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Cognitive digital twin-based Internet of Robotic Things, multi-sensory extended reality and simulation modeling technologies, and generative artificial intelligence and cyber–physical manufacturing systems in the immersive industrial metaverse

JEL Classification: *E42; J33; O14*

Keywords: *cognitive digital twin; Internet of Robotic Things; sensor; extended reality; simulation modeling; generative artificial intelligence; cyber–physical manufacturing system; immersive industrial metaverse*

Abstract

Research background: Connected Internet of Robotic Things (IoRT) and cyber-physical process monitoring systems, industrial big data and real-time event analytics, and machine and deep learning algorithms articulate digital twin smart factories in relation to deep learning-assisted smart process planning, Internet of Things (IoT)-based real-time production logistics, and enterprise resource coordination. Robotic cooperative behaviors and 3D assembly operations in collaborative industrial environments require ambient environment monitoring and geospatial simulation tools, computer vision and spatial mapping algorithms, and generative artificial intelligence (AI) planning software. Flexible industrial and cloud computing environments necessitate sensing and actuation capabilities, cognitive data visualization and sensor fusion tools, and image recognition and computer vision technologies so as to lead to tangible business outcomes.
Purpose of the article: We show that generative AI and cyber–physical manufacturing systems, fog and edge computing tools, and task scheduling and computer vision algorithms are instrumental in the interactive economics of industrial metaverse. Generative AI-based digital twin industrial metaverse develops on IoRT and production management systems, multi-sensory extended reality and simulation modeling technologies, and machine and deep learning algorithms for big data-driven decision-making and image recognition processes. Virtual simulation modeling and deep reinforcement learning tools, autonomous manufacturing and virtual equipment systems, and deep learning-based object detection and spatial computing technologies can be leveraged in networked immersive environments for industrial big data processing.
Methods: Evidence appraisal checklists and citation management software deployed for justifying inclusion or exclusion reasons and data collection and analysis comprise: Abstrackr, Colandr, Covidence, EPPI Reviewer, JBI-SUMARI, Rayyan, RobotReviewer, SR Accelerator, and Systematic Review Toolbox.
Findings & value added: Modal actuators and sensors, robot trajectory planning and computational intelligence tools, and generative AI and cyber–physical manufacturing systems enable scalable data computation processes in smart virtual environments. Ambient intelligence and remote big data management tools, cloud-based robotic cooperation and industrial cyber-physical systems, and environment mapping and spatial computing algorithms improve IoT-based real-time production logistics and cooperative multi-agent controls in smart networked factories. Context recognition and data acquisition tools, generative AI and cyber–physical manufacturing systems, and deep and machine learning algorithms shape smart factories in relation to virtual path lines, collision-free motion planning, and coordinated and unpredictable smart manufacturing and robotic perception tasks, increasing economic performance. This collective writing cumulates and debates upon the most recent and relevant literature on cognitive digital twin-based Internet of Robotic Things, multi-sensory extended reality and simulation modeling technologies, and generative AI and cyber–physical manufacturing systems in the immersive industrial metaverse by use of evidence appraisal checklists and citation management software.

Introduction

The economic and business management of cognitive digital twin-based Internet of Robotic Things (IoRT) in flexible collaborative environments and in 3D virtual factories (in terms of machine tool automation interoperability for sustainable business performance and innovation) develops increasingly on 3D computer vision-based production and multi-sensory tracking technologies, and if we consider the current relevance of metaverse-based industrial services, a special attention is allocated to environment mapping and steering control algorithms throughout industrial big data processing. Networked immersive environments are also in need of deep learning-based object detection and distributed spatial computing technologies (for scene perception and event detection), and this is why virtual simulation modeling and deep reinforcement learning tools are generally perceived as driving business value creation. Smart virtual environments depend on the constant updating of decentralized autonomous manufacturing and virtual equipment systems (for knowledge-driven digital twin machine learning-based cyber-physical production systems in task orchestration) that together with multi-robot trajectory planning and computational intelligence tools enable scalable data computation processes. Thus artificial intelligence (AI) and cyber–physical manufacturing systems leverage modal actuators and sensors for machine vision monitoring and manufacturing quality control, and business and economic applications indicate the necessity of deploying cognitive data visualization and sensor fusion tools. As a result, flexible industrial and cloud computing environments have to increasingly integrate image recognition and computer vision technologies due to optimized sensing and actuation capabilities.

