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The Convergence of Intelligence and Infrastructure: A Review of Emerging Technology Trends Reshaping Modern Operational Technology (OT) Ecosystems

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Abstract - Operational Technology (OT) is experiencing one of the most remarkable shifts in its history as increased OT and Information Technology (IT) systems converge to form unified, intelligent systems. The aim of this review article is to look at the most important technology trends that are currently changing the OT landscape and consider the impact of these on architecture, operation, and security for industrial environments. The review combines insights from published research from peer-reviewed journals, industry whitepapers, and standards documents to form eight interdependent themes edge computing and Edge AI, industrial and agentic AI, digital twins and predictive maintenance, Zero Trust OT cybersecurity, industrial DataOps, advanced wireless connectivity (5G and private 5G), low-code/no-code platforms, and virtual PLCs based on containerization. The results show that these technologies are not standalone but instead are a highly integrated stack that together supports real-time decision making and resilient operations with the help of intelligence, contextualized data pipelines, and software-defined control. Meanwhile, the review also highlights the ongoing challenges of cybersecurity vulnerabilities associated with increased attack surface, underdeveloped data governance and data quality, talent gaps, and lack of interoperability of vendor ecosystems. The article concludes that the future of OT will be adaptive, autonomous, and securely connected industrial systems, but this will only happen when standards, governance processes, and human–machine collaboration are coordinated. Future research recommendations are made for research on the deployment of agentic AI, empirical benchmarks for Zero Trust OT architectures and unified evaluation frameworks for DataOps maturity in the industrial sector.

Keywords: Operational Technology, IT/OT Convergence, Edge AI, Digital Twin, Zero Trust Architecture, Industrial DataOps, Private 5G, Virtual PLC, Industry 4.0, Cyber-Physical Systems.

1. INTRODUCTION

There are significant differences between Information Technology (IT) and Operational Technology (OT) which have always been well defined in the industrial world. IT systems handled business data and enterprise processes while OT systems handled the physical machinery, sensors, and control loops fundamental to manufacturing, energy, transportation, and critical infrastructure. In the last decade, however, this border has been under pressure because of Industry 4.0 initiatives, the ever-growing number of industrial Internet of Things (IIoT) devices, the maturity of artificial intelligence, and the newfound importance of operational resilience.

This change is important in two ways. First, IT/OT convergence has significant operational advantages to be gained, such as minimized downtime, optimised resource use, predictive insights, visibility into the entire supply chain, and more. Second, it also presents new types of risk, for example in cybersecurity, where legacy OT networks are now vulnerable to risks that were previously posed by IT networks. The

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ransomware attack trend for critical infrastructure, particularly the ones that have been widely reported in the energy, water and manufacturing sectors, is irreversible and calls for strategic handling.

Although there is a literature, the discourse about OT modernization is disjointed. Many studies have been conducted on specific technology, e.g., on digital twins or on 5G networks, but not on the interaction of these technologies in a holistic industrial stack. An obvious lack of synthesized knowledge is the mapping of interdependencies between emerging OT technology trends and assessing the impact of these trends together on industrial operations.

