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ARTICLE

Information and Communication Technology for Efficient Operations Management: A Comprehensive Review, Research Gaps, and Strategic Framework

Attia Hussien Gomaa [1,*]

[1] Faculty of Engineering, Mechanical Engineering Department, Benha University, Cairo, Egypt

[*]Corresponding author. Email: attia.goma@feng.bu.edu.eg

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Abstract

The rapid evolution of Information and Communication Technology (ICT) is transforming operations management (OM), driving efficiency, agility, and competitiveness. Traditional systems—such as Enterprise Resource Planning (ERP), Supply Chain Management (SCM), and Decision Support Systems (DSS)—are increasingly enhanced by Industry 4.0 technologies, including artificial intelligence, the Internet of Things, blockchain, and digital twins. Yet, ICT adoption in OM remains fragmented, challenged by technological limitations, organizational misalignment, workforce skill gaps, and systemic vulnerabilities. This study presents a comprehensive review of ICT applications in operations management, with emphasis on production planning, logistics, quality management, and performance optimization. The challenges of ICT adoption are classified into four dimensions: technological, organizational, human-centric, and systemic. Despite ICT's transformative potential, critical gaps remain, including the absence of integrated performance evaluation frameworks, limited incorporation of sustainability and ethics, and insufficient adaptability of ICT models across diverse industrial and socio-economic contexts. To address these shortcomings, the study introduces a strategic framework structured around five pillars: technological infrastructure, organizational alignment, human-centric development, systemic and ethical integration, and continuous improvement. This framework positions ICT as a catalyst for operational excellence, resilience, and sustainable value creation, while bridging theoretical foundations with practical applications to accelerate digital transformation in operations management.

Keywords: Information and Communication Technology (ICT); Operations Management; Supply Chain Management; Digital Transformation; Industry 4.0; Industry 5.0

1. INTRODUCTION

Information and Communication Technology (ICT) refers to a diverse set of technologies that enable the creation, access, management, and dissemination of information across multiple communication networks, as shown in Figure 1. Beyond its technical applications, ICT serves as a key driver of digital transformation, facilitating knowledge exchange and promoting socio-economic development. The concept of ICT was first formalized by the Natural Resources, Energy, and Science Authority of Sri Lanka [1].

In the era of digital transformation, ICT has become a cornerstone of economic development, industrial competitiveness, and organizational sustainability. By enabling the collection, processing, storage, and exchange of information across global networks, ICT reshapes how organizations operate, collaborate, and innovate. Its applications extend beyond efficiency, serving as a driver of agility, resilience, and long-term competitiveness in increasingly volatile and interconnected markets. At the operational level, ICT improves visibility, accuracy, and coordination in logistics, inventory management, and production scheduling. Strategically, it enhances decision-making, fosters collaboration across the value chain, and supports adaptability in response to market shifts. ICT also enables the creation of new

distribution channels and niche markets that were previously difficult to access, functioning as both a technological enabler and a strategic lever for sustained competitive advantage [2].

Artificial Intelligence (AI) systems are inherently data-driven, relying on continuous information streams to strengthen decision-making, predictive accuracy, and organizational adaptability. When integrated with ICT, AI-driven decision support systems enhance managerial capacity by deepening analytical insights, enabling real-time knowledge exchange, and supporting agile responses to dynamic market conditions. This convergence improves operational efficiency and strategic foresight through scenario modeling, pattern recognition, and optimized resource allocation, while ICT simultaneously streamlines product flows, services, and information management in real time. Encompassing a wide spectrum of computing and telecommunication technologies—including hardware, software, and digital infrastructures—ICT underpins the Internet, cloud computing, and the Internet of Things (IoT), with emerging platforms such as blockchain, digital twins, and the metaverse further expanding its scope. Through its convergence with AI, big data, and cyber-physical systems, ICT accelerates the transition toward Industry 4.0 and 5.0, positioning itself as the backbone of intelligent, human-centric, and sustainable industrial ecosystems. Nonetheless, enduring concerns over transparency, accountability, data privacy, bias, and ethical governance highlight the need for robust frameworks that foster trust, fairness, and sustainable organizational value [3].

The evolution of Operations Management (OM) illustrates ICT's transformative role. Traditional systems such as Management Information Systems (MIS) and Material Requirements Planning (MRP) provided limited scheduling functions. The emergence of Enterprise Resource Planning (ERP) systems integrated core functions, while Supply Chain Management (SCM), Customer Relationship Management (CRM), and e-business platforms extended integration across organizational boundaries. More recently, Decision Support Systems (DSS) and Business Intelligence (BI) tools have strengthened forecasting, resource allocation, and strategic planning. Today, ICT has evolved from a supportive function to the strategic backbone of OM, enabling real-time monitoring, collaborative decision-making, and sustainable resource management. In sectors such as construction, ICT also facilitates circular economy initiatives by integrating design, production, usage, and end-of-life stages, promoting reuse and responsible material management [4].

Digitalization and Industry 4.0 technologies—including IoT, AI, blockchain, cloud computing, and digital twins—have further redefined ICT's role in OM. Smart, interconnected, and adaptive systems now support predictive and prescriptive decision-making, allowing firms to anticipate disruptions, respond with agility, and dynamically optimize performance. Beyond efficiency, ICT has become critical for resilience and sustainability, both essential in volatile, uncertain, complex, and ambiguous (VUCA) environments [5].

Despite these advances, research on ICT in OM remains fragmented. Most studies focus on isolated systems rather than ICT's systemic role in integrating operations. While efficiency and coordination benefits are well established, emerging priorities such as sustainability, resilience, circular economy integration, and human–technology collaboration remain underexplored. Moreover, few frameworks link ICT adoption with organizational capabilities, competitiveness, and long-term value creation, limiting both theoretical understanding and managerial practice.

To address these gaps, this study addresses three objectives. First, it reviews ICT applications in Operations Management. Second, it identifies critical research gaps. Third, it proposes a strategic framework positioning ICT as a driver of operational excellence.

The remainder of this paper is organized as follows. Section 2 reviews ICT applications in Operations Management. Section 3 highlights critical research gaps, and Section 4 presents a strategic framework positioning ICT as a driver of operational excellence. Section 5 concludes by summarizing theoretical and practical contributions and suggesting directions for future research.

Figure 1. Information Communication Technology (ICT) Concept.

