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Engineering Education in the Context of Industry 4.0

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Abstract. An approach is made to engineering studies in the face of the fusion of physical, digital, and biological technologies, which are transforming the society of the Fourth Industrial Revolution, or Industry 4.0. Methodologically, an analytical-prospective approach was applied, sustained by a conceptual review and the theoretical integration of Aldert Kamp, Klaus Schwab, and Nagib Callaos. The results demonstrate that contemporary digitalization does not constitute a technological phenomenon solely, but rather a cultural and structural transformation of production, knowledge management, and organizational dynamics. The cases of Ireland, Colombia, and Peru show different levels of digital readiness, connectivity, and development of innovative ecosystems. Likewise, the expansion of Generative AI (GAI) and other converging technologies, such as IoT, cloud computing, Blockchain, Big Data, and intelligent automation, requires redefining the engineer's profile toward systemic analysis competencies, ethical validation, and the interdisciplinary resolution of complex problems. It is suggested that universities and organizations move toward flexible, integrated educational models oriented toward technological adaptation. Weaknesses were identified in enabling infrastructure, both for computing and for quality connectivity. To build bridges toward technology-supported entrepreneurship, business models using "Startups" are suggested, through the Lean Canvas template, their "Business Model," and validation with GAI. It is concluded that the relevance of the contemporary professional depends on their capacity to adapt, overcome, and emerge strengthened within a context of legal certainty and technical infrastructure; both of which are pillars for Industry 4.0.

Keywords: Industry 4.0, Higher Education, Generative AI, Stakeholder Capitalism, Knowledge Society.

1. Introduction

The transition toward the “Digital Era” constitutes one of the most significant transformation processes since the classical Industrial Revolution. The convergence among massive connectivity, advanced automation, artificial intelligence, and cyber-physical systems has impacted economic, productive, and educational structures on a global scale (Avella Guevara, 2024). The so-called Fourth Industrial Revolution is not limited to the incorporation of new technologies; it represents a profound modification of the relationships among information, knowledge, labor, and innovation capacity. Progressive digitalization forces a review of human talent formation with the purpose of developing competencies aligned with the demands of automated productive environments (Hariharasudan & Kot, 2018).

In Latin America, this review is urgent due to the existing gap between university graduation and the actual operational requirements of organizations. Additionally, these competencies must be oriented toward complex problem-solving and the management of disruptive technologies. In this context, engineering ceases to be conceived exclusively as a technical discipline associated with industrial processes and transforms into a space of interdisciplinary integration among computing, data analytics, automation, ethics, and sustainability.

The technological acceleration following the COVID pandemic intensified the expansion of digital models based on cloud computing, telecommuting, intelligent automation, and artificial intelligence platforms. This process has been consolidating a new productive logic characterized by hyperconnectivity, the integration of digital ecosystems, and the centrality of data as a strategic resource. Contemporary engineering thus faces the obligation to train professionals capable of operating in dynamic environments where the physical, the digital, and the biological converge.

The relevance of the study lies in the fact that multiple Latin American educational institutions still maintain curricular models conceived for industrial contexts prior to the expectation of accelerated progressive digitalization. The distance between emerging technological demands and traditional educational capacities could generate significant gaps in innovation, competitiveness, and productivity. This situation acquires special importance in the face of the expansion of Generative Artificial Intelligence (GAI), which is capable of intervening in processes of design, programming, simulation, and industrial optimization.

Consequently, this article aims to analyze the relationship between progressive digital transformation, Industry 4.0, and engineering education; integrating as a possible alternative the approaches of the triad of authors: Kamp (2016), who projects a professional profile with adaptability for 2030 that combines deep specialization in a specific area with transversal skills and basic knowledge in other disciplines ("T-shaped"); Schwab (2018), with his proposal of Stakeholder Capitalism for sustainable ventures, positing the transition toward a multivariate commitment structure with all stakeholders as a vector of social justice (Schwab, as cited in Roberts, 2019); and Callaos (2015, 2018), who redefines Engineering for Development through the distinction between: Instrumental Instruction and Holistic Education.

