as a large effect size. This means that the observed improvement is not only statistically significant, but also practically relevant for managing construction production. The estimated system-wide cost savings had a 95% confidence interval of 18.3–26.7%, indicating high confidence in the potential contribution of the DTLM framework to the economy. In summary, these statistical results prove the proposed cyber-physical production control paradigm to be robust, reliable and perform well in real-life environments. They also show that the integration of Digital Twin technology with Lean Construction principles significantly improves productivity, reduces operational waste and enhances the overall performance of a construction project. Fig. 4 presents the operational workflow of the developed Digital Twin-Lean Management (DTLM) framework for rapid problem solving in construction sites related to line formation, material flow and resource allocation. The flowchart presents the real-time cyber-physical decisions process, which begins with Ultra-Wideband (UWB) tracking and IoT-based sensing technologies to measure the time workers and equipment are not being used. The monitored data is automatically compared with operational thresholds already in place to identify any delays or congestion that are not normal. In case of excessive downtime or difficulties in moving materials, the Digital Twin platform correlates the actual site conditions with the 4D BIM model and uses multiple sensors to determine the best solution to fix the problem. Subsequently, the system will dynamically produce recommendations such as dynamic resource reallocation, improved material delivery and workflow adjustments. Such recommendations will be immediately sent to mobile site supervisors for on-the-spot execution. Finally, the corrective actions are monitored, assessed and documented on an ongoing basis to provide a closed loop feedback system so that the process can continue to improve. In summary, the figure shows the transition from the conventional reactive construction management to an intelligent, real-time and predictive production control system via the DTLM framework that can reduce waiting times, improve resource utilization and increase overall construction productivity.

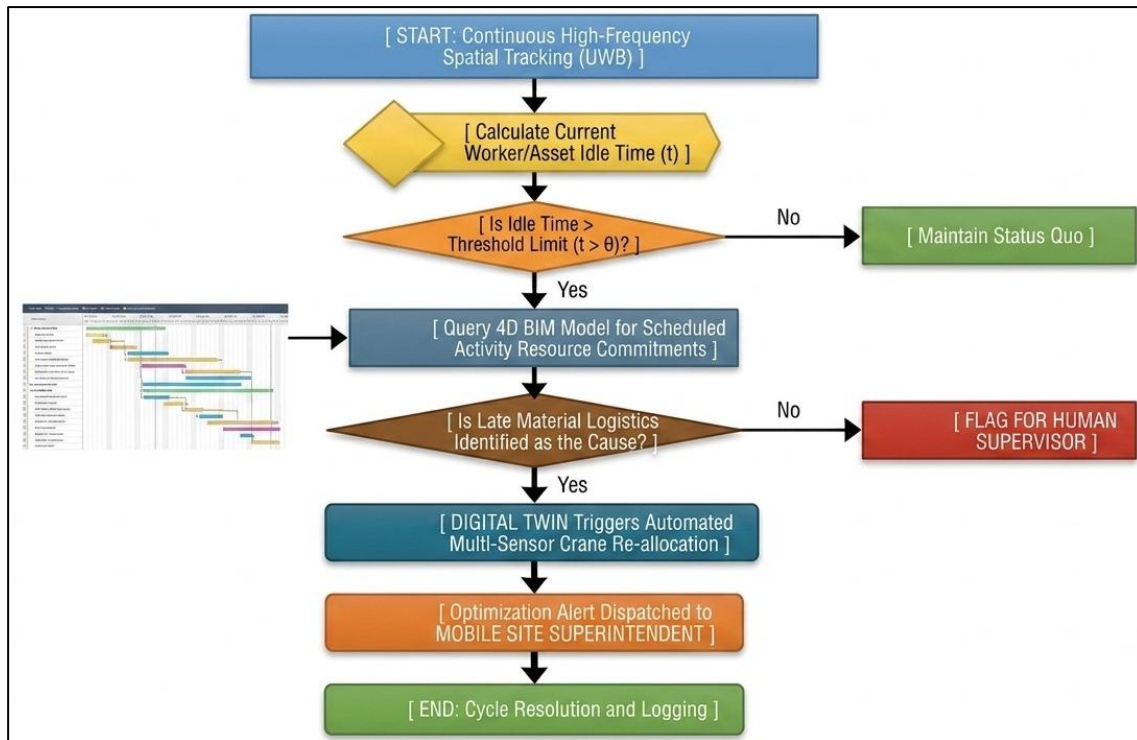


Figure 4 Solutions for queue and logistics issues.