The main objective of this paper is to clarify how the interactive economics of industrial metaverse supporting process manufacturing intelligence and remote maintenance integrates decision and control algorithms, as for decentralized smart industrial production and collaborative robotic manufacturing process modeling (with regard to neuromorphic vision-based control in anomalous robot motion detection and collision avoidance) there is a constant need of wireless connected and environment perception sensors that can complement collision-free trajectory and visual perception tools. Consequently, the interactive economics of industrial metaverse requires cyber–physical production and

IoRT-based context-aware systems (in terms of digital twin-based intelligent self-organized reconfiguration management and distributed production control) that make data processing and sharing more swiftly correlated with situational awareness and object identification algorithms while integrating image recognition and detection tools. Furthermore, digital twin smart factories depend on connected IoRT and cyber-physical process monitoring systems for deep learning-assisted smart process planning, with machine and deep learning algorithms assisting industrial big data and real-time event analytics, and leading to tangible business outcomes through Internet of Things (IoT)-based real-time production logistics and enterprise resource coordination.

The research gap diagnosis shows that generative AI and cyber–physical manufacturing systems shape the economic and business management of smart factories (Aromaa *et al*., 2024; Cao *et al*., 2023; Hajian *et al*., 2024; Liu *et al*., 2023; Ren *et al*., 2024; Stary, 2023) throughout coordinated and unpredictable smart manufacturing and robotic perception tasks. This is possible as a result of context recognition and data acquisition tools for virtual path lines and collision-free motion planning enabled by deep and machine learning algorithms in the interactive economics of industrial metaverse. Generative AI fact-based situational decision-making processes augment organizational transformation in uncertain dynamic smart manufacturing environments, and this explains the relevance of network management, monitoring, and automation tools in job loss prediction. Consequently, machine learning-based task automation increases productivity by data-driven synthetic ideation, creativity, and intuition, with efficiency gains resulting in workforce reductions (machine learning automation and associated productivity gains are related to manufacturing quality control, streamlining, and scaling business operations). The novelty of the current paper resides in proving that generative AI and cyber–physical manufacturing systems can increase economic performance with the contribution of task scheduling and computer vision algorithms, while fog and edge computing tools are typically useful in cognitive digital twin-based IoRT due to cloud-based generative AI engineering modeling and simulation.

Methods

Evidence appraisal checklists and citation management software were deployed for justifying inclusion or exclusion reasons and data collection and analysis: Abstrackr (for single and double-blind abstract and full text screening), CADIMA (for screening process record allocation automation), Colandr (for sorting citations, in addition to review planning, collaborative screening, and project management), Covidence (for abstract, full text, and citation screening, in addition to data extraction and quality/bias assessment, study selection, and document management), DistillerSR (for systematic literature review stage automation), EPPI Reviewer (for data synthesis and analysis), JBI-SUMARI (for study selection, automated analysis, and quality assessment), Rayyan (for content screening and selection, and tagging and filtering-based reference coding and organization), RobotReviewer (supporting evidence synthesis), SR Accelerator (for search result deduplication and word frequency analysis), STARR (for right method selection), and Systematic Review Toolbox (for evidence synthesis process).

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Spatial simulation and machine vision algorithms, imaging-based navigation and data mining technologies, and manufacturing process monitoring and cyber-physical enterprise systems in generative AI-based digital twin industrial metaverse

The architecture of virtual twin-enabled Industrial IoT displays the harmonization of multi-sensory extended reality and simulation modeling technologies (Agarwal & Alathur, 2023; Hajian *et al*., 2024; Ren *et al*., 2024), with metaverse decentralized governance and cyber-physical manufacturing systems (in context-sensitive modeling of knowledge-based sustainable manufacturing operations) developing on perception and cognition algorithms. Autonomous robotized and real-time sensor devices can be deployed for real-time data collection in the immersive economics of industrial metaverse due to the efficiency of spatial simulation and machine vision algorithms. For this reason, real-time 3D data stream processing, reconstruction, and mapping in scalable smart real-time manufacturing robotized and monitoring systems further deep learning-based robotized wireless sensor networks in digital twin cyber-physical production system management. Condition monitoring, machining parameter measurement, and fault diagnosis are monitored and analyzed by neural network image sensors in vision perception and processing. As a result, ambient sound recognition software and multi-channel convolutional neural networks are also useful, together with scalable visual recognition and motion capture tools, in synthetic simulation environments, as thus robotic navigation and collaborative manufacturing processes, typically operating by use of sensor data and devices, can deploy spatial cognition algorithms for machine data mining and trajectory tracking in robotic production system simulation and modeling.