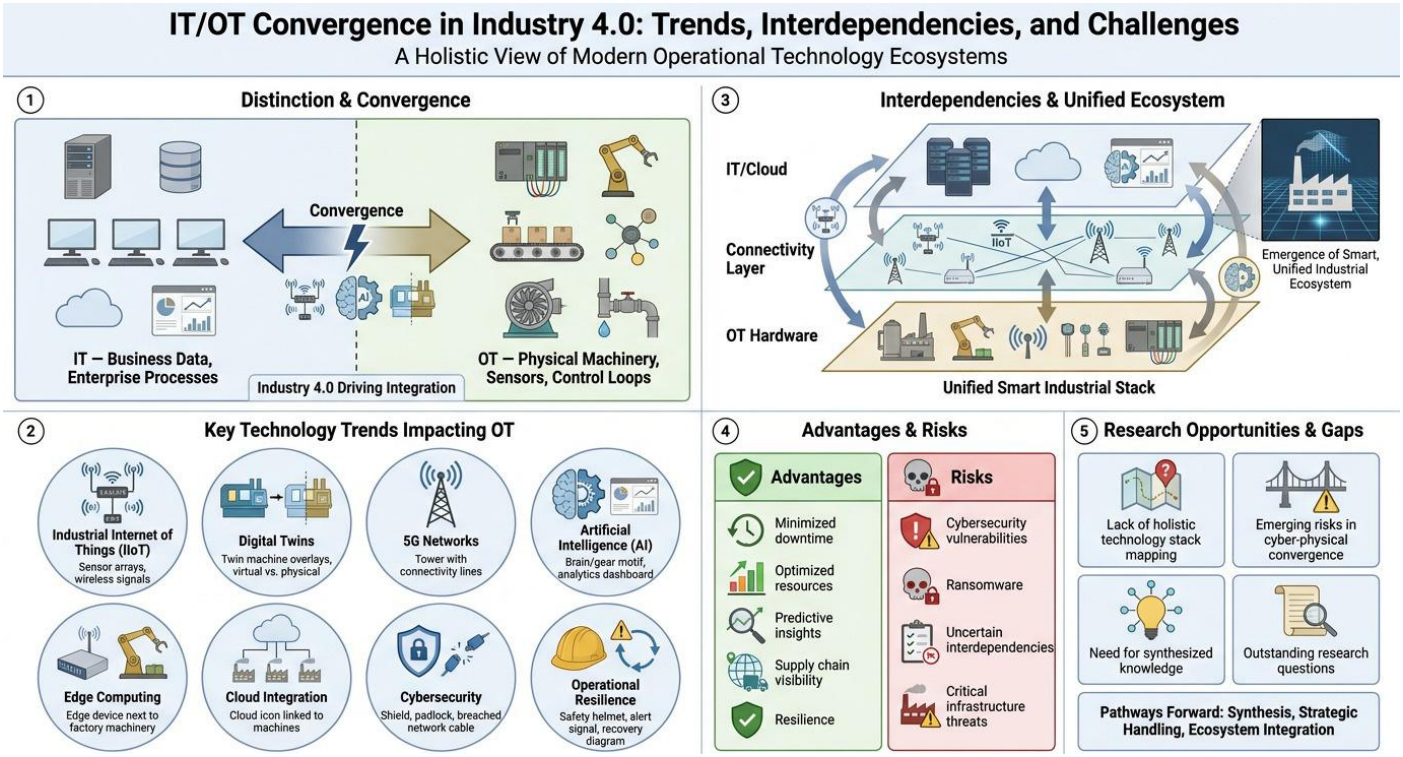

Fig -1: IT/OT Convergence in Industry 4.0 Trends, Interdependencies, and Challenges

This review attempts to fill in that gap by considering eight key technology trends that affect OT today. The goals of the review are: (1) identify and describe the key technology trends that are impacting OT ecosystems (2) examine the interdependencies and relationships between the identified trends and (3) identify outstanding issues and suggest ways forward for research and practice. The review is, therefore, guided by the following three questions:

1. Which are the prevailing OT technology trends shaping the OT landscape.
2. What are the interplay between these trends and how do they allow for unified and smart industrial ecosystems to emerge.
3. What are the current gaps, risks and research opportunities regarding their adoption and deployment.

2. REVIEW METHOD

The methodology used in this review was structured narrative review and it was based on systematic literature review (SLR) practice. Sources were identified using Scopus, Web of Science, IEEE Xplore and ScienceDirect and some gray literature from industry sources like Gartner, World Economic Forum, International Society of Automation (ISA) and National Institute of Standards and Technology (NIST).