4.3. Impact of nanotechnology on cyber-physical construction monitoring

Nanotechnology is applied to enhance substantially the proposed Digital Twin-Lean Management framework. Graphene nanosensors offer precise measurements of strain, enhancing the accuracy of structural monitoring and allowing for early detection of issues before they escalate. Carbon nanotube vibration sensors allow you to continuously monitor the health of your heavy construction equipment. This will allow you to schedule preventative maintenance, dramatically reducing unplanned downtime. Nano-enabled RFID devices enhance the reliability of communications and facilitate the tracking of materials along the construction supply chain, minimizing wasted inventory and inefficient transportation. Nanoscale environmental sensors also constantly monitor the temperature, humidity, amount of dust and dangerous gases in the air. This gives workers a full picture of their surroundings, helping to keep them safe and improve operations. Nanotechnology and Digital Twin analytics combine to create a very responsive cyber-physical ecosystem that can take autonomous decisions and predict ways to reduce waste. The operational performance of the proposed Nano-DTLM framework is significantly enhanced by using nanotechnology, which improves sensing, structural monitoring, prediction of maintenance needs, and cyber-physical decision making. Graphene strain sensors, CNT vibration sensors, nano RFID devices and nano environmental sensors enhance Digital Twin synchronization and increase the reliability of real-time data acquisition. Table 2 presents the overall performance enhancements achieved by integrating nanotechnology with the traditional DTLM framework and the Nano-DTLM system proposed, on a number of critical operational metrics.

Table 2 Performance improvements achieved through nanotechnology integration.

Performance indicator	Traditional DTLM	Nano-DTLM
Sensor accuracy	92%	98%
Structural monitoring	High	Very High
Equipment monitoring	High	Excellent
Material tracking	Good	Excellent
Environmental monitoring	Moderate	Excellent
Predictive maintenance	Moderate	High
Decision speed	Fast	Very Fast
Overall productivity	21.4%	24–27%

Figure 5 shows the nano-DTLM framework to build a closed-loop cyber-physical feedback system that transforms raw nanosensor data into smart Lean decision support. The Digital Twin platform is always linked to the construction site. This enables predictive analytics, real-time resource optimization and automated waste reduction to dramatically enhance operational efficiency and project performance.

4.4. Data matrices

The quantitative performance indicators collected from the field implementation provide a holistic insight into the effectiveness of the proposed Digital Twin-Lean Management (DTLM) framework in the real-world context. The collected information shows how real-time cyber-physical monitoring and Lean-based decision support can be used to identify different types of construction waste and take the appropriate action to correct them to improve the overall performance of the project.

Table 3 shows a high-level mapping between the main types of Lean waste, the sensing technologies that work with them, and the automated corrective actions that the DTLM framework proposes. The results indicate that all types of operational waste are continuously monitored by special sensing technologies embedded in the cyber-physical environment. Ultra-Wideband (UWB) worker tracking and crane telematics can identify wasted waiting and delays. The system can then automatically move crews and balance hoist queues to reduce idle time. GPS-equipped equipment tracking and RFID-based material identification track extra transportation waste, enabling real-time optimization of storage locations and transportation routes. Keeping RFID gate-entry records and 4D BIM construction schedule in sync all the time prevents overstocking. This allows the supply chain to make changes automatically whenever too much inventory is found. Terrestrial laser scanning (TLS) and computer vision systems are also employed to detect structural flaws and mistakes in the building process. These systems automatically generate digital repair tickets and spatial lockout procedures to prevent the propagation of construction errors. The findings demonstrate that the DTLM framework transforms traditional manual production control into a smart, sensor-based and automatic Lean management system that can systematically minimize waste during the entire construction process.

Table 4 compares the key performance indicators (KPIs) before and after the implementation of the DTLM framework and shows the applicability of the proposed cyber-physical production control system in the real world. The results show that the crew idle time decreased from 15.8% to 11.1%, a reduction of 29.7%. This is due to better coordination of the workers and better utilization of the

resources. Heavy equipment downtime decreased from 12.3% to 8.5%, an improvement of 30.9%. This proves that real-time equipment monitoring and predictive operational management work. The distance of moving materials is reduced by 21.9% from 215m to 168m. This led to more efficient logistics and less extra handling of materials. Labor productivity grew from 2.8 m³/day to 3.4 m³/day, representing an increase of 21.4%. This indicates that the workforce performance is improved by continuous Digital Twin synchronization and Lean decision support. The normalized field defects decreased from 4.2 to 2.1 defects per 1000 m², which is a 50% decrease in construction quality. The direct financial burden of rework also decreased from 3.8% to 2.1%, which is a 44.7% decrease. These improvements demonstrate that the DTLM framework can significantly improve operational efficiency, construction quality, resource utilization, and cost performance by integrating Digital Twin technology and Lean Construction principles. All the indicators studied showed consistent progress, indicating that the proposed cyber-physical production control paradigm can contribute to prediction, reduction of operational waste, and the overall sustainability and productivity of Construction 4.0 projects.