2. LITERATURE REVIEW ON ICT IN OPERATIONS MANAGEMENT

Information and Communication Technology (ICT) has evolved from a supportive infrastructure into a strategic enabler of competitiveness, resilience, and sustainability in Operations Management (OM). By facilitating the collection, processing, and real-time exchange of data, ICT enhances visibility, coordination, and informed decision-making, allowing firms to move from reactive problem-solving to predictive and prescriptive intelligence. Initially, ICT applications focused on efficiency and cost reduction through systems such as Enterprise Resource Planning (ERP), Management Information Systems (MIS), and cloud platforms. Over time, ICT capabilities expanded to enable real-time monitoring, predictive analytics, and integrated decision-making, underpinning intelligent, adaptive, and resilient operational processes [6].

ICT is also central to modern Supply Chain Management (SCM), transforming fragmented networks into integrated, collaborative systems. Studies show that ICT improves information accuracy, reduces transaction costs, enhances responsiveness, and strengthens coordination across suppliers, manufacturers, and distributors [7-10]. Beyond operational efficiency, ICT fosters knowledge management, innovation, and organizational learning, particularly when supported by leadership, cultural readiness, and workforce engagement [11,12]. ICT thus serves as a strategic backbone for operational efficiency, supply chain integration, and readiness for Industry 4.0 and 5.0 technologies.

The advent of Industry 4.0 has amplified ICT's role, providing the foundation for IoT, artificial intelligence (AI), cyber-physical systems (CPS), cloud computing, and blockchain [13,14]. These technologies enable real-time monitoring, predictive maintenance, and data-driven decision-making, enhancing operational efficiency, agility, and resilience. Industry 5.0 further extends ICT to human-centric, sustainable, and ethical operations, leveraging infrastructures such as 5G/6G, edge computing, and quantum-enabled systems [15,16].

Emerging ICT applications, including digital twins, predictive analytics, and blockchain, strengthen lifecycle optimization, transparency, and supply chain resilience. Adoption challenges persist, especially for SMEs, and holistic frameworks that align agility, resilience, and human-centric principles remain limited. Organizations must integrate technology adoption with leadership, workforce development, and sustainability strategies to fully harness ICT's potential [17-19].

Operations Management 4.0 (OM 4.0) represents a transition from linear operations to intelligent, autonomous, and interconnected systems. Enabling technologies—IoT, AI, CPS, digital twins, big data analytics, and cloud computing—support predictive maintenance, adaptive control, and dynamic process optimization. When combined with Lean, Agile, and Six Sigma (DMAIC) methodologies, these technologies enhance operational flexibility, responsiveness, and decision-making precision. Cloud computing integrated with machine learning optimizes resource allocation and production scheduling [20-22], while CPS and digital twins enhance operational visibility, control, and simulation-based optimization [23-25]. AI and ML facilitate predictive maintenance, fault detection, and intelligent scheduling, reducing downtime and improving productivity [26,27], and IoT enables real-time monitoring, adaptive manufacturing, and sustainability [28-30]. Fuzzy logic and other advanced methods help manage uncertainty and strengthen operational resilience [31]. Collectively, these technologies transform operations into intelligent, data-driven systems capable of sustaining competitive advantage.

SCM 4.0 leverages ICT to create agile, transparent, and collaborative supply networks. Core technologies include IoT and CPS for real-time monitoring and decentralized control [32,33], AI and machine learning for autonomous decision-making and adaptive planning [34,35], blockchain for secure, immutable, and transparent data exchange supporting trust and ESG compliance [36], and advanced analytics for inventory optimization, risk mitigation, and strategic decision-making [37,38]. Cloud and edge computing provide scalable infrastructure, system integration, and enhanced collaboration [39,40]. Recent research emphasizes the integration of Lean principles with digital technologies, embedding waste reduction, value stream mapping, and continuous improvement with advanced ICT tools. Sustainability and circular economy practices are increasingly embedded in SCM 4.0, aligning digital innovation with environmental, social, and governance (ESG) objectives [41,42].

Despite extensive adoption, literature reveals fragmentation and a lack of unified frameworks linking OM and SCM transformations. Many studies are technology-centric, overlooking the integration of digital capabilities with organizational structures, workforce competencies, and strategic objectives. To address these gaps, Gomaa [43,44] proposed comprehensive frameworks integrating AI, IoT, blockchain, digital twins, and autonomous systems within Lean, Agile, and DMAIC methodologies. These frameworks emphasize predictive maintenance, smart forecasting, cybersecurity, workforce upskilling, and sustainable transformation, demonstrating ICT's strategic value in achieving operational excellence, resilience, and sustainability.

In summary, ICT has transitioned from a supporting technology to a strategic cornerstone of OM and SCM, driving competitiveness, integration, resilience, and sustainability. Future success depends on embedding ICT within holistic strategies that align technology, leadership, organizational culture, and sustainability principles. Such integration enables firms to thrive in human-centric, resilient, and sustainable Industry 5.0 and 6.0 ecosystems, leveraging ICT as a central driver of digital transformation, strategic decision-making, and long-term value creation.

Table 1 presents a comprehensive overview of key Information and Communication Technology (ICT) components and their operational and strategic roles across Operations Management (OM) and Supply Chain Management (SCM). It demonstrates how traditional and emerging digital technologies—from ERP and MIS systems to Industry 5.0–oriented tools—enable organizations to enhance efficiency, integration, resilience, and sustainability. By linking operational applications to strategic outcomes, the table highlights ICT's dual role as both a functional enabler and a driver of organizational competitiveness [43,44].

Enterprise systems, including ERP, MIS, and cloud platforms, underpin OM and SCM integration by supporting production scheduling, resource allocation, and inventory coordination, while enhancing real-time decision-making and process efficiency [20-22]. Cyber-Physical Systems (CPS) and digital twins further enable real-time monitoring, predictive maintenance, and process simulation in OM, alongside smart logistics and scenario planning in SCM [23-25,45], providing transparency, lifecycle optimization, and operational agility.

Artificial Intelligence (AI) and Machine Learning (ML) facilitate predictive maintenance, fault detection, intelligent scheduling, demand forecasting, autonomous planning, and inventory optimization, enhancing data-driven decision-making, responsiveness, and risk mitigation [23,26,27,46]. IoT and sensor networks complement these capabilities by enabling real-time material and goods tracking, improving visibility, responsiveness, and cross-functional coordination in both OM and SCM [28-30,32,33].

Blockchain and smart contracts support secure, transparent transactions and supply chain traceability [36], while Big Data and advanced analytics facilitate forecasting, scenario simulation, and performance monitoring [37,38]. Cloud and edge computing provide scalable infrastructure for distributed processing, system integration, and collaborative platforms, enhancing operational agility and connectivity [39,40].