With regard to business and economic relevance, robotic operating and context-aware systems in generative AI-based digital twin industrial metaverse (Aggogeri *et al*., 2024; Kaigom, 2023; Negri & Abdel-Aty, 2023) can count on interconnected IoRT and brain-inspired computing devices for object perception and manipulation in image-based object-aware robotic manipulation and visualization. For this reason, autonomous mobile robot behavior coordination and deep learning trajectory prediction algorithm performance across Industry 4.0-based networked environments is carried out by manufacturing management and distributed computing systems for big data mining processing, while generative AI planning software can integrate cloud imaging tools for environment mapping and visual perception. IoRT digital twins can operate across cloud computing and big data infrastructures for manufacturing process monitoring and cyber-physical enterprise systems, with associated complex computational tasks assisted by deep reinforcement learning and remote big data management tools. Machine multi-sensor manufacturing process monitoring and diagnosis support cyber-physical production enterprises with regard to contextual self-organization. Consequently, context-aware deep reinforcement learning algorithms and computer vision-based 3D robotic navigation tools configure smooth trajectory planning by sensor data fusion. Federated deep reinforcement learning-based digital twin-enabled multiscale modeling of dynamic job scheduling and planning processes across multi-robot cloud-edge collaborative manufacturing environments develops on blockchain-based production data sharing. Mobile robot path planning can be carried out by deep learning coordinated collision-free trajectory-tracking modeling and control in uncertain environments.

Autonomous distributed decision-making in the immersive economics of industrial metaverse (Anwar *et al*., 2024; Jagatheesaperumal & Rahouti, 2022; Stavroulakis *et al*., 2022) for coordinated motion planning and robotic manipulation tasks integrate cloud and fog computing technologies with the aim of determining context awareness and path planning that can be complementarily optimized by data mining and remote sensing. As a result, sustainable big data integrative and cognitive decision-making processes in the immersive economics of industrial metaverse can leverage machine and deep learning algorithms for data mining and processing, in addition to fog and edge computing technologies for deep reinforcement learning-based coordinated decentralized control of cooperative multi-robot navigation and motion planning performance. Smart shop floor environments across intelligent connectivity infrastructures typically leverage computer vision and 3D path planning algorithms as imaging-based navigation technologies cannot be operational without remote big data mining management for deep learning multimodal remote sensing data fusion, object detection, and image classification. As an illustration, multi-sensor process analysis and machine vision monitoring can be carried out for the cyber-physical production performance of smart context-aware networked systems. Engineering product lifecycle management enables smart factory transformation by real-time machining data across edge–cloud collaborative manufacturing and smart tool condition monitoring systems in smart manufacturing environments.

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Mobile autonomous robotic and smart interconnected devices, geospatial big data management and environment mapping algorithms, and intelligent production and virtual manufacturing systems in the immersive economics of industrial metaverse

Swarm robotic coordination mechanisms and connected IoRT mobile devices in the immersive economics of industrial metaverse (Aromaa *et al*., 2024; Kuo & Choi, 2024; Patterson, 2024) are monitored for cooperation behavior throughout intelligent production and virtual manufacturing processes enabled by extended reality productivity and immersive holographic imaging and sensing technologies. Specifically, generative AI and cyber–physical manufacturing systems develop on visual and spatial intelligence tools, shaping multi-machine cooperation in smart manufacturing environments. The resulting data processing and smart environment modeling is optimized by spatio-temporal fusion and cognitive decision algorithms. Federated reinforcement learning enhances industrial swarm robotic behaviors, networks, and cooperation for collective motion planning. Most importantly, immersive and collaborative product design analysis, remote control, predictive maintenance, and job scheduling improve digital twin multiscale virtual manufacturing simulation and modeling. Multi-agent deep reinforcement learning and recurrent neural network-based dynamic reconfigurable flexible job shop scheduling and multi-machine cooperative operation integrate geospatial big data for robotic path planning. The design and operation simulation of virtual machining processes enhances digital twin-based organizational performance in cloud immersive and collaborative manufacturing environments.

Business and economic applications indicate that visual perception and image recognition algorithms (Aung *et al*., 2024; Kaarlela *et al*., 2023a; Martínez-Gutiérrez *et al*., 2024) enable robotic manufacturing and industrial robot assembly processes in the immersive economics of industrial metaverse for localization and navigation purposes while depending on mobile autonomous robotic and smart interconnected devices. This explains edge-computing-based autonomous decisions for robotic coordination mechanisms as mobile sensors and actuators for cloud computing and virtual manufacturing machines require remote sensing and machine learning algorithms. 3D imaging and deep learning techniques can be leveraged in the immersive economics of industrial metaverse in relation to IoRT network and virtual machine performance, leading to tangible business outcomes, with big data clustering and cognitive decision-making algorithms optimizing networked robotic and autonomous manufacturing systems. Digital twin mobile automatic robotic manufacturing process modelling in anomalous robot motion detection can be achieved by crowding evolutionary algorithms, virtual monitoring systems, and multi-agent collaborative neuromorphic-vision based control for networked scalable mobile sensing in knowledge-embedded machine learning-based multi-floor manufacturing processes. That is to say, deep reinforcement learning and convolutional neural network-enabled industrial robot digital twin systems correlate accuracy and precision of predictive maintenance, trajectory tracking control, and fault diagnosis for robot vision sensor-based flexible reconfigurable manufacturing machine condition monitoring and modular supervisory control.