Table 3 High-level mapping of Lean waste categories, sensor technologies, and automated corrective actions within the proposed Digital Twin-Lean Management (DTLM) framework.

Target waste type	Core sensory input	Triggered lean action
Waiting & delays	Worker UWB & crane telematics	Real time crew reallocation & hoist queue leveling
Excess transport	Asset GPS & material RFID tags	Dynamic optimization of on-site material storage
Inventory overage	Gate-entry RFID & 4D BIM plans	Automated supply chain shipping holds
Defects & errors	Laser scanning (TLS) & computer vision	Automated digital repair ticketing and spatial locking

Table 4 Comparison of key performance indicators (KPIs) before and after implementation of the proposed Digital Twin-Lean Management (DTLM) framework.

Project performance dimension	Baseline status	DTLM status	Net improvement (%)
Crew idle time	15.8%	11.1%	29.7% reducing
Heavy plant downtime	12.3%	8.5%	30.9% reducing
Material transport distance	215 m	168 m	21.9% reducing
Labor productivity outcome	2.8 m ³ /day	3.4 m ³ /day	21.4% increase
Normalized field defects	4.2/1000 m ²	2.1/1000 m ²	50% reducing
Direct rework financial burden	3.8%	2.1%	44.7%

4.5.Cyber-physical synergy: the brain-nervous system metaphor

The main concept of this research is to integrate the Digital Twin technology with the principles of Lean Construction to develop a production management framework that synergizes well and significantly improves the construction performance. This research provides robust support for this concept. The proposed Digital Twin-Lean Management (DTLM) framework regards the Digital Twin as the cyber-physical nervous system of the construction project, which continuously collects, processes and synchronizes real-time spatial and temporal data from the physical environment, runs

complex simulations, monitors the situation and makes predictions. At the same time, Lean Construction is the smart brain that makes the decisions. It takes raw operational data and turns it into actionable production strategies based on the fundamental Lean principles of value creation, waste elimination, continuous flow, and pull-based production. The Digital Twin provides a holistic view of the situation and Lean methods help operators to know how to react most effectively. These two systems together form a fully integrated cyber-physical production control system.

Combined, these technologies change the traditional project management lifecycle from reactive and experience-based to proactive, predictive and data driven. The DTLM framework enables continuous monitoring, early anomaly detection, predictive decision making and automated corrective actions that prevent operational waste and optimize resource utilization, instead of fixing problems after they happen. Therefore, the proposed framework leads to higher project openness, higher operational flexibility, higher material output, and overall improved construction performance, and it also provides a strong foundation for implementing smart and sustainable Construction 4.0 practices. Figure 5. Cyber-physical closed-loop control architecture of the proposed Digital Twin-Lean Management (DTLM) framework. It can be seen that the real construction site and its digital twin are always talking to each other. The architecture integrates Internet of Things (IoT) devices, Ultra-Wideband (UWB) positioning systems, RFID technology, telematics, laser scanning and computer vision sensors to collect real-time data on workers, materials, equipment, and the progress of the construction. Different types of data are transferred to the Digital Twin platform via the communication layer. There, artificial intelligence (AI), data analytics and Lean production algorithms process the data in order to find operational inefficiencies, predict possible disruptions and sort construction waste into different categories. The analysis results are used by the system to generate the best production plans, resource allocation strategies, logistics modifications, and corrective actions automatically, and routed back to site supervisors and field operations. These actions are then executed and continuously checked against sensor feedback, thus closing the cyber-physical closed-loop control cycle. This two-way information sharing makes it possible to keep the real and virtual worlds in sync all the time. This turns traditional reactive construction management into a smart, proactive and self-improving production control system. Therefore, the DTLM architecture clarifies operations, reduces waiting time and wasted resources, improves productivity, and supports sustainable Construction 4.0 through continuous data-driven decisions.