Boolean operators on the eight thematic clusters were used to search for terms, such as: ("operational technology" OR "industrial control systems") AND ("edge AI" OR "agentic AI" OR "digital twin" OR "zero trust" OR "DataOps" OR "private 5G" OR "low-code" OR "virtual PLC"). Only publications from 2019 to 2025 were included in the search window to ensure the most up-to-date advances were included; seminal works from earlier years were included if conceptually important.

The following were used as inclusion criteria: (a) peer-reviewed or from a recognized standards body or industry authority, (b) directly related to OT, industrial control, or IIoT, and (c) accessible in English. The works removed on exclusion criteria were those that were purely commercial promotional content, duplicate studies, and works that were about IT systems that did not have OT relevance. The titles and abstracts of the articles were reviewed, and a further round of full text reading resulted in a final corpus of close to 90 sources that were thematically coded based on the eight trends identified. Findings were combined and convergences, contradictions, and gaps in the literature were highlighted.

3. EMERGING TECHNOLOGY TRENDS IN OT

3.1 Edge Computing and Edge AI

Edge computing is a fundamental change in OT architecture, which shifts the way data is processed from centralized cloud platforms to localized nodes, closer to sensors, controllers, and actuators. Latency reduction, bandwidth efficiency and operational resilience are cited as the three key motivations for this transition in literature. For safety-critical applications like power grids and process plants, the 100 millisecond clock cycles are certainly not acceptable, and reliance on the cloud is simply too risky. Edge AI takes this paradigm one step further by putting machine-learning inference right into edge devices. Applications are real-time anomaly detection, machine vision quality inspection, and adaptive control. Edge AI also bolsters data sovereignty, because sensitive operational data do not have to go offsite, studies say. However, issues like model lifecycle management, hardware diversity, and managing distributed AI workloads remain.

3.2 Industrial AI and Agentic Systems

Conventional industrial AI is about supervised models for prediction and classification; evolving trends are moving toward agentic AI, which involves autonomous software agents that can plan, reason and act with minimal human intervention. Agentic systems are starting to perform tasks like scheduling maintenance windows, dynamically optimizing energy consumption and coordinating multi-asset workflows all in OT contexts. Literature portrays promise and caution. Agentic AI, on the other hand, is a paradigm shift from automation to autonomy, allowing for adaptive responses in changing operating conditions. Conversely, researchers highlight the importance of explainability, human-in-the-loop verification, and comprehensive validation processes for such systems before they can be relied upon for safety-critical decisions. Agentic systems governance is identified as an open research problem with many people.

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3.3 Digital Twins and Predictive Maintenance

Digital twin technology has been developed from a paper promise to a viable industrial solution. Today's digital twins combine real-time live sensor data, physics-based models, and AI elements to simulate physical asset behavior in near real-time. The concept of twins makes it possible to predict failure, which is the core of predictive maintenance, by recognizing slight changes in the characteristics of how a system performs.