Emerging technologies, including AR/VR, 5G/6G networks, autonomous vehicles, and human-centric collaborative platforms, expand ICT's strategic impact. AR/VR supports operator training and process simulation [19], 5G/6G ensures low-latency IoT communications [14,15], autonomous vehicles optimize material handling and last-mile delivery [32,35], and human-centric platforms enhance decision support, workflow coordination, and innovation [16,47].

Lean and continuous improvement methodologies integrated with digital technologies support waste reduction, process optimization, and value stream mapping [48]. Sustainability- and circular economy–oriented ICT tools embed ESG principles, lifecycle management, and resource efficiency across OM and SCM, reinforcing resilience and long-term competitiveness [17-19,41,42]. Advanced Planning and Scheduling (APS) systems further improve operational efficiency and responsiveness through multi-tier optimization and dynamic scheduling [49,50].

Overall, Table 1 underscores that ICT has evolved from a supportive tool into a strategic cornerstone of modern operations and supply chain management. By integrating traditional, Industry 4.0, and emerging Industry 5.0 technologies, organizations can achieve intelligent, adaptive, and sustainable operations, bridging technology adoption with leadership, workforce engagement, and long-term strategic objectives [43,44].

Table 1. ICT Technologies and Their Operational and Strategic Roles in OM and SCM.

#	ICT Component / Technology	Applications in OM	Applications in SCM	Strategic Role	Representative Studies
1	Enterprise Systems (ERP, MIS, Cloud)	Production scheduling, resource allocation, cost control	Integrated planning, inventory coordination	Efficiency, integration, and real-time decision-making	Cao et al. (2016); Wang et al. (2018); Tripathi et al. (2022)
2	Cyber-Physical Systems (CPS) & Digital Twins	Real-time monitoring, predictive maintenance, process simulation	Smart logistics, scenario planning, predictive maintenance	Transparency, lifecycle optimization, agility, resilience	Frazzon et al. (2017); Tan et al. (2019); Lee et al. (2020); Eunike et al. (2022); Liu et al. (2023)
3	Artificial Intelligence & Machine Learning	Predictive maintenance, fault detection, and intelligent scheduling	Demand forecasting, autonomous planning, and inventory optimization	Data-driven decisions, adaptive operations, risk mitigation	Morariu et al. (2020); Serrano-Ruiz et al. (2022); Teoh et al. (2021); Frazzon et al. (2019); Helo & Hao (2022); Mhaskey (2024)
4	Internet of Things (IoT) & Sensors	Smart manufacturing, material tracking, and real-time monitoring	Real-time tracking of goods, warehouse monitoring, and fleet management	Visibility, responsiveness, connectivity	Li et al. (2017); Ren et al. (2018); Tripathi et al. (2021, 2022); Tjahjono et al. (2017); Pasi et al. (2020)
5	Blockchain & Smart Contracts	Secure, tamper-proof production records	Traceability, supplier verification, secure transactions	Trust, transparency, ESG compliance	Wang et al. (2023)
6	Big Data & Advanced Analytics	Forecasting, scenario simulation, KPI monitoring	Disruption detection, predictive inventory, risk analysis	Strategic decision-making, performance monitoring	Patel (2023); Saif-Ur-Rehman et al. (2024)
7	Cloud & Edge Computing	Distributed processing, system integration, collaboration	Integrated data sharing, collaborative platforms	Scalability, operational agility, seamless connectivity	Hofmann et al. (2019); Mhaskey (2024)
8	Lean & Continuous Improvement Integration	Waste reduction, value stream optimization	Process standardization, operational alignment	Operational excellence, alignment with digital transformation	Rossini et al. (2023)

Table 1 (Continued). ICT Technologies and Their Operational and Strategic Roles in OM and SCM.

#	ICT Component / Technology	Applications in OM	Applications in SCM	Strategic Role	Representative Studies
9	Sustainability & Circular Economy Tools	Lifecycle management, waste minimization, resource efficiency	Resource tracking, circular practices, ESG reporting	ESG alignment, resilience, and long-term competitiveness	Demestichas & Daskalakis (2020); Yu et al. (2022); Liu et al. (2023); Chauhan et al. (2022); Samper et al. (2022)
10	Augmented Reality (AR) & Virtual Reality (VR)	Operator training, maintenance guidance	Visual planning, warehouse training, simulation	Workforce upskilling, safety, and operational efficiency	Liu et al. (2022)
11	5G/6G & High-Speed Networks	Real-time data transfer, remote monitoring	Low-latency logistics communication, IoT enablement	Connectivity, responsiveness, coordination	Sigov et al. (2024); Peraković et al. (2019)
12	Human-Centric & Collaborative Platforms	Decision support, workflow coordination, team collaboration	Supplier coordination, knowledge sharing, workflow optimization	Employee engagement, innovation, human–technology synergy	Pozzi et al. (2023); Mubarik & Khan (2024)
13	Autonomous Vehicles & Robotics	Automated material handling, shop floor robotics	Automated warehousing, last-mile delivery	Operational efficiency, faster cycle times, and cost reduction	Helo & Hao (2022); Tjahjono et al. (2017)
14	Advanced Planning & Scheduling Systems (APS)	Production scheduling, resource allocation	Multi-tier optimization, dynamic scheduling	Operational efficiency, responsiveness, integration	Fatorachian & Kazemi (2021); Govindan et al. (2022)

3. CHALLENGES AND RESEARCH GAPS ANALYSIS

The adoption of ICT in Operations Management (OM) and Supply Chain Management (SCM) offers substantial opportunities for improving efficiency, agility, and competitiveness, yet it also presents complex challenges. Table 2 organizes these challenges into four dimensions: Technological, Organizational, Human-Centric, and Systemic & Ethical. This categorization highlights the multifaceted nature of ICT integration, encompassing technical limitations, organizational readiness, workforce capability, ethical considerations, and systemic vulnerabilities. Understanding these challenges provides a foundation for developing targeted strategies and identifying critical research gaps.

Technological challenges include integration and interoperability issues, as legacy systems and heterogeneous platforms often fail to communicate effectively, creating fragmented data flows and costly integration efforts. Cybersecurity and data privacy risks are elevated, exposing organizations to attacks, breaches, and compliance violations. Data overload and inconsistent quality from IoT, ERP, and cloud systems reduce analytics reliability, while system reliability and real-time responsiveness are critical, as downtime and unstable infrastructures hinder monitoring, control, and rapid decision-making.