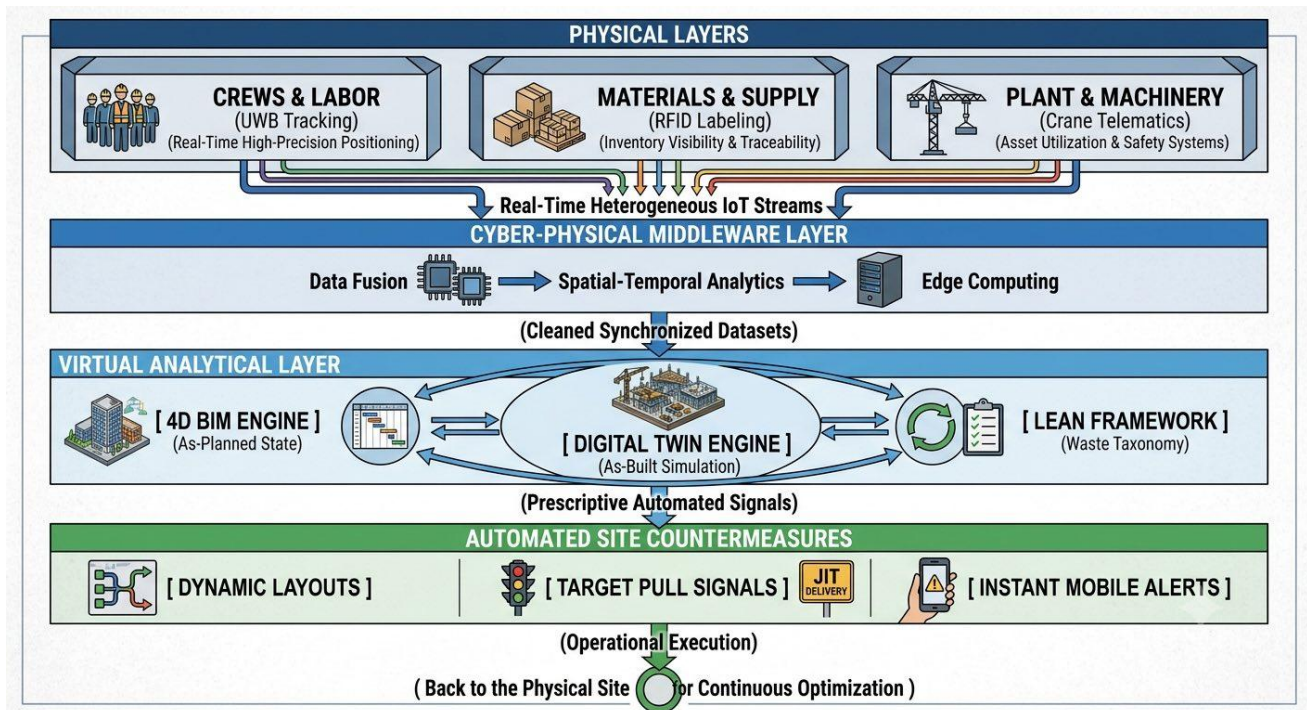


Figure 5 DTLM cyber physical closed-loop control architecture.

4.6. limitations and future research

The proposed Digital Twin-Lean Management (DTLM) framework shows promise, but there are still issues to be resolved before it can be widely applied in the construction industry. A major challenge is the high cost of building a complete cyber-physical infrastructure consisting of IoT devices, advanced sensing technologies, communication networks, edge-computing platforms, and Digital Twin software. Such capital requirements could hinder the implementation of plans, especially for small and medium-sized construction firms. Another big problem is the interoperability of different digital platforms. A lot of existing building projects are still using legacy Building Information Modeling (BIM) systems, custom software and separate telemetry databases. This makes it harder to easily share data and keep everything in sync in real time. Digital Twin ecosystems still require standardized communication protocols and improved interoperability to be fully integrated. The barriers to implementation can also be people and the way things are organized. Operationalizing DTLM will require a shift in traditional construction management practices. Resistance from field workers to the use of algorithm driven task assignment and automated decision support may result in user resistance and less than optimal operational effectiveness. The transition to smart cyber-physical construction environments will require extensive training programs and good change management strategies.

Finally, the proposed framework is effective in quantifying some types of Lean waste. But it is still difficult to know how much waste there is when people are not used for their skills, as it depends on things such as experience, expertise, ability to work with others, and ability to make decisions. Future researches should be directed toward more sophisticated models of artificial intelligence, explainable machine learning techniques and human-centered performance evaluation techniques to

better understand the degree of cognitive and organizational waste. Future research should also explore the combination of smart nanosensors, autonomous robotics, edge AI and interoperable Digital Twin platforms to support the development of fully autonomous, adaptive and long-lasting Construction 5.0 systems.