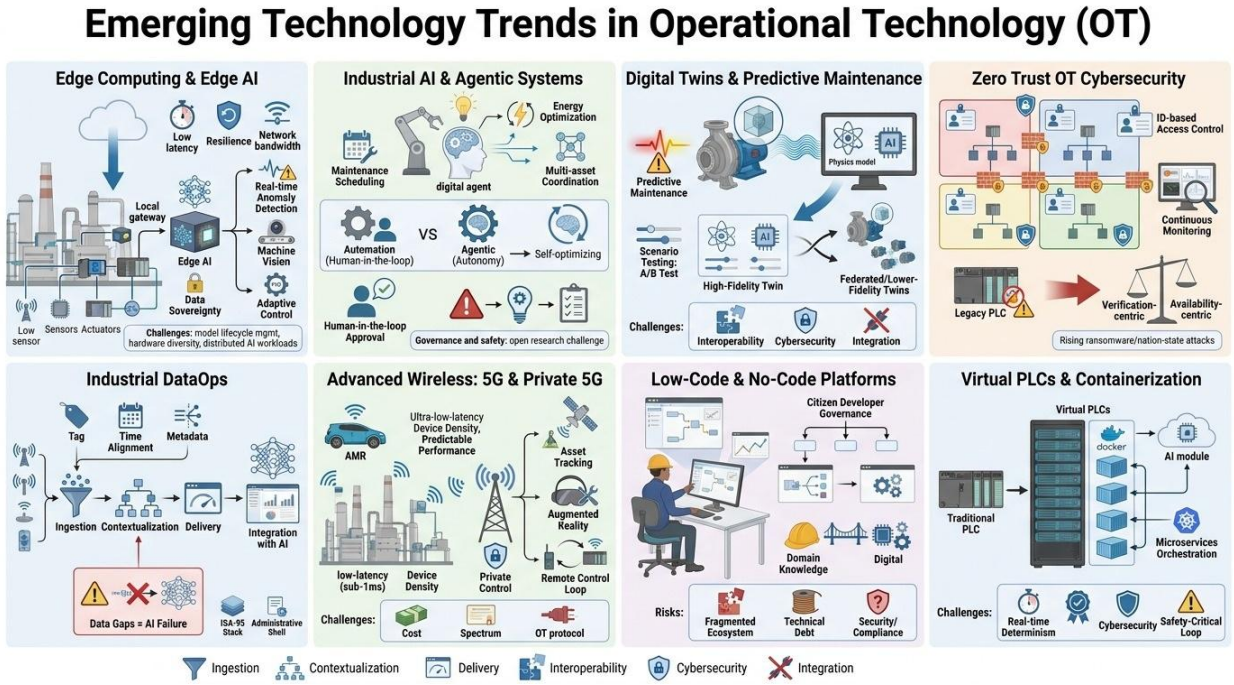

Fig -2: Emerging Technology Trends in Operational Technology (OT)

The reviewed studies all point to the benefits of digital twins with respect to downtime reduction, scenario testing, and lifecycle optimization. But there are some conflicts around fidelity and scalability. Others in the research community believe that the more fidelity a twin has the closer it is to its asset the better and that they should be federated and lower fidelity, allowing them to be scaled across enterprises. Typical challenges involve integration with other DataOps and cybersecurity processes, as well as interoperability between different vendor platforms.

3.4 Zero Trust OT Cybersecurity

When OT systems are heavily networked, legacy perimeter security are no longer sufficient. Zero Trust Architecture (ZTA) is an approach to creating a system of no trust, based on the premise that you don't trust anyone on the network. In OT, the concept of ZTA is implemented using network segmentation, Identity Based Access Control, continuous monitoring, and using least privilege policies.

In the literature, a significant growth of ransomware and nation-state attacks against industrial targets is reported, thus stressing the importance of implementing ZTA. However, Zero Trust in OT is not easy many legacy controllers cannot use the cryptographic methods or computing power required for modern authentication schemes. The Zero Trust principle is more verification centric than availability, whereas OT is more availability focused that a path towards OT-specific Zero Trust Architecture (ZTA) reference architectures is indicated.

3.5 Industrial DataOps

Industrial DataOps is a new discipline that is built on the management of the operational data lifecycle from ingestion to contextualization to delivery for downstream analytics. Although there is a lot of raw sensor data available, it is often not structured, untagged, and not associated with the assets and processes it is in reference to. DataOps leverages data engineering, data governance, and continuous integration principles to make this data available for AI, dashboards, and decision support systems. The importance of context, such as asset hierarchies, time alignment and engineering metadata in determining the value of OT data is a common theme in literature. But, as studies outline, AI projects in the OT space are bound to fail if DataOps maturity is not achieved, no matter how advanced the AI models are. ISA-95, the asset administration shell and other standards are more referenced.