Organizational challenges involve high adoption costs, particularly for SMEs, and difficulties in measuring intangible benefits such as agility, resilience, and collaboration. Limited digital literacy, weak strategic alignment, and resistance to change among employees and managers can further impede ICT-driven transformation, especially when workflows and roles are disrupted.

Human-centric challenges emphasize workforce readiness and cultural alignment. Skill gaps and insufficient training slow adoption, while cultural resistance may hinder acceptance of ICT-driven processes. Over-automation risks marginalizing human judgment, raising concerns about accountability, trust, and engagement.

Systemic and ethical challenges address sustainability, governance, and societal impact. ICT expansion increases energy use and e-waste, posing environmental pressures and complicating circular economy objectives. Regulatory complexity and misaligned standards across stakeholders challenge governance and collaboration. Ethical concerns—including workforce displacement, algorithmic bias, and transparency—underscore the need for responsible ICT deployment. Crisis events, such as the COVID-19 pandemic, have further exposed ICT vulnerabilities, revealing risks in supply chain continuity, cybersecurity, and remote operations.

In conclusion, ICT adoption in OM and SCM represents a multidimensional challenge requiring integrated strategies that align technology, organizational processes, workforce capabilities, and ethical governance. Effectively addressing these challenges enables organizations to leverage ICT as a strategic enabler of operational excellence, resilience, and sustainable competitive advantage, while highlighting critical areas for future research to support holistic and scalable solutions.

Table 2. Challenges in ICT-Enabled Operations Management.

Category	Challenge	Description
Technological	Integration & Interoperability	Legacy and heterogeneous systems often lack compatibility, creating fragmented data flows and costly integration efforts.
	Cybersecurity & Data Privacy	Digitalization increases exposure to cyberattacks, breaches, and compliance risks threatening operational continuity.
	Data Quality & Overload	Large volumes of IoT, ERP, and cloud data are often inconsistent or inaccurate, limiting analytics reliability.
	System Reliability & Real-Time Response	Downtime, latency, and unstable infrastructures hinder monitoring, control, and rapid decision-making.
Organizational	High Adoption Costs	Investments in infrastructure, software, and training can be prohibitive, especially for SMEs.
	Measuring Value & ROI	Conventional metrics often fail to capture benefits such as agility, resilience, and collaboration, complicating justification.
	Leadership & Change Management	Limited digital literacy and weak alignment hinder leaders from driving ICT transformation.
	Resistance to Change	Workforce reluctance arises from disruption, shifting roles, or perceived loss of autonomy.
Human-Centric	Workforce Skill Gaps	Specialized skills are required for ICT adoption, but training and upskilling often lag.
	Cultural Misalignment	ICT-driven processes may conflict with existing norms, slowing acceptance and implementation.
	Human–Technology Balance	Over-automation can marginalize human judgment, raising accountability and trust concerns.
Systemic & Ethical	Sustainability & Environmental Impact	ICT expansion increases energy use and e-waste, challenging environmental and circular economy goals.
	Regulatory Complexity	Evolving global regulations complicate governance, compliance, and cross-border ICT deployment.
	Stakeholder Coordination	Digital ecosystems often face misaligned standards and maturity levels among suppliers, regulators, and customers.
	Ethical & Social Concerns	Issues like workforce displacement, algorithmic bias, and transparency affect fairness and inclusiveness.
	Crisis Vulnerabilities	Events like COVID-19 reveal ICT fragility in supply chains, cybersecurity, and remote operations.

Table 3 outlines key operational amendments addressing challenges in ICT-enabled Operations Management (OM) and Supply Chain Management (SCM), organized into four dimensions. The main insights are as follows:

1) Knowledge & Awareness: Digitized training and awareness programs enhance workforce ICT literacy, operational coordination, and efficiency. Future research opportunities include AI-driven adaptive learning and continuous upskilling to further strengthen human capital in digital operations.

2) Data & Information Management: Challenges such as time zone inconsistencies, incorrect workload sheets, and undefined constraints are mitigated through online systems, data validation, and digitized information transfer. These measures ensure accurate, synchronized data, faster decision-making, and optimized workflows. Research directions include predictive AI for workload allocation and real-time global data synchronization.

3) Resource & Operations Management: Issues such as resource unavailability, frequent production goal changes, manual scheduling, and decentralized stores are addressed via real-time reporting, monitoring, and remote data access. Benefits include improved utilization, flexibility, and responsiveness.

Future research may focus on IoT-enabled resource management, AI-driven scheduling, and blockchain-based inventory tracking.

4) ICT Infrastructure & Guidelines: Missing ICT components and outdated protocols are resolved through cloud computing and digitized guidelines, enabling scalable, reliable, and standardized operations. Future directions include hybrid cloud architectures and AI-supported knowledge management systems.

Overall, these amendments demonstrate that effective ICT-enabled operations require integrated strategies across technological, organizational, human, and systemic dimensions, enhancing performance, resilience, and innovation.

Table 3. ICT-Enabled Operational Enhancements and Research Directions.

Category	Issue	Impacted Areas	Solution	Benefits	Performance Impact	Research / Future Directions
Knowledge & Awareness	Knowledge gaps	Data handling, operations, and workforce	Digital training & awareness	Improved ICT literacy	Fewer errors, better coordination	AI-driven adaptive learning & continuous upskilling
Data & Information Management	Time zone inconsistencies	Production, workflow, data accuracy	Online information systems	Synchronized global data	Faster decisions, reduced delays	Real-time global synchronization via cloud/edge computing
	Incorrect workload sheets	Resource planning, operations setup	Online data validation	Accurate task allocation	Higher productivity, less rework	AI-driven predictive workload allocation
	Undefined constraints	Workforce, machinery, operations	Digital information transfer	Clear operational guidelines	Reduced bottlenecks, optimized workflow	Adaptive constraint modeling & decision-support tools
Resource & Operations Management	Resource unavailability	Operational objectives	Real-time reporting	Timely allocation	Reduced downtime, improved utilization	IoT-enabled predictive resource management
	Frequent changes in production goals	Product quality, standardization	Real-time reporting	Rapid adaptation	Increased flexibility, fewer defects	Predictive analytics with dynamic goal management
	Manual scheduling	Workforce, equipment, completion times	Real-time monitoring	Automated scheduling	Higher throughput, reduced idle time	AI-enabled self-optimizing scheduling
	Decentralized stores	Inventory, production timing	Remote data access	Centralized control	Streamlined inventory, faster response	Blockchain-enabled inventory tracking
ICT Infrastructure & Guidelines	Missing ICT components	Configuration, databases, processes	Cloud-based solutions	Scalable, integrated environment	Reliable systems, better collaboration	Hybrid and cloud-native architectures
	Outdated guidelines	Process authenticity, allocation accuracy	Digitized guidelines	Standardized protocols	Consistent quality, improved compliance	AI-supported guideline updates & knowledge management

Table 4 highlights the key research gaps in ICT-enabled Operations Management (OM) across four domains: Technological Integration, Organizational Strategy, Human-Centric Capabilities, and Systemic & Ethical Considerations.

