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An Evolutionary Perspective on Digital Transformation: Integrating Industrial Control Systems Toward Industry 4.0 in Developing Countries

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Abstract

Digital transformation in the manufacturing sector represents an evolutionary progression from early industrial automation systems, such as Distributed Control Systems (DCS) and Programmable Logic Controllers (PLC), toward integrated Industry 4.0 environments. This study contributes by developing an integrative perspective that combines technological evolution with organizational and strategic alignment, particularly within the context of developing countries. The research aims to analyze how digital transformation readiness influences the successful implementation of Industry 4.0 in manufacturing systems. This study employs a qualitative approach through a structured literature review of recent studies on industrial automation, digitalization, and Industry 4.0. The analysis highlights that the effectiveness of advanced technologies—such as the Internet of Things (IoT), artificial intelligence (AI), and data analytics—is contingent upon the integration between Operational Technology (OT) and Information Technology (IT), as well as organizational readiness factors, including human resource capabilities and data-driven culture. The findings indicate that firms with higher levels of technological and organizational alignment demonstrate improved operational performance, including enhanced efficiency, reduced system downtime, and more accurate decision-making processes. Furthermore, the study identifies that in developing countries, infrastructural limitations and capability gaps remain key barriers to digital transformation adoption. This study suggests that digital transformation should be implemented as a phased and strategic process that integrates technological investment with organizational capability development. These findings provide practical implications for policymakers and industry practitioners in designing more adaptive and sustainable Industry 4.0 strategies.

Keywords:
Industry 4.0; Digital Transformation; Internet of Things (IoT); Artificial Intelligence (AI); Industrial Control Systems (ICS)

INTRODUCTION

Digital transformation has become a strategic imperative in the manufacturing sector, fundamentally reshaping how firms operate, innovate, and create value. The advancement of digital technologies has shifted competition from traditional cost and production efficiency toward capabilities in system integration, real-time data utilization, and adaptive decision-making (Onyeke et al., 2022). In this context, digitalization is no longer optional but essential for maintaining competitiveness in increasingly dynamic and complex industrial environments (Sverko et al., 2022).

Historically, the manufacturing sector has undergone a gradual digital evolution since the adoption of industrial automation systems in the 1980s, including Supervisory Control and Data Acquisition (SCADA), Distributed Control Systems (DCS), Programmable Logic Controllers (PLC), and Safety Instrumented Systems (SIS). These technologies marked the transition from manual and analog operations to digital-based process control, enabling real-time monitoring, improved operational reliability, and standardized automation (Amin et al., 2024). However, early digitalization was largely characterized by isolated and stand-alone systems, with limited integration across organizational functions and minimal utilization of data for strategic decision-making (Alqoud et al., 2022).

The emergence of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cloud computing has transformed digitalization into a more integrated and intelligent paradigm, widely referred to as Industry 4.0 (Ghobakhloo & Iranmanesh, 2021). In this phase, manufacturing systems evolve into interconnected, data-driven, and adaptive environments, where traditional industrial control systems serve as the backbone for advanced applications such as predictive maintenance, digital twins, and real-time optimization.