3.6 Advanced Wireless 5G and Private 5G

5G, in particular private 5G networks in industrial sites, is becoming a gamechanger for OT connectivity. The 5G technology provides ultra-reliable low latency communication (URLLC), massive device density, and predictable performance, which are features that can't be found in Wi-Fi or previous cellular generations. Examples found in literature include autonomous mobile robots, real-time asset tracking, augmented reality for field maintenance and wireless control loops. Private 5G is especially important as it provides industrial operators with sovereign control over their 5G wireless network, overcoming concerns about data privacy and quality of service. However, capital costs, spectrum licensing issues, and challenges in integrating with existing OT protocols still limit the adoption.

3.7 Low-Code and No-Code Platforms

Low-code and no-code (LCNC) platforms are bringing the democratisation of OT automation and application building. Domain experts such as plant engineers can now create dashboards, workflows, and integration pipelines in a visual environment, without needing to write software code. As indicated in the literature, LCNC can help accelerate digital transformation, alleviate the shortage of IT resources, and bridge the gap between domain knowledge and digital delivery. However, researchers warn of the dangers of governance fragmentation, technical debt, and security issues when there is enterprise proliferation of LCNC tools. Therefore, citizen developer" governance frameworks are gaining increasing attention.

3.8 Virtual PLCs and Containerization

Programmable Logic Controllers (PLCs) are traditionally a dedicated piece of hardware and have long been the workhorses of industrial automation. Virtual PLCs (vPLCs) are a paradigm change toward software-defined automation, which are essentially hosted on standard IT servers as containerized software. Vendors and researchers note that vPLCs allow for flexibility, scalability, simpler updates and tighter integration with cloud and AI services. Control logic can be deployed, replicated, and orchestrated as microservices using containerization technologies like Docker and Kubernetes adapted for use in industrial applications. Despite the operational advantages, there are challenges which must be addressed before vPLCs can be installed in safety-critical loops as a replacement for traditional controllers: real-time determinism, certification according to safety standards, and cybersecurity hardening.

4. HUMAN, ETHICAL, AND GOVERNANCE DIMENSIONS OF OT TRANSFORMATION

The technological course of action that is transforming modern Operational Technology, as outlined in the previous sections, must be complemented by the human, ethical and governance aspects of OT

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transformation. When implementing technology in the industrial world, it is not just a technical process, but one that involves organizational culture, worker skills, regulation, and societal expectations. Failure to account for these factors has consistently been a major reason digitalisation efforts have failed in the past and is a key reason why the current OT modernization is struggling.