1) Technological Integration: ICT-enabled operations face challenges with legacy systems, fragmented platforms, and the absence of standardized protocols. Cybersecurity research remains largely IT-focused, often overlooking sector-specific vulnerabilities. High-volume, multi-source data frequently lacks real-time validation and governance, while existing decision-support tools are primarily descriptive, limiting predictive and prescriptive capabilities. Addressing these gaps requires interoperable architectures, adaptive cybersecurity frameworks, AI-driven data quality management, and integrated platforms for predictive and prescriptive analytics.

2) Organizational Strategy: Key organizational challenges include inadequate ICT value measurement, leadership and change management deficiencies, and insufficient attention to SME adoption. Traditional metrics often fail to capture intangible benefits such as agility, resilience, and innovation. Cultural resistance and low digital maturity impede transformation, while most adoption frameworks focus on large firms. Research should prioritize multidimensional performance metrics, leadership and cultural strategies, and scalable ICT frameworks for SMEs.

3) Human-Centric Capabilities: Workforce skill gaps, limited understanding of human–technology interaction, and overlooked socio-cultural contexts constrain ICT adoption. Research should focus on adaptive reskilling programs, socio-technical models balancing automation and human oversight, and context-sensitive approaches to improve ICT acceptance and sustainability.

4) Systemic & Ethical Considerations: Lifecycle sustainability, fragmented regulations, algorithmic bias, and vulnerability to global disruptions remain pressing concerns. Research directions include sustainability assessment frameworks, harmonized governance policies, ethical ICT design, and resilient ICT architectures to address environmental, social, and operational risks.

Collectively, these domains underscore the need for integrated frameworks aligning technology, organizational strategy, human capability, and ethical governance, enabling ICT to drive operational excellence, resilience, and sustainable competitive advantage.

Table 4. Key Research Gaps in ICT-Enabled Operations Management.

Domain	Identified Gap	Underlying Cause	Strategic Research Direction
Technological	ICT–Operations Integration	Legacy systems, fragmented platforms, and lack of standards	Develop modular, interoperable architectures with standardized integration protocols
	Cybersecurity	IT-focused research neglects sector-specific vulnerabilities	Design adaptive cybersecurity frameworks for production systems, supply chains, and critical assets
	Data Quality & Governance	Multi-source, high-volume data lacks real-time validation	Implement AI-driven frameworks for continuous data quality management and governance
	Real-Time Decision Support	Tools are primarily descriptive with limited predictive capabilities	Develop integrated platforms combining predictive, prescriptive, and adaptive analytics
Organizational	ICT Value Measurement	Traditional metrics overlook agility, resilience, and innovation	Create multidimensional ICT performance metrics capturing tangible and intangible benefits
	Change Management	Leadership gaps, cultural resistance, and low digital maturity hinder adoption	Explore leadership models, maturity frameworks, and cultural strategies for ICT transformation
	SME-Oriented Adoption	Frameworks focus on large firms, neglecting SMEs	Develop scalable, cost-effective ICT adoption models suitable for SMEs
Human-Centric	Workforce Skills & Reskilling	Persistent skill gaps due to limited training and weak HR–ICT alignment	Design adaptive lifelong learning and reskilling programs for digital operations
	Human–Technology Interaction	Limited understanding of trust, accountability, and decision-making	Develop socio-technical models balancing automation efficiency with human oversight
	Socio-Cultural Factors	Cultural and regional contexts are often overlooked	Conduct cross-cultural, context-sensitive studies on ICT acceptance and sustainability

Table 4 (Continued). Key Research Gaps in ICT-Enabled Operations Management.

Domain	Identified Gap	Underlying Cause	Strategic Research Direction
Systemic & Ethical	ICT Sustainability	Lifecycle impacts (energy, e-waste, emissions) remain underexplored	Develop sustainability assessment models (e.g., LCA, circular ICT frameworks)
	Governance & Regulatory Alignment	Fragmented regulations hinder compliance and interoperability	Propose harmonized ICT governance and cross-national regulatory frameworks
	Ethical & Inclusive Design	Algorithmic bias, limited transparency, and workforce exclusion persist	Advance ethical, transparent, and inclusive ICT frameworks
	Resilience to Global Disruptions	Vulnerable to pandemics, climate risks, and geopolitical crises	Design adaptive, resilient ICT architectures for systemic disruptions

4. STRATEGIC FRAMEWORK FOR ICT-ENABLED OPERATIONS MANAGEMENT

The strategic framework for ICT-enabled Operations Management (OM) is organized around five interrelated pillars that address technological, organizational, human-centric, ethical, and continuous improvement dimensions. It offers a structured roadmap to overcome ICT adoption challenges, align advanced technologies with organizational strategy, and enhance operational resilience and sustainability. Table 5 summarizes the framework, detailing each pillar's objectives and strategic priorities.

1) Technological Infrastructure: This pillar focuses on building a secure, interoperable, and future-ready ICT foundation. Key priorities include modular architectures that integrate legacy and emerging systems, AI-driven data governance, predictive and prescriptive analytics via digital twins and big data, and cybersecurity-by-design. By addressing integration, interoperability, and real-time decision-making challenges, it enables proactive operations, reduced downtime, and enhanced system resilience.

2) Organizational Alignment: Aligning ICT with strategy, culture, and performance systems ensures investments deliver both tangible and intangible benefits. Priorities include developing multidimensional performance frameworks, strengthening digital leadership, supporting scalable adoption for SMEs, and integrating operations across supply chains, production, and asset management. This pillar addresses leadership gaps, cultural resistance, and ROI measurement challenges, ensuring ICT drives enterprise-wide operational improvements.

3) Human-Centric Development: People are central to digital transformation. This pillar emphasizes adaptive reskilling and upskilling programs, balanced human–technology collaboration, and culturally sensitive training and adoption strategies. It directly addresses workforce skill gaps, cultural misalignment, and risks from over-automation, fostering engagement, trust, and effective ICT adoption.