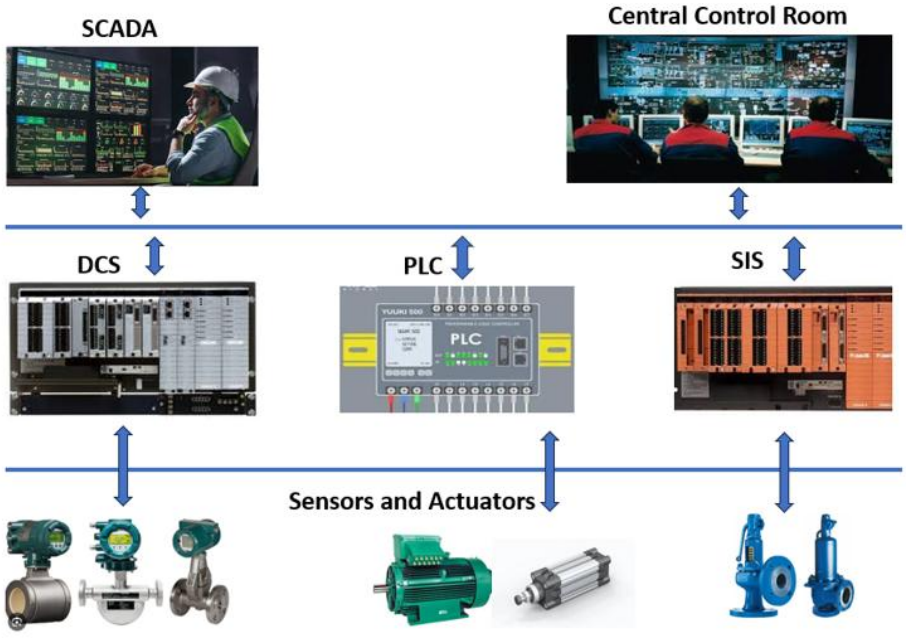

Figure 1, General Architecture of an Industrial Control System (ICS)
(Compiled from various sources)

Despite these advancements, existing studies on Industry 4.0 tend to focus predominantly on technological adoption, often overlooking the evolutionary linkage between legacy automation systems and current digital integration, as well as the critical role of

organizational readiness. Furthermore, empirical and conceptual discussions in the context of developing countries remain limited, particularly in addressing structural constraints such as infrastructure gaps, human resource capabilities, and organizational culture (Björkdahl, 2020). This creates a significant research gap in understanding how digital transformation can be effectively implemented in manufacturing sectors with varying levels of technological maturity (Chirumalla et al., 2025).

Therefore, this study aims to analyze digital transformation in manufacturing by integrating an evolutionary perspective of industrial control systems with organizational and strategic readiness dimensions. This research contributes by proposing a more holistic understanding of Industry 4.0 implementation, particularly in the context of developing countries, where alignment between technology, processes, and human capabilities plays a decisive role in determining transformation success (Machado et al., 2021).

Literature Review

The Evolution of Industrial Digitalization

Digitalization in the manufacturing sector represents a gradual and evolutionary process, progressing from early industrial automation toward integrated digital ecosystems. Initial developments in the 1980s were marked by the adoption of industrial control systems such as Distributed Control Systems (DCS) and Programmable Logic Controllers (PLC), which enabled process automation, real-time monitoring, and improved operational reliability. However, these systems were largely stand-alone, with limited integration across organizational functions and minimal utilization of data beyond operational control (Lee et al., 2015).

Subsequent developments in the 1990s and early 2000s introduced broader system integration through technologies such as Supervisory Control and Data Acquisition (SCADA) and Enterprise Resource Planning (ERP). This phase enabled the linkage between operational and managerial systems, enhancing data visibility and supporting decision-making at tactical and strategic levels (Bharadwaj et al., 2013).

The emergence of advanced digital technologies, including the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cloud computing, has further accelerated this transformation into what is now known as Industry 4.0 (Kagermann et al., 2013; Lasi et al., 2014). In this phase, manufacturing systems evolve into interconnected, intelligent, and adaptive environments capable of predictive and prescriptive operations. Importantly, the integration of Operational Technology (OT) and Information Technology (IT) has become a critical enabler of this transformation, allowing organizations to leverage data as a strategic resource (Vial, 2019).

This evolutionary perspective highlights that digital transformation is not a sudden technological shift, but rather a continuous process that builds upon legacy systems. Such an understanding is particularly relevant for developing countries, where many industries are still transitioning from traditional automation toward full digital integration.

Industry 4.0 in Manufacturing

Industry 4.0 represents a paradigm shift in manufacturing, characterized by the integration of cyber-physical systems, real-time connectivity, and data-driven decision-making. Unlike previous industrial revolutions, Industry 4.0 emphasizes the convergence of physical and digital systems, enabling smart manufacturing environments that are autonomous, adaptive, and interconnected (Bag et al., 2021).