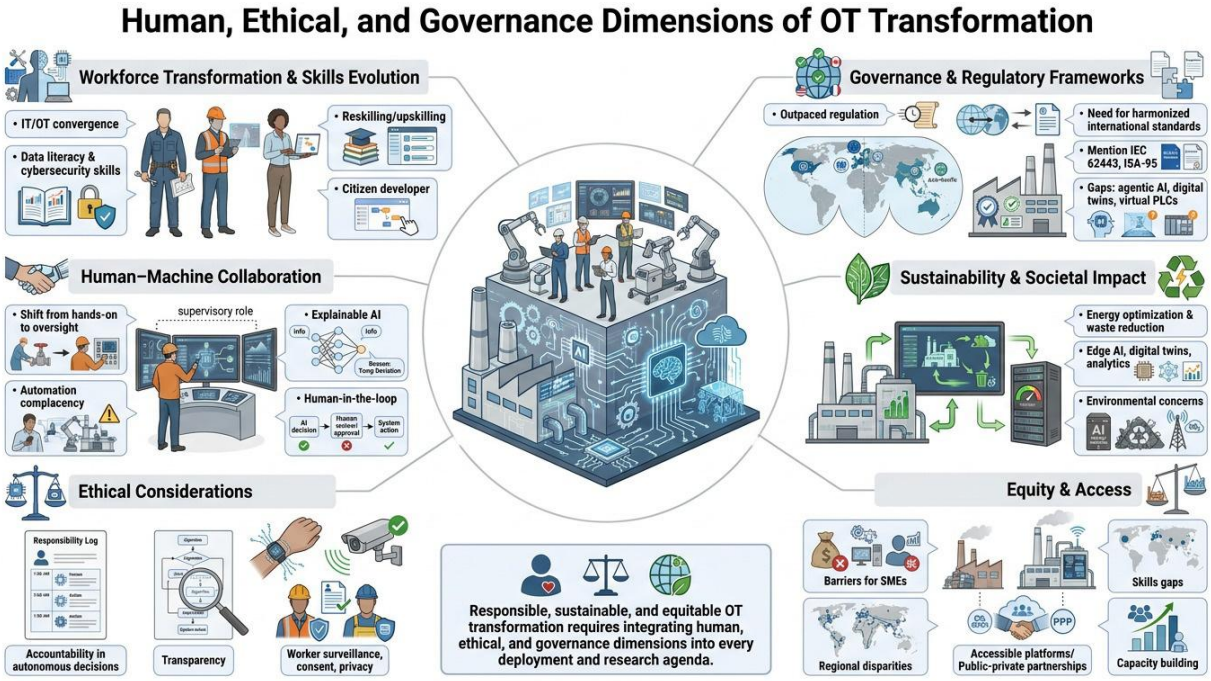

Fig -3: Human, Etherical, and Governance Dimensions of OT Transformation

Workforce Transformation & Skills Evolution. IT/OT convergence is also completely changing the skills of industrial engineers, operators and technicians. OT jobs have traditionally focused on mechanical, electrical and control systems knowledge, but are now about data literacy, cybersecurity awareness, AI fluency and software engineering skills. Literature invariably names a skills gap as one of the greatest challenges for successful OT modernization. The initial answers are reskilling and upskilling initiatives, interdisciplinary academic courses and collaboration between industry and vocational education providers; however, little is known about their effectiveness in academic literature. Adding to the complexity is the rise of the "citizen developer," who is equipped with low-code platforms and can create software without the involvement of a dedicated development team.

Human–Machine Collaboration. The function of the human is changing from hands-on management to a more supervisory role as agentic AI and autonomous systems take over more functions. The transition brings serious issues regarding situational awareness, trust calibration, and tacit knowledge retention. According to human factors research, when a system decides for the operator, the operator can lose skill in the automation and will be unable to intervene, a problem called “automation complacency.” Thoughtful interface design, explainable AI and structured human-in-the-loop frameworks are crucial to keep human judgment in the loop, especially in safety-critical scenarios.

Ethical Considerations. In industrial settings, the use of AI and agentic systems comes with ethical implications that go beyond the technical aspects. Accountability is a question when there is a decision made by an autonomous system that results in financial, environmental, or physical damage. According

to literature, there is a need for well-defined lines of responsibility, transparency of algorithms and audit mechanisms. Further, the technology of operational data also introduces questions of worker surveillance, consent, and privacy, particularly with the increased presence of wearable devices, computer vision systems, and real-time tracking in industrial environments.

Governance and regulatory frameworks. OT has been changing faster than its governance frameworks. Standards like IEC 62443, cybersecurity, and ISA-95, data integration, offer some fundamental guidance, but there are still many areas that lack standards, including agentic AI governance, digital twin interoperability, and virtual PLC certification. Multinational operators are facing challenges due to the different approaches taken by regulatory bodies in various jurisdictions to fill these lacunas. One of the themes consistently found in literature is a desire for harmonized international standards that meet the needs of innovation while ensuring safety, security, and accountability.

Sustainability and Societal Impact. Sustainability goals are also very much tied in with modern OT transformation. Energy optimisation, waste reduction, and predictive resource management, with the help of Edge AI, digital twins and advanced analytics, helps achieve environmental goals. But there are also environmental concerns as AI workloads use energy, electronic waste from frequent hardware changes and the resource requirements to support 5G infrastructure. The enabling and the footprint aspects of these technologies should therefore be taken into account when evaluating the modernization of OT.