4) Systemic & Ethical Integration: Embedding ICT within sustainable, ethical, and resilient operational ecosystems is crucial. Key priorities include green ICT practices, harmonized governance for regulatory compliance, ethical design principles, and resilient infrastructures against cyber, environmental, and geopolitical risks. This pillar mitigates systemic and ethical challenges while promoting responsible and sustainable operations.

5) Continuous Improvement & Feedback: Adaptability requires iterative learning and monitoring. This pillar highlights real-time benchmarking, feedback systems, Lean ICT, and Kaizen 4.0 practices, alongside collaboration with industry, academia, and policymakers. Continuous improvement ensures agility, resilience, and alignment with emerging digital innovations.

In conclusion, ICT has evolved from a supportive tool into a strategic enabler of Operations and Supply Chain Management, enhancing efficiency, integration, resilience, and sustainability. As illustrated in Table 5, this framework integrates technological, organizational, human-centric, ethical, and continuous improvement dimensions into a cohesive roadmap. By addressing technological, organizational, human, and systemic challenges, organizations can transform operations into intelligent, adaptive, and resilient systems, achieving sustainable competitive advantage and readiness for Industry 4.0 through Industry 6.0.

Table 5. Strategic Framework for ICT-Enabled Operations Management.

#	Pillar	Objective	Strategic Priorities
1	Technological Infrastructure	Build a secure, interoperable, and future-ready ICT foundation.	• Develop modular architectures integrating legacy and emerging systems. • Implement AI-driven data governance for accuracy and traceability. • Deploy predictive and prescriptive analytics via digital twins and big data. • Embed cybersecurity-by-design to ensure resilience in connected environments.
2	Organizational Alignment	Align ICT deployment with strategy, culture, and performance objectives.	• Establish ICT performance frameworks covering efficiency, agility, resilience, and sustainability. • Strengthen digital leadership and change management. • Provide scalable, cost-effective ICT adoption pathways for SMEs. • Ensure enterprise-wide integration across supply chain, production, and asset management.
3	Human-Centric Development	Empower the workforce as active participants in digital transformation.	• Launch adaptive reskilling and upskilling programs supported by AI. • Promote human–technology collaboration in decision-making. • Customize training and adoption strategies to organizational and cultural contexts. • Enhance trust, engagement, and accountability in ICT-enabled operations.
4	Systemic & Ethical Integration	Embed ICT within sustainable, ethical, and resilient operational ecosystems.	• Adopt green ICT practices to reduce energy use, emissions, and e-waste. • Ensure compliance through harmonized governance and regulatory frameworks. • Integrate ethical principles (transparency, inclusiveness, fairness) into ICT design. • Build infrastructures resilient to cyber, environmental, and geopolitical risks.
5	Continuous Improvement & Feedback	Foster adaptability through iterative learning and innovation.	• Implement real-time monitoring, benchmarking, and feedback mechanisms. • Apply Lean ICT and Kaizen 4.0 for continuous process optimization. • Promote collaboration among industry, academia, and policymakers to accelerate knowledge sharing and best practices.

5. CONCLUSION AND FUTURE WORK

This study examines the evolving role of Information and Communication Technology (ICT) in operations management (OM), highlighting its transformative impact on efficiency, agility, resilience, and sustainability. It reviews ICT applications across production planning, logistics, quality management, and performance optimization, showing how ICT has advanced from traditional systems—such as Enterprise Resource Planning (ERP), Supply Chain Management (SCM), and Decision Support Systems (DSS)—to digital ecosystems powered by Industry 4.0 technologies, including artificial intelligence (AI), the Internet of Things (IoT), blockchain, digital twins, and advanced analytics. These innovations enable real-time integration, predictive insights, and collaborative decision-making, thereby strengthening organizational competitiveness. Yet, ICT adoption remains fragmented, hindered by technological limitations, organizational misalignment, workforce skill gaps, cybersecurity risks, and the absence of integrated digital strategies.

Challenges are classified into four dimensions: technological, organizational, human-centric, and systemic. Key gaps include the lack of comprehensive performance evaluation frameworks, limited integration of sustainability and ethics, and poor adaptability of ICT models across diverse industrial and socio-economic contexts. To address these issues, the study proposes a strategic framework built on five pillars: technological infrastructure, organizational alignment, human-centric development, systemic and ethical integration, and continuous improvement. This framework positions ICT as a catalyst for

operational excellence, resilience, and sustainable value creation, bridging theoretical foundations with practical pathways for digital transformation in OM.

Theoretical Implications: The study contributes to theory by framing ICT in OM as a socio-technical system, integrating digital, organizational, and human factors. It extends existing literature by proposing a holistic framework that links ICT adoption with resilience, sustainability, and operational excellence.

Practical Implications: For practitioners, the framework offers actionable guidance to align ICT strategies with business objectives, strengthen resilience, embed sustainability, and address security and ethical considerations in operations.

Managerial Implications: The findings highlight the role of leadership in enabling digital transformation through workforce empowerment, cross-functional collaboration, and long-term investment in technological and human capabilities.

Study Limitations: As a conceptual study, the framework requires empirical validation. Its applicability may vary across industries, organizational sizes, and cultural settings, which future research should address.

Future Research Directions: This study highlights several avenues for advancing research on Information and Communication Technology (ICT) in operations management (OM). Future inquiry should validate the proposed framework, explore the role of disruptive technologies, and integrate sustainability, inclusivity, and human-centric values into ICT-enabled OM. The following research streams and propositions provide a structured agenda.

1) Empirical Validation of the Framework: The proposed framework requires systematic empirical testing across industries, organizational scales, and cultural contexts to establish robustness and adaptability. Both longitudinal and cross-sectional designs are needed to capture evolving ICT–OM dynamics.

- Proposition 1: The effectiveness of the ICT–OM framework varies across industrial sectors, firm sizes, and cultural contexts, requiring contextualized adaptation.
- Proposition 2: Longitudinal analysis will reveal how ICT adoption reshapes workforce competencies, organizational resilience, and performance over time.

2) Integration of Emerging Technologies: Disruptive technologies—including quantum computing, 6G communication, edge intelligence, and emotional AI—offer transformative potential for OM but remain insufficiently studied, particularly regarding ethical and environmental implications.

- Proposition 3: Integrating disruptive technologies enhances agility, resilience, and decision-making in OM but also introduces ethical, cybersecurity, and governance risks.
- Proposition 4: Hybrid ICT ecosystems that combine legacy systems with emerging technologies achieve superior outcomes compared to reliance on either alone.