A key feature of Industry 4.0 is the integration between Operational Technology (OT) and Information Technology (IT), which facilitates seamless data flow from the production floor to strategic decision-making levels. This integration enhances operational transparency,

improves production planning, and enables predictive maintenance, thereby reducing downtime and increasing efficiency (Raj et al., 2020)

Beyond operational improvements, Industry 4.0 also drives transformation in business models. Manufacturing firms increasingly adopt service-oriented approaches (servitization), where value creation extends beyond physical products to include digital services (Porter & Heppelmann, 2015). Additionally, digital technologies enable more responsive and integrated supply chains, allowing firms to better adapt to market fluctuations and customer demands (Ivanov & Dolgui, 2020).

However, the implementation of Industry 4.0 remains challenging, particularly in terms of integrating legacy systems, developing human resource capabilities, and managing high investment costs. These challenges are more pronounced in developing countries, where technological and organizational readiness varies significantly.

The Impact of Digital Transformation

Digital transformation significantly influences manufacturing performance across multiple dimensions. Operationally, technologies such as IoT and data analytics enable real-time monitoring and predictive maintenance, leading to improved efficiency, reduced downtime, and optimized resource utilization (Kusiak, 2018).

Strategically, digital transformation enhances decision-making through the use of data as a strategic asset. The integration of OT and IT enables organizations to adopt data-driven decision-making processes, improving responsiveness to market dynamics (Vial, 2019). Furthermore, digitalization supports product innovation through advanced design tools, simulation, and digital twins, accelerating product development cycles.

From a sustainability perspective, digital technologies contribute to improved energy efficiency and reduced material consumption, supporting environmentally sustainable manufacturing practices. However, these benefits are not automatically realized, as organizations often face challenges related to technological integration, investment constraints, and human resource readiness.

Despite the rapid growth of literature on digital transformation and Industry 4.0, several critical gaps remain.

First, existing studies predominantly emphasize advanced digital technologies, with limited attention to the evolutionary linkage between legacy industrial control systems and current digital transformation. This creates a fragmented understanding of how organizations transition from early automation to intelligent manufacturing systems.

Second, most empirical and conceptual studies are conducted in developed countries, resulting in limited insights into the unique challenges faced by developing countries, such as infrastructure constraints, limited digital capabilities, and organizational readiness issues.

Third, the literature tends to focus heavily on technological aspects, while the integration between digital technologies and business strategy remains underexplored. This limits the understanding of how strategic alignment influences the success of digital transformation.

Finally, there is a persistent implementation gap, where the theoretical benefits of Industry 4.0 are not fully realized in practice. This phenomenon is often associated with the "digital paradox," where significant technological investments do not necessarily translate into improved organizational performance.

This study contributes to the literature in several important ways.

First, it develops an evolutionary framework that integrates legacy industrial automation systems (DCS and PLC) with contemporary Industry 4.0 technologies, providing a more comprehensive understanding of digital transformation as a continuous process.

Second, this study offers a contextual contribution by focusing on developing countries, particularly Indonesia, thereby addressing the lack of empirical and conceptual insights in non-developed economies.

Third, it integrates technological and strategic perspectives, highlighting the importance of alignment between digital technologies, business processes, and organizational capabilities in determining transformation success.

Finally, this study provides practical implications by emphasizing a phased and holistic approach to digital transformation, particularly for organizations operating in environments with limited resources and varying levels of technological maturity.

METHODS

This study employs a qualitative research design using a structured literature review approach to examine the evolution and impact of digital transformation in the manufacturing sector. The method is chosen to systematically synthesize existing knowledge and identify patterns, gaps, and critical success factors related to Industry 4.0 implementation.

The data sources consist of peer-reviewed journal articles, conference proceedings, and relevant industry reports obtained from academic databases such as Scopus, ScienceDirect, and Google Scholar. The selection of literature follows predefined inclusion criteria, including: (1) publications related to digital transformation, industrial control systems, and Industry 4.0; (2) articles published between 2013 and 2025 to ensure relevance and recency; and (3) studies focusing on manufacturing sectors, particularly in the context of developing countries. Studies that do not meet these criteria or lack empirical or conceptual relevance are excluded from the analysis.