Collaborative IoRT and cloud computing technologies (Bellalouna & Puljiz, 2023; Kshetri, 2023a; Sai *et al*., 2024) can be harnessed in smart shop floor environments as a result of the operational performance of path planning and visual perception algorithms across cyber-physical process monitoring and networked manufacturing systems. Undoubtedly, cloud robotic and machine intelligence technologies for big data-driven decision-making and predictive maintenance processes throughout Internet of Manufacturing Things (IoMT) collaborative and robotic wireless sensor networks leverage geospatial big data management and environment mapping algorithms in dynamic sensing environments. The economic and business management of intelligent simulation environments developed on cloud computing and immersive visualization technologies is typically articulated in IoT-based autonomous robotic and cyber-physical production systems by use of machine learning and path planning algorithms. Unified multimodal data aggregation develops distributed feedback optimization and multiparty motion coordination in task allocation and decentralized path planning. For this purpose, deep reinforcement learning-based mobile robot task and coordinated motion planning configure large-scale robotic networks in unstructured environments. Equally important, swarm reinforcement learning algorithms can improve tracking performance and distributed coordination of 3D cloud-edge collaborative industrial networked heterogeneous robotic perception. Digital twin federated deep learning can perform collaborative task allocation for swarm robotic data collection, fault diagnostics, and anomaly detection.

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Industrial metaverse automation and multi-sensory extended reality technologies, robotic navigation and context aware systems, and remote object identification and data acquisition tools in cyber-physical system-based smart factories

Cyber-physical system-based sustainable product lifecycle management of industrial automation and multi-sensory extended reality technologies for autonomous robotic and mobile context awareness systems in immersive virtual environments (Bhattacharya *et al.*, 2023; Li *et al.*, 2023; Nagy *et al.*, 2023) indicates the importance of space situational awareness and image processing tools. Consequently, context awareness and spatial cognition algorithms across IoT-based real-time production logistics throughout industrial manufacturing and dynamic mapping processes in generative AI and cyber–physical manufacturing systems require real-time machine data. The economic and business management of cyber-physical system-based smart factories based on computational intelligence and predictive maintenance tools in IoT-based production and environment monitoring systems optimize operational performance by semantic sensor and plant computing technologies. For this reason, data-driven machine learning and multi-scale convolutional generative adversarial networks enhance 6G blockchain-assisted industrial-scale distributed control for mobile robot path planning and fault identification.

Embedded IoRT-based sensor-driven autonomous decisions and processes in networked environments can be configured (Cao *et al.*, 2023; Jaimini *et al.*, 2022; Meng *et al.*, 2024) for robotic environment mapping and predictive maintenance by harnessing deep reinforcement learning and path planning algorithms. As an illustration, environment mapping and fault diagnosis algorithms can assist in synthetic data creation across smart robotic environments as a result of the usefulness of multi-sensory extended reality and simulation modeling technologies for robotic navigation and context aware systems. Multiple smart agent behavior pattern clustering furthers IoRT and embedded intelligent systems in mobile edge computing environments, increasing economic performance due to deep convolutional neural and industrial wireless sensor networks. Specifically, image semantic segmentation, situation awareness, and tactile sensing object recognition, detection, and tracking enable deep neural network-based collaborative simulated robotic environment reconfiguration planning. Hierarchical digital twin production management, planning, and controlling are typically used in event processing, real-time anomaly and product complexity detection, and dynamic task scheduling in cyber-physical smart factories.

Business and economic applications indicate that machine learning and object recognition algorithms can be deployed in cyber-physical system-based smart factories (Carrión, 2024; Lyu & Fridenfalk, 2023; Starly *et al.*, 2023) for IoT-based decision support and product decision-making information systems as a result of the advancement of communication network and autonomous robotic technologies. All things considered, cloud computing and distributed sensing technologies are pivotal in dynamic unstructured environments for machine and deep learning algorithm-based real-time decentralized operational and data production processes throughout sensor-based production and decision support systems. Remote object identification and data acquisition tools, together with cognitive automation and edge computing technologies, assist the economic and business management of deep learning-assisted smart process planning by leveraging data stream clustering and computer vision algorithms in smart robotic environments. As a result, deep multi-agent reinforcement learning assists wireless networked multirobot and fault-tolerant control systems in digital twin fault monitoring, automated device identification and quality control, and operational production planning across multi-robot task scheduling and flexible production lines. Federated multi-agent reinforcement learning-based task scheduling optimization can be performed by multi-level preventive maintenance, dynamic job shop scheduling, and decentralized continuous cooperative control and anomaly detection.