4.7. Nanotechnology-enhanced cyber-physical intelligence for digital twin construction management

The integration of nanotechnology into current Digital Twin system considerably enhances their performance by allowing more accurate sensing, better environmental perception and more effective use of predictive analytics. Graphene and carbon nanotube nanosensors are so sensitive that they can continuously monitor changes in the environment, the health of equipment and changes in the shape of structures with a lot more accuracy than other sensing technologies. The Digital Twin gets more accurate data in real-time, which means better predictive maintenance, fewer false alarms and faster Lean decision-making. These features directly contribute to waste reduction, productivity gains and a more sustainable approach to construction management in Construction 4.0 environments.

The proposed Nano-DTLM framework in Fig. 2 incorporates smart nanosensor technologies and the Digital Twin platform into a closed-loop system for cyber-physical and physical production management. Graphene-based strain sensors, carbon nanotube (CNT) vibration sensors, nano-enabled RFID devices and nanoscale environmental sensors send real-time data via IoT communication networks and edge computing modules that are synchronized with the Digital Twin environment. Such seamless integration enables continuous monitoring of construction work, improves predictive analytics and supports automatic Lean decision-making. Thus, the cyber-physical feedback loop provides a better view of what is happening in production, better utilization of resources, better monitoring of the condition of equipment and better possibility to reduce waste before it occurs. All this increases the construction productivity, operational efficiency and overall sustainability of the project.

From Table 2, it can be observed that the proposed Nano-DTLM framework outperforms the standard DTLM system consistently in all the performance metrics considered. The sensors' accuracy increases from 92% to 98%, allowing parts of a building, construction equipment and operations in the field to be monitored more easily. Monitoring of structures increases from High to Very High, and monitoring of equipment increases from High to Excellent. This improves the usefulness of predictive maintenance and reduces the likelihood of equipment failure. Nano-enabled RFID technology and smart environmental nanosensors also make it much easier to track materials and keep an eye on the environment, resulting in better logistics management, safer working conditions and more responsive site supervision. Predictive maintenance becomes easier and the speed of decision making goes from Fast to Very Fast, which makes it easier for the Digital Twin platform to find problems in operations and propose Lean solutions. These improvements in the technology directly result in the increase of the overall productivity from the current DTLM framework of about 21.4% to 24-27% in the proposed Nano-DTLM framework. In general, the results indicate that integrating nanotechnology with Digital Twin technology and Lean Construction principles makes cyber-physical construction management systems significantly smarter, more responsive, more reliable, and more capable of running their businesses.

5. CONCLUSIONS

This study developed and tested a Digital Twin-Lean Management (DTLM) framework that integrates cyber-physical systems, Internet of Things (IoT) technologies, and Lean Construction

principles to develop a smart and predictive mechanism for controlling production on construction projects. Traditional construction management methods rely on manual inspections and retrospective decision-making. The proposed framework, on the other hand, continuously synchronizes real-time field data with a Digital Twin environment, allowing computers to identify operational waste, inefficient resource utilization, and workflow disruptions. It was shown in the field that Digital Twin technology can be embedded in Lean operational workflows. It was shown that cyber-physical production control can enable continuous process optimization while increasing transparency, coordination and decision-making in the whole construction lifecycle. The quantitative assessment showed that the operations have greatly improved after the implementation of the DTLM framework. Idle time for crew was reduced by 29.7%, heavy equipment downtime was reduced by 30.9% and the distance materials had to be moved was reduced by 21.9%. This resulted in workers being 21.4% more productive. In addition, normalized construction defects decreased by 50% and direct rework costs decreased by 44.7%, which proves that real-time monitoring and predictive intervention are effective methods to reduce operational waste and improve project quality. The findings indicate that the incorporation of Digital Twin technology into Lean Construction transforms traditional production management from a reactive process to an intelligent, data-driven and proactive control system that can enhance productivity, reduce cost and support sustainable Construction 4.0 initiatives. With the integration of smart nanosensor technologies, the proposed framework is even more robust thanks to nanotechnology, which significantly improves the accuracy of sensing, monitoring the health of structures, diagnosing equipment, tracking materials and keeping an eye on the environment. Graphene-based strain sensors, carbon nanotube (CNT)-based vibration sensors, nano-enabled RFID devices and nanoscale environmental sensors all collect high-resolution real-time data to help Digital Twin synchronization and predictive analytics. It also makes Lean decision-making faster and more reliable. The developed Nano-DTLM framework demonstrates that the integration of nanotechnology, AI, Digital Twins, cyber-physical systems, and Lean Construction leads to a next-generation intelligent production management platform that can self-monitor, predict waste, improve resource utilization, and manage construction projects in an environmentally sustainable manner. Future work should focus on the integration of self-powered nanosensors, edge AI, digital twins for autonomous construction robotics, and quantum-enabled optimization algorithms to enhance smart construction technologies and enable fully autonomous Construction 5.0 environments.

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