3) ICT Adoption in SMEs: Small and medium-sized enterprises (SMEs) encounter structural barriers—financial, technical, and human—that limit ICT adoption. Research should design modular, affordable models that reflect SME realities and leverage supportive ecosystems.

- Proposition 5: Tailored ICT adoption models for SMEs improve efficiency, competitiveness, and inclusivity more effectively than generalized strategies.
- Proposition 6: Policy incentives, collaborative partnerships, and digital ecosystems significantly accelerate ICT adoption in SMEs.

4) ICT and Sustainability Nexus: Sustainability remains underdeveloped in ICT-enabled OM. Future research should advance "green ICT" frameworks integrating life-cycle assessment, carbon reduction, and circular economy principles.

- Proposition 7: Green ICT adoption reduces the environmental footprint of OM processes while strengthening long-term competitiveness.
- Proposition 8: ICT-enabled OM systems that embed circular economy principles achieve superior sustainability outcomes compared to efficiency-focused approaches.

5) Human-Centric and Ethical Dimensions: The human and ethical aspects of ICT adoption warrant deeper investigation, including workforce empowerment, digital stress, algorithmic bias, and responsible applications of emotional AI.

- Proposition 9: Human-centric ICT strategies that prioritize workforce development and digital well-being increase adoption success and resilience.
- Proposition 10: Ethical integration of emotional AI in OM improves collaboration and decision quality while reducing risks of bias and mistrust.

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REFERENCES

1. Dissanayake, D.R., 2011. Information communication technology (ICT) policy of Sri Lanka and its impacts to socioeconomic development: A review of Sri Lankan experience. Journal of Education and Vocational Research, 1(2), pp.53-59.
2. Adeola, O. and Evans, O., 2020. ICT, infrastructure, and tourism development in Africa. Tourism Economics, 26(1), pp.97-114.
3. Willie, M.M., 2025. Managing Data Saturation in AI Systems: A Cross-Domain Framework Integrating Human Insights and Algorithmic Verification. Interdisciplinary Systems for Global Management, 1(1), pp. 52-58.
4. Gomaa, A.H., 2023. Improving Supply Chain Management Using Lean Six Sigma: A Case Study. International Journal of Applied & Physical Sciences, 9(1), pp.9-25.
5. Gomaa, A.H., 2024. Boosting Supply Chain Effectiveness with Lean Six Sigma. American Journal of Management Science and Engineering. 9(6), pp. 156-171.
6. Gomaa, A.H., 2025c. Optimizing Manufacturing Supply Chains Using a Strategic Lean Six Sigma Framework: A Case Study. International Journal of Inventive Engineering and Sciences (IJIES). 12(3), pp. 20-33.
7. Colin, M., Galindo, R. and Hernández, O., 2015. Information and communication technology as a key strategy for efficient supply chain management in manufacturing SMEs. Procedia Computer Science, 55, pp.833-842.
8. García-Alcaraz, J.L., Perez Lopez, R.J., Olguin Tiznado, J.E., Mojarro Magaña, M., Camargo Wilson, C. and Lopez Barreras, J.A., 2021. Integrating and Controlling ICT Implementation in the Supply Chain: The SME Experience from Baja California. Instituto de Ingeniería y Tecnología.
9. Pérez-López, R.J., Olguín-Tiznado, J.E., García-Alcaraz, J.L., Camargo-Wilson, C. and López-Barreras, J.A., 2018. The role of planning and implementation of ICT in operational benefits. Sustainability, 10(7), p.2261.
10. Pérez-López, R.J., Olguin Tiznado, J.E., Mojarro Magana, M., Camargo Wilson, C., Lopez Barreras, J.A. and García-Alcaraz, J.L., 2019. Information sharing with ICT in production systems and operational performance. Sustainability, 11(13), p.3640.
11. Yunis, M., Tarhini, A. and Kassar, A., 2018. The role of ICT and innovation in enhancing organizational performance: The catalysing effect of corporate entrepreneurship. Journal of Business Research, 88, pp.344-356.
12. Agrawal, A., Kumar, C. and Mukti, S.K., 2021. Role of information and communication technology

(ICT) to enhance the success of knowledge management (KM): A study in a steel plant. Journal of the Knowledge Economy, 12(4), pp.1760-1786.
13. Aceto, G., Persico, V. and Pescapé, A., 2019. A survey on information and communication technologies for industry 4.0: State-of-the-art, taxonomies, perspectives, and challenges. IEEE Communications Surveys & Tutorials, 21(4), pp.3467-3501.
14. Peraković, D., Periša, M. and Zorić, P., 2019. Challenges and Issues of ICT in Industry 4.0. Design, simulation, manufacturing: The innovation exchange, pp.259-269.
15. Sigov, A., Ratkin, L., Ivanov, L.A. and Xu, L.D., 2024. Emerging enabling technologies for industry 4.0 and beyond. Information Systems Frontiers, 26(5), pp.1585-1595.
16. Pozzi, R., Rossi, T. and Secchi, R., 2023. Industry 4.0 technologies: critical success factors for implementation and improvements in manufacturing companies. Production Planning & Control, 34(2), pp.139-158.
17. Demestichas, K. and Daskalakis, E., 2020. Information and communication technology solutions for the circular economy. Sustainability, 12(18), p.7272.
18. Yu, Y., Yazan, D.M., Junjan, V. and Iacob, M.E., 2022. Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies. Journal of cleaner production, 349, p.131335.
19. Liu, L., Song, W. and Liu, Y., 2023. Leveraging digital capabilities toward a circular economy: Reinforcing sustainable supply chain management with Industry 4.0 technologies. Computers & Industrial Engineering, 178(1), p.109113.
20. Cao, Z., Lin, J., Wan, C., Song, Y., Zhang, Y. and Wang, X., 2016. Optimal cloud computing resource allocation for demand side management in smart grid. IEEE Transactions on Smart Grid, 8(4), pp.1943-1955.
21. Wang, J.B., Wang, J., Wu, Y., Wang, J.Y., Zhu, H., Lin, M. and Wang, J., 2018. A machine learning framework for resource allocation assisted by cloud computing. IEEE Network, 32(2), pp.144-151.
22. Tripathi, V., Saraswat, S. and Gautam, G.D., 2022. Improvement in shop floor management using ANN coupled with VSM: a case study. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 236(10), pp.5651-5662.
23. Frazzon, E.M., Albrecht, A., Pires, M., Israel, E., Kück, M. and Freitag, M., 2017. Hybrid approach for the integrated scheduling of production and transport processes along supply chains. International Journal of Production Research, 56(5), pp.2019-2035.
24. Tan, Q., Tong, Y., Wu, S. and Li, D., 2019. Modeling, planning, and scheduling of shop-floor assembly process with dynamic cyber-physical interactions: a case study for CPS-based smart industrial robot production. The International Journal of Advanced Manufacturing Technology, 105(9), pp.3979-3989.
25. Lee, J., Azamfar, M. and Bagheri, B., 2021. A unified digital twin framework for shop floor design in industry 4.0 manufacturing systems. Manufacturing Letters, 27(1), pp.87-91.
26. Morariu, C., Morariu, O., Răileanu, S. and Borangiu, T., 2020. Machine learning for predictive scheduling and resource allocation in large scale manufacturing systems. Computers in Industry, 120(1), p.103244.
27. Serrano-Ruiz, J.C., Mula, J. and Poler, R., 2022. Development of a multidimensional conceptual model for job shop smart manufacturing scheduling from the Industry 4.0 perspective. Journal of Manufacturing Systems, 63(1), pp.185-202.
28. Li, D., Tang, H., Wang, S. and Liu, C., 2017. A big data enabled load-balancing control for smart manufacturing of Industry 4.0. Cluster Computing, 20(2), pp.1855-1864.
29. Ren, S., Zhao, X., Huang, B., Wang, Z. and Song, X., 2019. A framework for shopfloor material delivery based on real-time manufacturing big data. Journal of Ambient Intelligence and Humanized Computing, 10(3), pp.1093-1108.
30. Tripathi, V., Chattopadhyaya, S., Mukhopadhyay, A.K., Sharma, S., Singh, J., Pimenov, D.Y. and Giasin, K., 2021. An innovative agile model of smart lean–green approach for sustainability enhancement in Industry 4.0. Journal of Open Innovation: Technology, Market, and Complexity, 7(4), p.215.
31. Caiado, R.G.G., Scavarda, L.F., Gavião, L.O., Ivson, P., de Mattos Nascimento, D.L. and Garza-Reyes, J.A., 2021. A fuzzy rule-based industry 4.0 maturity model for operations and supply chain