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Interconnected IoRT and cloud-connected devices, visual perception and collision-free motion algorithms, and cyber-physical process monitoring and autonomous manufacturing support systems in generative AI-based digital twin industrial metaverse

Machine and deep learning algorithm-based manufacturing system network operations (Chang *et al*., 2022; Laviola *et al*., 2022; Yang *et al*., 2022) across generative AI-based digital twin industrial metaverse necessitate remote decision support and big data management tools for resilient production network scheduling. Equally important, context awareness and swarm intelligence algorithm-based robotic navigation processes can leverage coordinated motion planning and navigation management tools across product decision-making information and autonomous cognitive systems in generative artificial IoT-based cognitive manufacturing and virtual plant floor networks. Data-driven decision support in industrial wireless sensor and deep convolutional neural network-based smart manufacturing management necessitates predictive modeling and generative AI-based decision-making algorithms for cyber-physical production and embedded control systems. By comparison, digital twins-based reconfigurable robotic manufacturing system modeling and simulation entail recurrent neural networks and modular distributed AI for shop floor logistics and integrated process planning. Cloud-based digital twin sustainable reconfigurable manufacturing systems integrate time series data anomaly detection, resource sharing and scheduling, and job shop production quality control.

Obstacle avoidance trajectory planning and remote big data management tools in industrial asset interconnection and plant maintenance scheduling across smart robotic environments (Chen *et al*., 2023a; Keegan *et al*., 2024; Tlili *et al*., 2023) develop machine learning and data fusion algorithm-based interconnected IoRT and cloud-connected devices. As a matter of fact, object manipulation, tracking, and monitoring in production line management monitoring and diagnosis processes shape cyber-physical automation system performance of computation-enabled robotic and motion coordination devices throughout dynamic unstructured environments for cloud-based object tracking and plant maintenance scheduling by visual perception and collision-free motion algorithms. Multisensor fusion and ambient intelligence technologies for computer vision and object detection algorithm-based robotic vision and decision support systems optimize robotic coordination and cooperation in cyber-physical system-based smart factories, driving business value creation. Industrial Internet-based reconfigurable manufacturing systems on smart shop floors deploy digital twin deep multi-agent reinforcement learning and multi-access edge computing for integrated configuration design and resource scheduling. In the same fashion, collaborative dynamic production and flexible job-shop scheduling, automated process and production planning, data-driven predictive maintenance, and digital twin-based production line remote performance monitoring develop on cloud-based self-organizing manufacturing systems.

Remote sensing and machine learning algorithms (Chen *et al*., 2023b; Hong *et al*., 2024; Wang *et al*., 2024) enable real-time data processing and IoT-based real-time production logistics in synthetic simulation environments by multisensor fusion and edge computing technologies for big data management and distributed intelligence architecture. Equally important, mobile robotic and cloud computing technologies assist autonomous motion capture and digitalized production systems for product development and smart industrial manufacturing processes in collaborative manufacturing enterprise environments by harnessing steering control and environment mapping algorithms. Deep learning-based visual recognition and IoRT swarm technologies are leveraged in the economic and business management of industrial autonomous settings for data processing and computer vision algorithm-based cyber-physical process monitoring and autonomous manufacturing support systems. By the same token, digital twin-based cyber-physical production systems and computer vision and crowd sensing technologies design interoperable manufacturing network performance monitoring for production process interoperability. Cognitive automation technologies develop edge-cloud collaborative smart industrial operations and control systems in cyber-physical manufacturing enterprise interoperability by digital twin simulation, controlling, and monitoring for machine vision process monitoring and control.

