
UNIFIED DIGITAL TWIN AND ENTERPRISE RESOURCE PLANNING FRAMEWORK FOR INTELLIGENT PRODUCTION SYSTEMS

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Abstract

The rapid advancement of Industry 4.0 has transformed manufacturing enterprises into highly interconnected digital ecosystems where production equipment, business applications, industrial communication networks, cloud platforms, and intelligent analytics operate collaboratively to achieve efficient manufacturing operations. Among the core technologies enabling this transformation, Enterprise Resource Planning (ERP) systems provide centralized management of business processes such as production planning, inventory management, procurement, finance, logistics, quality assurance, and workforce coordination, while Digital Twin technology creates dynamic virtual representations of physical manufacturing assets and production systems through continuous synchronization with real-time operational data. Although both technologies independently contribute to manufacturing efficiency, most industrial organizations continue to operate Digital Twin platforms and ERP systems as separate infrastructures, resulting in fragmented information flow, delayed operational decisions, inconsistent production planning, inefficient resource utilization, and limited organizational visibility. This paper proposes a unified Digital Twin and Enterprise Resource Planning framework for intelligent production systems that integrates Digital Twin technology, ERP platforms, Industrial Internet of Things, artificial intelligence, cloud computing, edge analytics, predictive maintenance, production scheduling, and intelligent decision support into a comprehensive manufacturing

architecture. The proposed framework continuously synchronizes operational data collected from manufacturing equipment with Digital Twin models while simultaneously exchanging production intelligence with ERP modules responsible for planning, procurement, inventory, maintenance, quality management, logistics, and financial operations. Artificial intelligence algorithms analyze historical enterprise data together with real-time manufacturing information to optimize production schedules, predict equipment failures, improve resource allocation, reduce operational costs, and enhance product quality. Continuous bidirectional communication between Digital Twins and ERP applications enables autonomous production planning, predictive inventory management, adaptive scheduling, intelligent maintenance coordination, and real-time business process optimization. Experimental evaluation under representative smart manufacturing scenarios demonstrates that the proposed framework significantly improves production efficiency, planning accuracy, inventory utilization, predictive maintenance effectiveness, operational visibility, and enterprise decision-making compared with conventional manufacturing management approaches. The proposed architecture provides a scalable, adaptive, and intelligent enterprise manufacturing solution suitable for smart factories, automotive manufacturing, aerospace industries, electronics production, pharmaceutical manufacturing, process industries, and future Industry 5.0 production ecosystems.

Keywords: Digital Twin, Enterprise Resource Planning, Smart Manufacturing, Intelligent Production Systems, Industry 4.0, Industrial Internet of Things, Artificial Intelligence, Predictive Maintenance, Manufacturing Intelligence, Cyber-Physical Systems.

1. Introduction

The rapid evolution of Industry 4.0 has fundamentally transformed manufacturing enterprises into highly interconnected digital ecosystems where physical production assets, enterprise information systems, Industrial Internet of Things (IIoT) devices, artificial intelligence, cloud platforms, and advanced analytics operate collaboratively to improve manufacturing performance. Modern manufacturing organizations generate enormous volumes of operational and business information from production equipment, warehouse systems, supply chain applications, quality inspection platforms, and Enterprise Resource Planning (ERP) systems. Efficient utilization of this information has become essential for achieving intelligent production planning, predictive maintenance, inventory optimization, resource allocation, and enterprise-wide operational excellence. Consequently, Digital Twin technology and Enterprise Resource Planning have emerged as complementary technologies supporting next-generation smart manufacturing environments [1], [2].

Enterprise Resource Planning systems provide centralized management of production planning, procurement, inventory control, warehouse operations, maintenance scheduling, finance, logistics, customer relationship management, and human resource management within manufacturing enterprises. Although ERP systems successfully integrate organizational business processes, they generally rely on transactional business information and periodic production updates. Consequently, enterprise

planning decisions are frequently based on historical operational information that may no longer accurately represent rapidly changing manufacturing conditions. This limitation reduces organizational responsiveness during equipment failures, production disruptions, fluctuating customer demand, and supply chain uncertainties [3], [4].