2. Background and Theoretical Framework

Contemporary digital transformation is based on abandoning a society conceived around the accumulation of information and accepting one oriented toward the generation of knowledge. One of the central elements of this revolution is the progressive disappearance of traditional boundaries between technical disciplines. Contemporary engineering develops on integrated architectures where sensors, algorithms, digital platforms, and communication networks interact permanently. Information constitutes a raw input, whereas knowledge emerges subsequently through processes of interpretation, contextualization, interaction with peers, and posterior application.

The reality of the digital society evidences that the amount of available information grows exponentially while human processing time tends to decrease. This condition generates phenomena of cognitive overload and "Infoxication," a situation that adds to the reasons for rethinking the function of higher education, and engineering in particular.

The "Phygital" concept or Cyber-physical systems precisely represents the context of hybrid integration between the tangible and the virtual. These systems allow the creation of digital twins capable of simulating industrial behaviors in real time, thereby modifying the logic that underpins design, manufacturing, and maintenance. The dominant and disruptive technologies that enable the Fourth Industrial Revolution result from the logical progression that began with Moore's Law and the exponential growth of technologies linked to electronics and telecommunications. Moore's Law was an empirical observation formulated by Gordon Moore, co-founder of Intel, in 1965, which establishes that the number of transistors on a microprocessor doubles approximately every two years, achieving greater processing power and cost reduction at the same time. Additionally, the rapid evolution and democratization of Artificial Intelligence (AI) emphasize the need for strategic academic integration to maintain institutional and professional competitiveness.

Digital transformation would force a reconsideration of traditional curricula, given that the model centered exclusively on technical instruction, memorization, and disciplinary knowledge proves insufficient in the face of the speed of technological change (Benešová & Tupa, 2017). Universities no longer face isolated subjects, but rather convergent technological ecosystems where artificial intelligence, data analysis, automation, cybersecurity, and business management interact. In light of this reality, modern engineering education must balance conceptual knowledge with cognitive flexibility to solve problems in environments of high uncertainty. In this scenario, professionals, according to Cornella (2009, 2016), must assume a hybrid role as a technological designer, innovation manager, and articulator of organizational transformation processes; an indispensable evolution considering that the convergence among the Internet of Things (IoT), Cloud Computing, Blockchain, Big Data, and intelligent automation configures the structural base of Industry 4.0.

Technological layer structures are established that do not operate in isolation, but instead constitute a cyber-physical tissue that redefines the analytical and creative capacity of contemporary engineering in multiple applications. Interoperability between technologies ceases to be an optional competitive advantage and becomes an essential condition for organizational functioning. According to the trends that the Gartner Group (2024) and other strategic analysts place as imperatives for 2024 and subsequent years, innovation could be backed by protecting investment via governance in code matters, the rise of creators through the democratization of generative tools, and the delivery of value through sustainable cyber-physical ecosystems. These trends would make a renewed contemporary engineering more viable and operational.

On the other hand, the evolution of Large Language Models (LLMs), which have evolved toward Generative Artificial Intelligence (GAI) or GenAI, constitutes one of the most disruptive changes today by offering systems based on multiple applications of free or commercial access endowed with powerful skills. This technology transforms the relationship between the human being and technical knowledge by delegating repetitive cognitive tasks to systems capable of generating text, code, simulations, and complex designs. By integrating areas such as Natural Language Processing, computer vision, and machine learning, GAI enables industrial models where data becomes the central resource for predictive decision-making. In the educational and professional field, this ecosystem redefines the processes of learning and software development in engineering (Rahman et al., 2026), since the engineer no longer must limit themselves to programming or designing conceptual structures, but is forced to develop critical capacities for ethical validation, algorithm auditing, and the design of complex prompts.

Below are some considerations of authors who shape the theoretical framework:

Kamp (2016) argues that 21st-century engineering requires professionals with transversal competencies, systemic thinking, and continuous adaptation capacity. He proposes changing the current objectives of the teaching-learning model and suggests those indicated in Table 1. Technological acceleration reduces the temporal validity of specialized knowledge and shifts the curricular emphasis toward cognitive skills of integration and complex problem-solving. The training of the engineer entails the reinvention of talent to migrate toward the vision of Kamp, who projects a professional for 2030 capable of managing uncertainty and interdisciplinary. When reviewing Kamp's work and his proposals for 2030, in addition to the change in study plans due to the advancement of technology, he suggests migrating from a model centered on technical instruction toward one useful for Industry 4.0. This model prioritizes interdisciplinary, systemic thinking, and the resolution of highly complex problems.