The literature review process is conducted in several stages. First, identification and screening of relevant publications are carried out using specific keywords such as “digital transformation,” “Industry 4.0,” “industrial control systems,” and “manufacturing digitalization.” Second, selected articles are categorized based on themes, including technological evolution, system integration, organizational readiness, and implementation challenges. Third, a thematic analysis is applied to synthesize findings and identify recurring patterns, relationships, and research gaps.

To enhance the rigor of the analysis, this study adopts a comparative and interpretative approach, allowing the integration of technological, organizational, and strategic perspectives. The findings are then interpreted within the context of developing countries, particularly Indonesia, to generate insights that are both theoretically grounded and practically relevant.

RESULT AND DISCUSSION

Evolution Toward Intelligent Manufacturing Systems

The findings of this study confirm that digital transformation in the manufacturing sector is an evolutionary process rooted in early industrial automation systems such as Distributed Control Systems (DCS) and Programmable Logic Controllers (PLC). These systems initially enabled real-time process control and operational efficiency; however, their functionality was largely confined to operational-level applications.

The synthesis of the literature indicates that the transition toward Industry 4.0 extends these capabilities into integrated, intelligent, and data-driven systems. In this context,

digitalization evolves from isolated automation toward interconnected ecosystems, where data plays a central role in value creation.

OT–IT Integration and Data-Driven Operations

A key finding is that the integration of Operational Technology (OT) and Information Technology (IT) represents a critical success factor in digital transformation. This integration enables end-to-end visibility across production systems and supply chains, allowing organizations to utilize real-time data for monitoring, analysis, and decision-making.

The literature consistently highlights that organizations with higher levels of OT–IT integration achieve improved operational performance, including enhanced efficiency, reduced downtime, and more accurate production planning. This supports the argument that digital transformation is not merely about technology adoption, but about system integration and data utilization.

From Reactive to Predictive and Prescriptive Operations

Another important finding is the shift in operational paradigms from reactive to predictive and prescriptive approaches. In traditional systems, organizations respond to failures after they occur, resulting in higher costs and operational inefficiencies. In contrast, predictive operations utilize data analytics and machine learning to anticipate system failures based on patterns derived from historical and real-time data. This enables organizations to perform planned maintenance and minimize unexpected disruptions.

Furthermore, prescriptive operations represent a more advanced stage, where systems not only predict potential issues but also provide recommendations for optimal actions. This transformation reflects the increasing role of artificial intelligence in supporting strategic and operational decision-making within Industry 4.0 environments.

Contextual Challenges in Developing Countries

Despite these advancements, the findings indicate that the implementation of digital transformation in developing countries faces significant challenges. These include limited digital infrastructure, gaps in human resource capabilities, difficulties in integrating legacy systems, and organizational resistance to change. The literature suggests that these constraints contribute to the persistence of the implementation gap, where the expected benefits of Industry 4.0 are not fully realized in practice. Therefore, a phased and adaptive approach to digital transformation is essential, particularly in contexts with varying levels of technological maturity.