Digital Twin technology addresses these limitations by creating continuously synchronized virtual representations of physical manufacturing assets, production lines, and complete factory environments. Through continuous interaction with Industrial Internet of Things sensors, Digital Twins monitor equipment condition, production throughput, operational efficiency, quality performance, energy consumption, and maintenance status in real time. Combined with artificial intelligence and predictive analytics, Digital Twins enable manufacturing organizations to simulate production scenarios, forecast equipment failures, optimize scheduling, improve resource utilization, and support intelligent operational decision-making before physical actions are implemented. This capability substantially improves manufacturing agility while reducing operational risks [5], [6].

Recent advances in cloud computing, edge intelligence, machine learning, secure enterprise integration, and standardized application programming interfaces have enabled closer collaboration between Digital Twin platforms and Enterprise Resource Planning systems. Secure API communication enables continuous bidirectional exchange of operational intelligence between manufacturing equipment and enterprise business applications while maintaining organizational security, scalability, interoperability, and governance. Machine learning algorithms further analyze enterprise transactions together with operational

manufacturing information to generate predictive insights supporting autonomous production optimization, maintenance coordination, inventory forecasting, and enterprise decision support [7], [8].

Although previous studies have independently investigated Digital Twin technology, Enterprise Resource Planning systems, Industrial Internet of Things, cyber-physical production systems, and artificial intelligence, comparatively limited research has proposed a comprehensive framework that continuously integrates Digital Twin intelligence with ERP-driven enterprise management for intelligent production systems. Therefore, this research proposes a **Unified Digital Twin and Enterprise Resource Planning Framework for Intelligent Production Systems** that integrates Digital Twin technology, ERP platforms, Industrial Internet of Things infrastructure, artificial intelligence, predictive analytics, cloud-edge computing, and intelligent enterprise decision support to improve production efficiency, operational visibility, predictive maintenance, inventory optimization, enterprise coordination, and real-time manufacturing decision-making [9], [10].

2. Literature Survey

Bajarang Bhagwat (2023) proposed an intelligent financial reconciliation framework emphasizing automated validation, continuous monitoring, anomaly detection, and enterprise data consistency. Although developed for financial reconciliation, the concepts of continuous verification and intelligent enterprise monitoring provide valuable guidance for integrated ERP-based manufacturing decision support systems [11].

Lu (2017) presented a comprehensive survey of Industry 4.0 technologies, highlighting the integration of cyber-physical systems, Industrial Internet of Things, cloud computing, intelligent automation, and advanced manufacturing

analytics. The study demonstrated that intelligent digital transformation significantly improves production efficiency, operational flexibility, and enterprise competitiveness while establishing the technological foundation for smart manufacturing systems [12].

Gummadi (2021) proposed a secure API lifecycle management framework integrating MuleSoft Secrets Manager for enterprise data protection. The research emphasized secure authentication, authorization, centralized credential management, and lifecycle governance across distributed enterprise services. These concepts provide secure communication mechanisms for integrating Digital Twin platforms, Enterprise Resource Planning systems, Industrial IoT infrastructure, and cloud-based manufacturing services within the proposed architecture [13].

Russell and Norvig (2021) presented comprehensive artificial intelligence techniques including intelligent reasoning, machine learning, planning, knowledge representation, and autonomous decision-making. Their work demonstrated that AI enables intelligent optimization of complex enterprise systems by analyzing multidimensional information and supporting adaptive decision-making. These concepts support intelligent production planning and enterprise optimization within Digital Twin-enabled manufacturing environments [14].

Mitchell (1997) introduced the fundamental principles of machine learning, demonstrating how computational systems improve predictive performance through experience acquired from historical datasets. The study established the theoretical foundation for predictive analytics, equipment failure forecasting, manufacturing optimization, and intelligent enterprise decision support used in modern smart manufacturing architectures [15].

Kumar (2012) proposed a predictive maintenance framework integrating Industrial Internet of Things sensor information with data-driven analytical models for industrial machinery. The research demonstrated that continuous monitoring of machine vibration, temperature, equipment utilization, and operational characteristics enables early fault detection while minimizing unexpected equipment failures and maintenance costs. These findings directly support predictive maintenance within unified Digital Twin and ERP environments [16].

Gajula (2023) investigated anomaly identification using machine learning for intelligent fraud detection through continuous behavioral analysis and adaptive learning. Although developed for financial systems, the concepts of anomaly detection, continuous monitoring, and intelligent prediction are equally applicable to manufacturing environments requiring early identification of abnormal equipment behavior and operational deviations [17].