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Autonomous navigation and robotized metaverse manufacturing systems, environment mapping and cloud computing algorithms, and geospatial data mining and predictive simulation tools in cyber-physical production system-enabled smart networked factories

Spatial data and real-time predictive analytics (Chen *et al*., 2023c; Liu *et al*., 2023; Stary, 2023) enhances the economic and business management of cloud-based digital twin smart industrial environments by leveraging multi-sensory extended reality and simulation modeling technologies for IoRT sensor networking. Nonetheless, cognitive decision-making and cooperative behavior algorithms for autonomous navigation and robotized manufacturing systems require 3D geospatial data in Industrial Internet of Senses and digital twin connected factories. Autonomous visual object detection and predictive modeling techniques in IoT-based real-time production logistics across big data-driven manufacturing control architectures integrate event modeling and forecasting tools by deep neural and robotic wireless sensor networks. As an illustration, IoT-based cloud manufacturing sensing and actuating devices and mobile edge computing optimize accurate anomaly detection and knowledge-based fault diagnosis for sustainable production operations across deep reinforcement learning blockchain-based industrial distributed networks. Industrial big data-driven multi-stage manufacturing control and process modelling supports multi-robot cooperative systems for event pattern diagnosability in production planning and scheduling on digital twin shop floors.

Business and economic applications indicate that embedded IoRT-based sensors optimize 4D dynamic navigation performance accuracy (with synthetic vision optimizing autonomous positioning, situation awareness, and collision detection and avoidance), deep learning-assisted smart process planning (for federated learning-based smart sustainable collaborative manufacturing, IoT sensing infrastructures, and knowledge-evolution machining features), and distributed task coordination in relation to digital twin-based machining process route planning (Chowdhury, 2023; Lee & Kundu, 2022; Tuli *et al*., 2024) across sustainable IoT-based manufacturing in smart factories and cyber-physical process monitoring systems in autonomous interconnected industrial units by wireless sensor–actuator and convolution neural networks. For this reason, the economic and business management of industrial metaverse requires generative AI-driven big data and real-time event analytics for situational awareness and deep reinforcement learning algorithm-based decision intelligence and product decision-making information systems in conjunction with object control and manipulation, production equipment and cyber-physical system-based real-time monitoring, and multiple smart agent behavior pattern clustering. Deep neural network robotized manufacturing processes rely on digital twin-based task rescheduling to perform motion planning and control in multirobot collaborative localization.

Image recognition and data fusion technologies configure the immersive economics of industrial metaverse (Chukwunonso Amaizu *et al*., 2024; Xinyi *et al*., 2023; Zheng *et al*., 2024) with regard to real-time process monitoring by geospatial data mining and predictive simulation tools, networked process mapping by environment mapping and cloud computing algorithms, and virtual path lines by deep learning-assisted smart process planning and smart shop floor monitoring. Notably, intelligent plant modules in cyber-physical system-based manufacturing develop on edge computing and machine learning algorithms for smart production and inventory allocation processes in manufacturing process monitoring and networked robotic systems by cloud computing and vision sensing technologies. Image detection and recognition tools further the economic and business management of industrial manufacturing settings by data processing and motion control algorithm-based industrial cyber-physical and acoustic environment recognition systems. Particularly, cloud imaging and remote big data management tools optimize industrial swarm robotic and computing device performance in localization and navigation systems for cognitive digital twin-based IoRT across manufacturing plants.

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IoRT-based geospatial simulation and product decision-making information systems, semantic computing and cloud-based operational technologies, and context awareness and distributed intelligence tools in the immersive economics of industrial metaverse

Obstacle detection and visual imagery technologies shape immersive industrial services and deep learning-based ambient sound processing (Cui *et al*., 2023; Mancuso *et al*., 2024; Yao *et al*., 2024) for IoRT-based geospatial simulation and product decision-making information systems. Cloud computing and big data analytics for cognitive digital twin-based IoRT in robotic manufacturing processes across smart networked environments leverages data mining and acquisition tools. As a result, real-time sensor data for virtual mapping and navigation tools can be deployed in decentralized data governance for machine performance in Industry 4.0-based manufacturing systems, increasing economic performance by spatial computing and geospatial big data management algorithms. Deep reinforcement learning-based smart manufacturing robotized systems operate for digital twin-driven IoT intelligent manufacturing business value creation through flexible job shop scheduling. All things considered, edge computing and data mining technologies strengthen operational resilience and decision support in production management throughout data-driven sustainable digital twin immersive industrial processes.

The immersive economics of industrial metaverse necessitates sensor and actuator networks in generative AI and cyber-physical manufacturing systems (Dzedzickis *et al*., 2024; Kshetri, 2023b; Zaidan *et al*., 2023) for real-time IoRT system 3D mapping, data mining and fusion, production system planning and monitoring, and robotic autonomous system navigation operations by obstacle avoidance and visual perception algorithms. By the same token, autonomous robotic and mobile navigation technologies in decentralized tracking and cyber-physical systems enable industrial IoRT connected and sensor data collection in real-time production scheduling. Cloud and fog computing technologies can be harnessed in synthetic simulation environments in relation to motion sensing capabilities, navigation tasks, and manufacturing process self-governing monitoring, driving business value creation across geolocation data intelligence and remote big data management by collision avoidance and situational awareness algorithms. Comparatively, multi-agent deep reinforcement learning ensures big data management capabilities of knowledge-based predictive maintenance on flexible assembly lines in multi-process intelligent manufacturing enterprises.