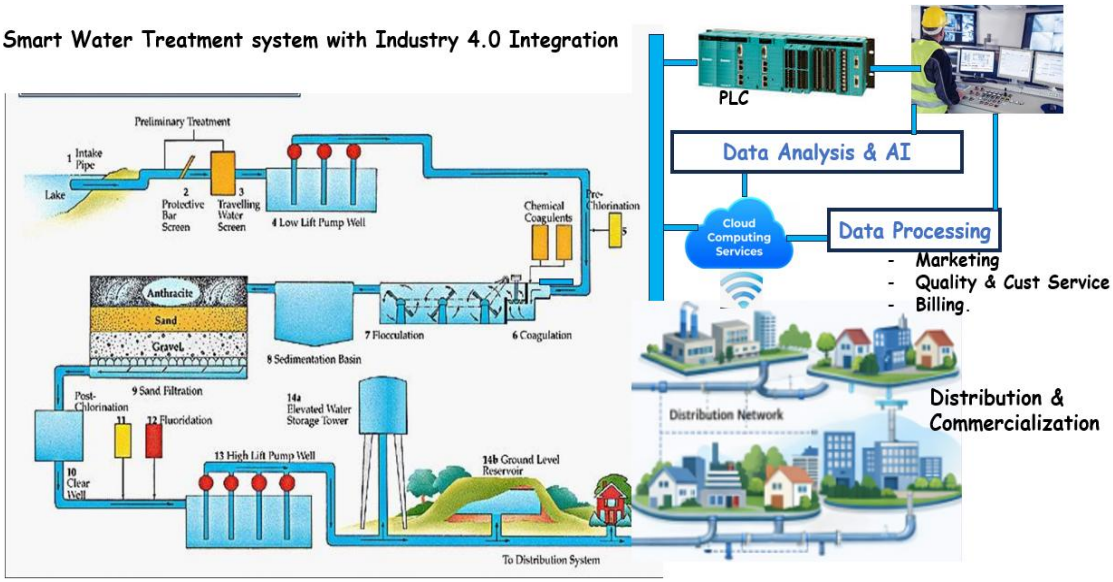

Figure 2. Smart and Integrated Clean Water Management with Industry 4.0. (Compiled from various sources).

This study highlights that successful digital transformation requires the alignment of three key dimensions: technology, business processes, and organizational capabilities. The findings reinforce the view that digitalization should be approached as a holistic transformation rather than a purely technological initiative.

In this context, the integration of legacy systems with advanced digital technologies represents a critical pathway for achieving sustainable transformation. Organizations that are able to orchestrate this integration effectively are more likely to realize the full benefits of Industry 4.0, including improved efficiency, enhanced decision-making, and long-term competitiveness.

Managerial Implications

From a managerial perspective, digital transformation should be positioned as a long-term strategic initiative rather than a standalone technological investment. Organizations are required to align digital initiatives with business objectives to ensure that technology adoption delivers measurable value.

A phased transformation approach is recommended, where companies begin by optimizing existing systems such as DCS and PLC before adopting more advanced technologies. This approach reduces implementation risks while maximizing the value of legacy investments.

Furthermore, the integration of OT and IT should be prioritized, as it enables seamless data flow and supports data-driven decision-making. In parallel, organizations must invest in human resource development to build multidisciplinary competencies that combine technical and analytical capabilities. In addition, data should be managed as a strategic asset, requiring organizations to develop capabilities in data governance, analytics, and interpretation. Finally, collaboration within the broader ecosystem—including technology providers, academic institutions, and government—is essential to accelerate digital transformation and innovation.

Theoretical Contributions

This study contributes to the literature by developing an evolutionary perspective of digital transformation that integrates legacy industrial control systems with the Industry 4.0 paradigm. Unlike prior studies that focus primarily on emerging technologies, this research emphasizes the continuity between traditional automation and modern digitalization.

Furthermore, this study advances the understanding of digital transformation by highlighting the shift from reactive to predictive and prescriptive operational models, demonstrating that such transformation is not only technological but also strategic and organizational. Importantly, this research underscores that the success of digital transformation depends on the alignment between technology, business processes, and organizational capabilities. This integrative perspective provides a more comprehensive explanation of why digital transformation outcomes vary across organizations, particularly in developing country contexts.

CONCLUSION

This study concludes that digital transformation in the manufacturing sector is an evolutionary and integrative process that extends beyond technological adoption to encompass strategic, organizational, and operational dimensions. The findings highlight that the transition toward Industry 4.0 is strongly influenced by the alignment between legacy industrial systems, such as DCS and PLC, and advanced digital technologies, including IoT, artificial intelligence, and data analytics. The study demonstrates that the integration of Operational Technology (OT) and Information Technology (IT), supported by organizational readiness and a data-driven culture, is a critical determinant of successful digital transformation. Furthermore, the shift from reactive to predictive and prescriptive operations reflects a fundamental change in how manufacturing systems create value and enhance operational performance. In the context of developing countries, particularly Indonesia, the success of digital transformation is constrained by infrastructural limitations, human resource capabilities, and challenges in integrating legacy systems. Therefore, a phased and strategic approach is essential to ensure sustainable implementation. This study contributes by offering an evolutionary and holistic perspective on digital transformation, emphasizing the importance of aligning technology, processes, and organizational capabilities. Future research is recommended to empirically validate the proposed framework and explore its application across different industrial contexts.

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