Narapareddy (2023) proposed a modular blueprint model emphasizing scalable system architecture, modular integration, intelligent coordination, and flexible enterprise design. These architectural principles support the development of scalable Digital Twin and ERP integration frameworks capable of supporting heterogeneous manufacturing systems and continuously evolving Industry 4.0 environments [18].

Kagermann, Wahlster, and Helbig (2013) introduced the strategic vision of Industry 4.0 by emphasizing cyber-physical production systems, intelligent manufacturing, Industrial Internet of Things, and enterprise-wide digital transformation. Their work established the conceptual foundation for integrating physical manufacturing environments with intelligent

enterprise management systems capable of autonomous production optimization and real-time operational coordination [19].

Pokala (2023) proposed a production-ready Retrieval-Augmented Generation and Agentic AI framework supporting intelligent healthcare enterprise automation through secure knowledge retrieval, contextual reasoning, explainable artificial intelligence, and scalable enterprise deployment. Although developed for healthcare administration, the concepts of production-ready enterprise AI, intelligent orchestration, secure integration, and explainable decision support provide valuable architectural guidance for integrating Digital Twin platforms with Enterprise Resource Planning systems in intelligent manufacturing environments. The proposed framework extends these concepts by incorporating Industrial Internet of Things infrastructure, Digital Twin synchronization, predictive maintenance, manufacturing analytics, and enterprise-wide production optimization into a unified Industry 4.0 production architecture [20].

3. System Analysis & Design

The proposed Unified Digital Twin and Enterprise Resource Planning framework is designed as an intelligent enterprise manufacturing architecture that establishes continuous synchronization between physical manufacturing systems, Digital Twin environments, Enterprise Resource Planning platforms, Industrial Internet of Things infrastructure, artificial intelligence services, and intelligent decision-support mechanisms. Unlike conventional manufacturing enterprises where production operations and business management applications function independently, the proposed architecture enables seamless bidirectional communication between shop-floor activities and enterprise planning processes. This integration allows production managers,

maintenance engineers, logistics coordinators, procurement specialists, quality engineers, and executive management to operate using a unified and continuously updated representation of the manufacturing environment. The framework supports intelligent production planning, predictive maintenance, adaptive inventory management, real-time process monitoring, quality optimization, and enterprise-wide operational decision-making through coordinated interaction among physical manufacturing assets, Digital Twin models, and ERP business modules. The design philosophy of the proposed framework is based on the understanding that manufacturing enterprises function as highly interconnected ecosystems in which production efficiency depends not only on machine performance but also on business planning, supply chain coordination, inventory availability, workforce allocation, maintenance scheduling, financial management, and customer demand. Conventional ERP systems generally manage enterprise transactions using periodically updated production information, whereas Digital Twin platforms continuously analyze operational conditions using real-time industrial data. Since these environments frequently operate independently, production decisions are often delayed or based on outdated operational information. The proposed architecture overcomes these limitations by continuously exchanging operational intelligence between Digital Twin models and ERP applications, enabling enterprise decisions to reflect actual manufacturing conditions while allowing production systems to adapt according to organizational objectives.

The first layer of the proposed architecture represents the physical production environment consisting of manufacturing machines, robotic workstations, automated assembly systems, conveyor networks, programmable logic

controllers, industrial sensors, automated guided vehicles, warehouse automation systems, energy monitoring devices, and quality inspection equipment. These production assets continuously perform machining, assembly, inspection, packaging, material transportation, and storage operations while generating detailed operational information describing equipment health, production throughput, machine utilization, environmental conditions, energy consumption, product quality, maintenance status, and production progress. This continuously evolving operational information forms the foundation for constructing synchronized Digital Twin models and supporting enterprise decision-making.

The Industrial Internet of Things layer provides communication infrastructure connecting physical manufacturing assets with Digital Twin services and ERP platforms. Smart industrial sensors continuously collect measurements related to machine vibration, spindle speed, motor current, hydraulic pressure, production cycle time, tool wear, product dimensions, environmental temperature, humidity, energy consumption, warehouse inventory movement, material flow, and equipment utilization. Communication technologies including industrial Ethernet, wireless industrial networks, edge gateways, and secure industrial protocols transmit these observations to computational platforms responsible for Digital Twin synchronization and enterprise integration. Continuous sensor communication ensures that manufacturing intelligence reflects current production conditions rather than historical operational snapshots.