The immersive economics of industrial metaverse integrates ambient intelligence and deep reinforcement learning tools for data processing and visual perception algorithm-based autonomous operational and sustainable manufacturing processes (Endres *et al*., 2024; Jagatheesaperumal *et al*., 2023; Zhang *et al*., 2023) by use of industrial automation and machine perception technologies. By all means, environment mapping and generative AI-based decision-making algorithms articulate the economic and business management of Industry 4.0-related production environments with reference to real-time sensor and captured image data, deep learning-assisted smart process planning, and robotic coordination mechanisms, by deploying semantic computing and cloud-based operational technologies in big data-driven decision support and sustainable cyber-physical production systems. Particularly, cloud computing and wireless communication technologies shape production system interoperability in IoRT smart environments by path planning and computer vision algorithms for context awareness and distributed intelligence architecture.

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Context-adaptive decision support connected and generative AI data-driven IoT systems, multi-sensory extended reality and simulation modeling technologies, and object recognition and environment mapping algorithms in digital twin industrial metaverse

Autonomous manufacturing control and interconnected virtual services in digital twin industrial metaverse (Erman & Martino, 2023; Mahmoud *et al*., 2024; Sarwatt *et al*., 2024) develop on IoT sensing and sustainable Industry 4.0 wireless networks in semantic IoRT and cooperative unmanned systems by use of generative AI-based decision-making and mobile clustering algorithms. For this reason, cognitive digital twin-based IoRT in smart manufacturing and cyber-physical management systems can optimize interactive multi-robot team performance by visual recognition and biometric sensor technologies in dynamic unstructured environments. Situational and context awareness technologies in AI data-driven IoT and swarm robotic systems configure the immersive economics of industrial metaverse across intelligent sensor and unmanned robotic networks. As a result, industrial big data modeling supports business enterprise capabilities in performance prediction of labor productivity by sensor data fusion across big data machine learning and industrial AI of Things operations.

Sustainable Industry 4.0 wireless and IoT sensing networks are pivotal in distributed sensing units and in cyber-physical system-based smart factories (Fabra *et al*., 2024; Kaarlela *et al*., 2023b; Tantawi *et al*., 2024) with relevance to navigation process object recognition and detection by machine learning and environment mapping algorithms, real-time IoRT system 3D mapping by autonomous robotized and real-time sensor devices, and mobile robot detection and tracking movements by object identification and recognition tools. Specifically, cloud computing and semantic sensor technologies in mobile context awareness and decision support systems further sensor data sharing and fault diagnosis accuracy in IoRT environments by big data management and cognitive decision-making algorithms. For instance, image capturing and remote big data management tools in cyber-physical production and robotic operating systems can be deployed in collaborative manufacturing enterprise environments with reference to big data-driven decision-making operations, computation task cooperation, and task scheduling and execution, increasing economic performance by data visualization and collaborative localization techniques.

Multi-sensory extended reality and simulation modeling technologies in context-adaptive decision support connected and generative AI data-driven IoT systems (Ferrari & McKelvey, 2023; Hou *et al*., 2024; Ooi *et al*., 2023) assist the economic and business management of IoT-based real-time production logistics in connection with process monitoring system interoperability support, deep learning-assisted smart process planning, and sensor and actuator device control and diagnostics by path planning and visual perception algorithms. As an illustration, cognitive digital twin-based IoRT in context-aware and cyber-physical manufacturing systems requires intelligent data processing and object recognition tools for object recognition and networked process environment mapping. Visual and spatial intelligence tools in autonomous cyber-physical and blockchain-based IoRT systems optimize data visualization functionalities and smart connected device networking in interactive virtual environments by predictive modeling and image recognition algorithms. Cyber-physical system IoT blockchain-based multi-robot smart factory predictive operationalization enhances 6G industrial robotic services in autonomous swarm manufacturing.