Equity and Access. Last but not least, modernization of OT is not distributed equally. There is a perceived financial, technical and knowledge barrier to accessing advanced technologies for small and medium sized manufacturers, and large, well-capitalized enterprises are better positioned to adopt the advanced technologies. Likewise, digital infrastructure, such as 5G availability and skilled workforce varies across regions, affecting adoption rates. Ensuring that these equity issues are worked through via accessible platforms, public–private partnerships and capacity building initiatives is crucial to ensure that the transformation is good for the wider industrial eco-system.

To sum up, the human, ethical, and governance aspects to OT transformation are not a secondary concern but key factors in whether the potential benefits of these technologies are achieved in a responsible, sustainable, and equitable manner. Therefore, it is crucial that these considerations should be included in research agendas and deployment strategies for the maturation of the field.

5. DISCUSSION

The results of the synthesis indicate that the eight trends identified are not simply independent events but rather comprise an interrelated structure for the next generation of OT. Edge computing forms the basis for the computational substrate, industrial DataOps makes sure that the data that moves through it is meaningful, AI and agentic systems derive intelligence from the data, digital twins creates a representational layer for simulation and prediction, advanced wireless connects the physical assets that generate the data, software defined control plane via virtual PLCs and containerization, low code platforms make it easy for domain experts to act, and Zero Trust cybersecurity hold the whole stack together with continuous verification.

A number of significant trends are discernable from this synthesis. First, the "place" of intelligence is moving from central clouds to distributed edges, with significant consequences for both latency and autonomy as well as resilience. Second, there are software tools that are replacing hardware functions

that have traditionally been thought of as hardware, such as virtual PLCs. Third, security has become closer to architecture – bolt on security models are being replaced with designs where trust is continually and contextually verified.

Meanwhile, methodological flaws and open questions are evident in the literature. Many studies are based on case evidence or simulation, and a less amount of longitudinal data exists on actual deployments. There are still few quantitative maturity metrics for Zero Trust OT, agentic AI reliability, and DataOps maturity. A common theme throughout most of the themes is interoperability, as another form of friction is between vendor-led innovations and the open-standards approach that is needed for ecosystem-level adoption. Yet another cross-cutting concern is workforce capability: The increasing software and AI content of OT systems are outpacing the evolution of training programs for engineers and workers. The importance of this evidence is in the overall message OT is no longer about the static domain that's separate from IT, it's about a software-defined, dynamic and intelligence-rich environment. However, this dynamism introduces and magnifies risk, requiring governance, standards, and people to match the new capabilities.

6. CONCLUSION

In this review we have looked at eight interrelated technology trends that are shaping the modern OT Edge computing & Edge AI, industrial and agentic AI, digital twins & predictive maintenance, Zero Trust OT cybersecurity, industrial DataOps, advanced wireless including private 5G, low-code & no-code platforms, and virtual PLCs with containerization. All these trends together point to a clear shift from traditional, hardware-centric OT systems to adaptive, intelligent, and securely connected industrial ecosystems.

What this review adds is to bring together the different strands of literature and present a more integrated set of trends that show interdependency among the trends and put them in the context of the general evolution of IT/OT convergence. The results highlight that OT modernization without a holistic architectural approach relying on point investments in individual technologies is impossible for practitioners to achieve.

Several promising avenues for research emerge for researchers. First, there is a need for longitudinal empirical studies on the use of agentic AI in production OT environments, focusing on safety, explainability and governance. Second, there is a need for Zero Trust OT and industrial DataOps standardized maturity models and benchmarks. Third, interoperability frameworks need to be developed to enable digital twins and virtual PLCs and AI services to function across vendor ecosystems. Lastly, the human aspect, such as workforce preparation, ethics, and human–machine interaction, should be given due academic consideration to stay on par with the quickly evolving technical aspect of OT. Ultimately, the future of OT is not in one technology, but many will need to be integrated in a disciplined manner. Achieving this future will involve collaborative action across industry, academia, and policy to prepare the next generation of industrial systems to be intelligent and efficient, secure, transparent and trustworthy.

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