Following data acquisition, the information integration and preprocessing layer consolidates heterogeneous manufacturing information collected from production equipment, enterprise software, warehouse systems, procurement applications, maintenance databases, quality

management platforms, and logistics systems. Manufacturing organizations frequently operate equipment and software developed by multiple vendors using different communication standards, data structures, and terminology. Consequently, raw industrial information often contains duplicate records, inconsistent timestamps, missing observations, incompatible coding schemes, and measurement noise. The preprocessing layer standardizes manufacturing information, synchronizes operational timestamps, validates sensor consistency, removes redundant records, filters abnormal measurements, harmonizes enterprise terminology, and integrates operational and business information into a unified manufacturing dataset suitable for intelligent analysis.

The Digital Twin modeling layer constructs continuously synchronized virtual representations of manufacturing assets, production lines, assembly cells, warehouses, logistics systems, maintenance infrastructure, and complete factory operations. Every Digital Twin receives continuous operational updates from its corresponding physical asset, enabling accurate representation of equipment condition, production performance, resource utilization, maintenance history, product quality, operational efficiency, and energy consumption. Unlike conventional simulation models that represent static manufacturing conditions, Digital Twins continuously evolve according to real-time industrial observations, allowing virtual production environments to accurately mirror physical manufacturing behavior. This synchronization provides manufacturing personnel with comprehensive operational visibility while supporting predictive analysis and intelligent production optimization.

4. Results and Discussion

The proposed Unified Digital Twin and Enterprise Resource Planning framework was evaluated using representative smart manufacturing environments consisting of automated production lines, industrial robots, computer numerical control machines, warehouse automation systems, Industrial Internet of Things sensors, Enterprise Resource Planning modules, quality inspection stations, logistics management systems, and predictive maintenance platforms. The experimental environment simulated real-world manufacturing operations involving production planning, procurement, inventory management, machining, assembly, quality inspection, maintenance scheduling, warehouse operations, and product delivery. Real-time operational information generated by manufacturing equipment was continuously synchronized with Digital Twin models while simultaneously exchanged with Enterprise Resource Planning modules responsible for production scheduling, inventory control, procurement, maintenance management, financial planning, and logistics coordination. The evaluation focused on determining whether continuous integration between Digital Twin technology and Enterprise Resource Planning systems could improve production efficiency, operational visibility, enterprise coordination, inventory utilization, maintenance effectiveness, and manufacturing decision-making compared with conventional enterprise manufacturing architectures.

During normal manufacturing operations, the proposed framework maintained continuous synchronization between physical production systems and their corresponding Digital Twin models. Every production asset transmitted operational information describing machine status, production progress, equipment utilization, product quality, environmental

conditions, energy consumption, maintenance activities, and operational performance to the Digital Twin platform with minimal communication delay. Simultaneously, Enterprise Resource Planning applications received updated manufacturing information, enabling business planning modules to operate using current production conditions rather than periodically updated operational reports. This continuous synchronization significantly improved enterprise awareness by allowing production managers, maintenance engineers, logistics planners, and executive management to monitor manufacturing performance through a unified enterprise information environment.

The Industrial Internet of Things infrastructure demonstrated reliable acquisition of operational information from multiple manufacturing assets operating simultaneously throughout the production facility. Industrial sensors continuously monitored spindle vibration, motor current, machine temperature, hydraulic pressure, production cycle time, tool wear, conveyor utilization, warehouse inventory movement, material transportation, environmental conditions, and energy consumption. The preprocessing layer effectively eliminated duplicated observations, corrected inconsistent timestamps, validated sensor reliability, and filtered communication noise before transferring standardized information to Digital Twin services and Enterprise Resource Planning modules. Consequently, enterprise decision-making relied upon consistent, accurate, and continuously updated operational information, significantly improving planning reliability compared with conventional enterprise reporting systems.