management. International journal of production economics, 231, p.107883.
32. Tjahjono, B., Esplugues, C., Ares, E. and Pelaez, G., 2017. What does industry 4.0 mean to supply chain? Procedia manufacturing, 13(1), pp.1175-1182.
33. Pasi, B.N., Mahajan, S.K. and Rane, S.B., 2020. Smart supply chain management: a perspective of industry 4.0. Supply Chain Management, 29(5), pp.3016-3030.
34. Frazzon, E.M., Rodriguez, C.M.T., Pereira, M.M., Pires, M.C. and Uhlmann, I., 2019. Towards supply chain management 4.0. Brazilian Journal of Operations & Production Management, 16(2), pp.180-191.
35. Helo, P. and Hao, Y., 2022. Artificial intelligence in operations management and supply chain management: An exploratory case study. Production Planning & Control, 33(16), pp.1573-1590.
36. Wang, Y., Yang, Y., Qin, Z., Yang, Y. and Li, J., 2023. A literature review on the application of digital technology in achieving green supply chain management. Sustainability, 15(11), p.8564.
37. Patel, K.R., 2023. Enhancing global supply chain resilience: Effective strategies for mitigating disruptions in an interconnected world. BULLET: Jurnal Multidisiplin Ilmu, 2(1), pp.257-264.
38. Saif-Ur-Rehman, K., Barson, N. and Hamdan, Y.H., 2024. Industry 4.0 technologies and firm performance with digital supply chain platforms and supply chain capabilities. Pakistan Journal of Commerce and Social Sciences (PJCSS), 18(4), pp.893-924.
39. Hofmann, E., Sternberg, H., Chen, H., Pflaum, A. and Prockl, G., 2019. Supply chain management and Industry 4.0: conducting research in the digital age. International Journal of Physical Distribution & Logistics Management, 49(10), pp.945-955.
40. Mhaskey, S.V., 2024. SCM 4.0: Navigating the Impact of Industry 4.0 on Supply Chain Management through Digitalization and Technology Integration.International Journal of Computer Engineering in Research Trends. 11(10), pp. 1-12.
41. Chauhan, S., Singh, R., Gehlot, A., Akram, S.V., Twala, B. and Priyadarshi, N., 2022. Digitalization of supply chain management with industry 4.0 enabling technologies: a sustainable perspective. Processes, 11(1), p.96.
42. Samper, M.G., Florez, D.G., Borre, J.R. and Ramirez, J., 2022. Industry 4.0 for sustainable supply chain management: Drivers and barriers. Procedia Computer Science, 203(1), pp.644-650.
43. Gomaa, A.H., 2025a. LSS 4.0: A Conceptual Framework for Integrating Lean Six Sigma and Industry 4.0 for Smart Manufacturing Excellence. Indian Journal of Management and Language (IJML), 5(1), pp. 8-29.
44. Gomaa, A.H., 2025b. SCM 4.0 Excellence: A Strategic Framework for Smart and Competitive Supply Chains. International Journal of Management and Humanities (IJMH), 11(8), pp. 24-44.
45. Eunike, A., Wang, K.J., Chiu, J. and Hsu, Y., 2022. Real-time resilient scheduling by digital twin technology in a flow-shop manufacturing system. Procedia CIRP, 107, pp.668-674.
46. Teoh, Y.K., Gill, S.S. and Parlikad, A.K., 2021. IoT and fog-computing-based predictive maintenance model for effective asset management in Industry 4.0 using machine learning. IEEE Internet of Things Journal, 10(3), pp.2087-2094.
47. Mubarik, M.S. and Khan, S.A., 2024. Firms Intellectual Capital and Digital Supply Chain Management. In The Theory, Methods and Application of Managing Digital Supply Chains (pp. 77-92). Emerald Publishing Limited.
48. Rossini, M., Powell, D.J. and Kundu, K., 2023. Lean supply chain management and Industry 4.0: a systematic literature review. International Journal of Lean Six Sigma, 14(2), pp.253-276.
49. Fatorachian, H. and Kazemi, H., 2021. Impact of Industry 4.0 on supply chain performance. Production Planning & Control, 32(1), pp.63-81.
50. Govindan, K., Kannan, D., Jørgensen, T.B. and Nielsen, T.S., 2022. Supply Chain 4.0 performance measurement: A systematic literature review, framework development, and empirical evidence. Transportation Research Part E: Logistics and Transportation Review, 164(1), p.102725.