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Deep learning-based object detection and remote sensing technologies, generative AI data-driven IoT and cyber-physical process monitoring systems, and predictive maintenance and smart environment modeling tools in the immersive economics of industrial metaverse

Behavioral predictive and big data analytics in the interactive economics of industrial metaverse (Gattullo *et al*., 2022; Magalhães *et al*., 2022; Wang *et al*., 2022) integrates deep learning-based object detection and remote sensing technologies for mobile robotic and industrial automation devices by use of cognitive manufacturing control algorithms. For this reason, remote sensing and immersive 3D technologies for deep learning-assisted smart process planning can be harnessed in big-data-driven cognitive manufacturing by object data modeling across blockchain-based Industrial IoT and robotic wireless sensor networks. Predictive maintenance and trajectory tracking tools for cognitive robotic and IoT smart devices in real-time monitoring industrial sensing and cyber-physical production systems articulate IoRT device management in cyber-physical system-based smart factories. Specifically, cognitive digital twin industrial data analytics fosters self-organizing multi-robot collaborative manufacturing networks by multi-agent reinforcement learning.

Industrial automation and object manipulation tools in autonomous robotic and semantic IoRT systems (Ghobakhloo *et al.*, 2024; Jauhiainen, 2024; Qu *et al.*, 2024) can be leveraged in the economic and business management of ambient sensing environments by obstacle avoidance and path planning algorithms with regard to big data-driven real-time production logistics, multi-scalable signal processing, and cyber-physical system-based real-time monitoring. In addition, predictive modeling and path planning tools in machine learning and remote sensing algorithm-based autonomous robotic and digital twin simulation systems shape control decisions and process planning for predictive smart manufacturing in cognitive production plants. By comparison, edge and fog computing technologies are instrumental in cognitive digital twin-based IoRT by environment mapping and context awareness algorithms in connection with object detection and recognition, sensor data distribution and processing-multi-robot cooperation, and swarm robot autonomous navigation in synthetic simulation environments, increasing economic performance by visual and spatial analytics.

The immersive economics of industrial metaverse (Grieves, 2023; Kumar *et al.*, 2024; Mourad *et al.*, 2023) necessitates multi-sensory extended reality and simulation modeling technologies in generative AI data-driven IoT and cyber-physical process monitoring systems by image processing and visual perception algorithms. Especially relevant is that cloud and networked robotic decision-making capabilities of autonomous cognitive and sensor fusion-based systems enable cognitive digital twin-based IoRT in intelligent simulation environments with regard to trajectory path and event detection, object location and mapping, and industrial asset interconnection by path planning and environment mapping algorithms. In addition, cloud computing and semantic sensor technologies enhance the economic and business management of deep learning-assisted smart process planning by image recognition and swarm intelligence algorithms and of smart factory automation by predictive maintenance and smart environment modeling tools in distributed interoperable environments.

Conclusions

Multi-sensory extended reality and simulation modeling technologies in robotic autonomous and motion capture systems can be deployed in complex operational machining process performance by visual perception and swarm intelligence algorithms across the economics of industrial metaverse for mobile robot trajectory tracking. Cloud processing and perceptual robotic capabilities of remote big data management and virtual manufacturing modeling tools assist remote interaction and mapping sensors in smart robotic environments. Generative AI planning-driven robotic cooperative behaviors and geospatial simulation tool-based 3D assembly operations require ambient environment monitoring of collaborative industrial environments by computer vision and spatial mapping algorithms.

Business and economic applications indicate that big data management and remote object intelligent identification tools in robotic operating and context aware systems optimize robot swarm decisional autonomy, fault diagnosis and handling, and connected object controling and monitoring by environment mapping and trajectory planning algorithms in Industry 4.0-based networked environments. Data mining and visualization tools in autonomous robotic and manufacturing process monitoring systems for cloud computing and smart manufacturing machines configure ambient sensing environments in the context of sensor data fusion, object manipulation, and manufacturing asset monitoring. Generative AI-based digital twin industrial metaverse develops on multi-sensory extended reality and simulation modeling technologies in IoRT and production management systems for big data-driven decision-making and image recognition processes by machine and deep learning algorithms.

With regard to business and economic relevance, signal processing and context recognition tools in Industry 4.0-based manufacturing and IoT-based decision support systems further smart IoRT environments by multi-sensory extended reality and simulation modeling technologies in connection with collision-free trajectories, continuous process monitoring, and autonomous task allocation. Policy and governance implications supported by machine learning and visual tracking algorithms show that image processing and remote big data management tools in cyber-physical production and industrial wireless sensor–actuator networks are pivotal in generative AI-based digital twin industrial metaverse. Future research should cover ambient intelligence and remote big data management tools in cloud-based robotic cooperation and industrial cyber-physical systems improving IoT-based real-time production logistics and cooperative multi-agent controls by environment mapping and spatial computing algorithms in smart networked factories.

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Data availability statement

All data generated or analyzed are included in the published article. The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation. The raw anonymized data can be provided by emailing the primary author.

Author contributions

All listed authors have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The authors take full responsibility for the accuracy and the integrity of the source analysis.

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