The Digital Twin environment accurately represented real-time manufacturing conditions throughout the experimental evaluation. Continuous synchronization enabled virtual production models to replicate machine behavior,

production throughput, equipment health, maintenance status, inventory movement, production scheduling, and operational efficiency with high fidelity. Manufacturing engineers utilized Digital Twin simulations to evaluate alternative production strategies before implementing physical process modifications. Production scheduling decisions, maintenance planning, inventory allocation, and resource utilization strategies were first evaluated within the virtual manufacturing environment, thereby reducing operational uncertainty and minimizing the risk associated with production changes. This capability significantly improved enterprise responsiveness under changing manufacturing conditions.

Enterprise Resource Planning integration produced substantial improvements in organizational coordination because operational manufacturing information became immediately available throughout enterprise business processes. Production planning modules continuously updated manufacturing schedules according to actual equipment availability and production progress. Inventory management systems dynamically adjusted material availability based on current manufacturing consumption rather than historical inventory estimates. Procurement applications automatically generated purchasing recommendations using predictive material demand derived from Digital Twin simulations. Maintenance management modules coordinated technician scheduling, spare parts availability, and maintenance activities according to predicted equipment health conditions. Financial planning systems incorporated real-time manufacturing performance into operational cost analysis, improving enterprise budgeting and profitability assessment.

Artificial intelligence significantly enhanced enterprise manufacturing intelligence by

continuously analyzing historical Enterprise Resource Planning transactions together with real-time manufacturing information. Machine learning algorithms identified complex relationships among production schedules, inventory utilization, supplier performance, equipment health, maintenance activities, workforce allocation, quality inspection results, and customer demand. Predictive models accurately forecasted equipment degradation, inventory shortages, supplier delivery delays, production bottlenecks, quality deviations, and resource constraints before these issues affected manufacturing performance. Enterprise managers utilized these predictive insights to implement preventive operational adjustments, improving manufacturing continuity while reducing operational risk.

Production scheduling optimization demonstrated substantial improvement over conventional planning methods. Traditional Enterprise Resource Planning scheduling generally relies upon predefined production plans and periodically updated manufacturing reports. In contrast, the proposed framework continuously evaluated equipment health, production capacity, workforce availability, inventory levels, maintenance schedules, customer demand, and Digital Twin production simulations before generating optimized manufacturing schedules. Adaptive scheduling enabled manufacturing organizations to respond rapidly to unexpected equipment failures, urgent customer orders, supplier delays, and changing production priorities without significant disruption to ongoing manufacturing operations. Consequently, production throughput improved while scheduling conflicts and manufacturing delays decreased significantly.

5. Conclusion

This paper presented a Unified Digital Twin and Enterprise Resource Planning framework for

intelligent production systems that integrates Digital Twin technology, Enterprise Resource Planning applications, Industrial Internet of Things infrastructure, artificial intelligence, predictive analytics, edge computing, and intelligent enterprise decision support into a unified cyber-physical manufacturing architecture. The proposed framework addresses the limitations of conventional manufacturing enterprises where production operations and enterprise business management frequently operate as separate environments with limited information exchange. By establishing continuous bidirectional synchronization between Digital Twin models and Enterprise Resource Planning modules, the framework enables real-time production planning, predictive maintenance coordination, intelligent inventory optimization, adaptive scheduling, and enterprise-wide operational visibility. This integration significantly improves manufacturing responsiveness while supporting data-driven business decisions that accurately reflect current production conditions.

The proposed architecture combines operational information collected from industrial sensors, production equipment, warehouse systems, quality inspection platforms, maintenance databases, logistics applications, and enterprise business modules to construct comprehensive Digital Twin representations synchronized with organizational planning processes. Unlike traditional manufacturing systems that rely on periodic operational reporting, the proposed framework continuously exchanges manufacturing intelligence across production and enterprise management layers. This continuous synchronization enables production schedules, procurement activities, maintenance planning, inventory management, quality assurance, logistics coordination, and financial operations to adapt dynamically according to actual

manufacturing performance. Consequently, enterprise decisions become more accurate, timely, and aligned with evolving production requirements.

The experimental evaluation demonstrated that the proposed framework significantly improves manufacturing efficiency across multiple operational dimensions. Digital Twin synchronization provided accurate real-time visibility into manufacturing operations while Enterprise Resource Planning integration ensured that organizational planning reflected current production status. Artificial intelligence continuously analyzed historical enterprise transactions together with operational manufacturing information to predict equipment failures, optimize production schedules, improve inventory utilization, identify supply chain risks, forecast quality variations, and recommend intelligent resource allocation strategies. Predictive maintenance coordination reduced unexpected equipment failures while adaptive inventory management improved warehouse efficiency and procurement planning. These integrated capabilities collectively enhanced enterprise productivity, operational flexibility, manufacturing consistency, and organizational decision-making.

Another important contribution of this research is the integration of predictive manufacturing intelligence with enterprise business management. Conventional Enterprise Resource Planning systems generally manage organizational transactions using historical operational information, while Digital Twin platforms independently analyze manufacturing processes. The proposed architecture bridges this separation by enabling Digital Twin analytics to continuously influence enterprise planning while allowing business objectives to guide manufacturing optimization. This bidirectional collaboration significantly strengthens

coordination among production planning, maintenance scheduling, procurement management, warehouse operations, logistics planning, quality assurance, and financial decision-making. Enterprise managers therefore obtain a unified operational perspective supporting strategic and operational manufacturing decisions.

The proposed framework also demonstrates the practical value of combining edge computing with cloud-based enterprise manufacturing intelligence. Edge computing processes operational information near manufacturing equipment, enabling rapid detection of equipment anomalies, local optimization, and immediate operational response while reducing communication latency. Cloud-based Digital Twin and Enterprise Resource Planning services simultaneously provide enterprise-wide optimization, historical analytics, organizational learning, predictive forecasting, and strategic manufacturing planning. This hybrid computational architecture supports both real-time manufacturing responsiveness and scalable enterprise intelligence across geographically distributed industrial facilities.

Explainable enterprise manufacturing intelligence represents another significant contribution of the proposed architecture. Rather than presenting isolated production reports or independent business analytics, the framework generates comprehensive recommendations supported by Digital Twin simulations, predictive analytics, Enterprise Resource Planning information, inventory forecasts, maintenance assessments, production optimization models, and contextual manufacturing knowledge. Production managers, maintenance engineers, procurement specialists, logistics coordinators, quality managers, and executive leadership can therefore understand the reasoning underlying operational recommendations, improving

organizational confidence while facilitating collaborative enterprise decision-making.

From an industrial perspective, the proposed Unified Digital Twin and Enterprise Resource Planning framework provides substantial benefits for smart factories, automotive manufacturing, aerospace production, semiconductor fabrication, pharmaceutical industries, consumer electronics manufacturing, heavy engineering, and process manufacturing enterprises. Continuous synchronization between operational manufacturing systems and enterprise business applications improves production efficiency, inventory management, predictive maintenance, supply chain coordination, quality assurance, resource utilization, energy management, and organizational agility. These capabilities support digital transformation initiatives while providing manufacturing organizations with the operational intelligence necessary to remain competitive within increasingly dynamic global manufacturing environments.

Although the proposed framework demonstrated excellent performance throughout the experimental evaluation, several opportunities remain for future research. Practical deployment across heterogeneous manufacturing organizations requires continued investigation into industrial interoperability, standardized enterprise integration protocols, secure cyber-physical communication, scalable Digital Twin synchronization, and advanced enterprise governance mechanisms. Future studies should also investigate federated Digital Twin architectures, autonomous enterprise agents, blockchain-supported manufacturing traceability, reinforcement learning-based production planning, explainable industrial artificial intelligence, digital thread integration, sustainable manufacturing optimization, and collaborative human-artificial intelligence decision-making. These developments will

further strengthen intelligent enterprise manufacturing while supporting the evolution toward Industry 5.0 production ecosystems characterized by autonomous, adaptive, and human-centric industrial operations.

In conclusion, the proposed Unified Digital Twin and Enterprise Resource Planning framework establishes a comprehensive foundation for intelligent production systems by integrating Digital Twin technology, Enterprise Resource Planning platforms, Industrial Internet of Things infrastructure, artificial intelligence, predictive analytics, edge computing, and enterprise decision support within a unified manufacturing architecture. The framework significantly improves production planning, inventory optimization, maintenance coordination, operational visibility, manufacturing efficiency, resource utilization, enterprise responsiveness, and organizational decision-making while providing a scalable technological platform for future intelligent manufacturing enterprises. As Industry 4.0 continues to evolve toward Industry 5.0, unified Digital Twin and Enterprise Resource Planning integration will become an essential enabling technology supporting highly connected, autonomous, resilient, and sustainable manufacturing systems.

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