Table 1: Trends to 2030: Suggested Changes for the Engineering Training Process

#	Current Status of Educational Objectives	Proposed Objectives to Follow according Kamp (2016)
1	Mono-disciplinary thinking	Multi-disciplinary and inter-disciplinary
2	Reductionism	Integration
3	Analysis	Synthesis
4	Abstract	Experimental with common sense
5	Developed and organized	Correlating chaos and resilience
6	Techno-scientific base	Humanity and empathy, business vision
7	Convergent thinking	Creativity
8	Precise understanding	Management of ambiguity and failure
9	Rational problem solving	Complex problem solving
10	Individual work	Collaborative work
11	Limited experience	Lifelong learning

Klaus Schwab (2018) defines the Fourth Industrial Revolution as a stage characterized by the fusion of the physical, digital, and biological worlds. This convergence is expressed through technologies such as the Internet of Things (IoT), cloud computing, artificial intelligence, robotic automation, virtual simulation, and cyber-physical systems. At the same time, Schwab introduces "Stakeholder Capitalism," where digital entrepreneurship must serve as an engine for a fair and sustainable future, integrating all interest groups into the value chain. The vision of Schwab, Founder and Executive Chairman of the World Economic Forum (WEF), suggests the reconfiguration of the business ecosystem. He proposes the transition from the traditional model of shareholder primacy toward a structure of multivariate commitment with all interest groups (stakeholders). The argumentative structure develops from the necessity of a fair and sustainable digital future, passing through the logic of new entrepreneurship, to the integration of technology as a useful vector for achieving improvements in social justice. It seeks to demonstrate that, in the era of Industry 4.0, economic profitability would be inseparable from ethical viability and environmental sustainability.

Nagib Callaos (2015, 2018) maintains that higher education must transcend simple technical instruction to orient itself toward human and social development. From this perspective, the engineer must not limit themselves to the instrumental mastery of technologies, but rather develop capacities for critical discernment, interdisciplinary integration, and systemic understanding. Under the lens of Callaos (2015), the agenda is articulated around two axes: the first axis, the division of a concept into two complementary but distinct aspects, between "technical instruction and integral education," and the second axis refers to the study of the ultimate ends or purposes of "engineering for development." It attempts to analyze how higher education must transcend or go beyond the mere transfer of data, transmission of information, and concepts to focus on the formation of character and wisdom. Callaos (2018) proposes that "Engineering for Development" move away from short-sighted specialization to embrace a systemic and humanistic vision. Thus, the structure of the analysis transitions from the semantic definition of pedagogical processes to proposing that the operationally of engineering be reached as a creative act oriented toward the common well-being.

3. Methodology

We developed this study through a qualitative approach of an analytical-prospective character. The primary sources are the cited authors and other references. A strategy of extractive and productive synthesis was applied, oriented toward identifying recurrent conceptual categories, systemic relationships, and emerging trends associated with digital transformation and engineering education. The procedure included three stages. Figure 1 shows these stages:

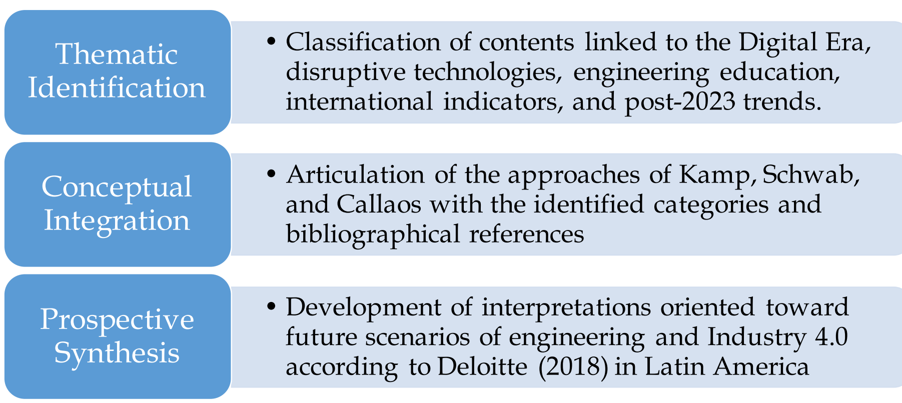

Figure 1: Stages of procedure

The analysis was sustained by references originating from international organizations, technological enterprises, and specialized authors cited in the text, including leading technology firms and technology vendors such as McKinsey (2018, 2023), Gartner (2024), Deloitte (2018), and organizations such as the World Economic Forum.

4. Results and Analysis

4.1. Digital Infrastructure and Technological Acceleration

The sources demonstrate that contemporary digital transformation depends on the simultaneous expansion of connectivity and computational capacity according to McKinsey (2018). The evolution of telecommunications evidences a leap from transmission speeds of 300 bps in 1990 to 5G networks capable of reaching 10 Gbps in 2019. Projections toward 2030 anticipate 6G technologies with transfer capacities measured in terabytes per second. In parallel, the density of transistors on microprocessors evolved from 2,300 transistors in 1971 to more than 114 billion in 2022. This computational hyper scalability constitutes the material base for the deployment of advanced models of artificial intelligence and digital simulation. The analysis demonstrates that technological infrastructure has evolved from a functional utility into the strategic core of economic and organizational competitiveness according to Telefónica (2023).

To fully synthesize this macro-technological shift, it is essential to incorporate the seminal framework established by Henning Kagermann, who officially coined and conceptualized the term *Industrie 4.0* as a strategic initiative for high-tech industrial transformation (Kagermann et al., 2013). Kagermann argues that the foundational bedrock of this revolution is the integration of Cyber-Physical Systems (CPS) into manufacturing and logistics, creating an intelligent infrastructure where machinery, storage systems, and operational facilities are autonomously networked. This vision implies that raw infrastructure parameters—such as the massive computational hyper scalability and bandwidth acceleration outlined by strategic reports—do not function merely as passive communication pipes. Instead, under Kagermann's structural approach, they represent the indispensable enabling environment required to decentralize industrial control, allow autonomous end-to-end digital integration, and shift global manufacturing paradigms from rigid centralized frameworks toward highly agile, hyper connected, and autonomous production networks.

4.2. Digital Ecosystems and Cyber-Physical Systems

The thematic analysis reveals that Industry 4.0 operates through integrated and hierarchical technological ecosystems. In this regard, architectures composed of sensors, programmable logic controllers, and supervisory control and data acquisition systems for industrial processes at a local or remote level (SCADA) are described. To this infrastructure are added specialized software platforms that monitor, control, and record productive processes in real time through MES (Manufacturing Execution System) systems, as well as enterprise resource planning (ERP) tools interconnected through cloud computing to integrate areas such as sales, inventory, finance, and human resources. Facing this complex network, the need is described for future engineers to understand the multidimensional interaction of data in real time (National Academies of Sciences, Engineering, and Medicine, 2016), which implies transitioning urgently from isolated laboratories toward learning platforms based on digital twins and cyber-physical simulation.

Said structures and systems allow the intelligent automation of industrial processes and the creation of adjustable or adaptable systems based on continuous data acquisition. In sectors such as energy and oil, the integration of analytics, Machine Learning (ML), and remote operation enables cost optimization and predictive maintenance. Technological convergence redefines the classical notion of industry. Contemporary production systems function as collaborative networks where suppliers, clients, and digital platforms share information in real time.

This intricate cyber-physical architecture is deeply grounded in the operational theories developed by Detlef Zühlke regarding the practical implementation of the "Factory-of-Things" (Zühlke, 2010). Zühlke pioneered the application of the Internet of Things (IoT) at the shop-floor level, demonstrating that the future factory must be broken down into smart, modular, and autonomous components equipped with localized processing power and ubiquitous wireless communication interfaces. According to Zühlke's paradigm, the traditional rigid automation pyramid—which strictly separated physical hardware from high-level enterprise software (ERP/MES)—is being dismantled and replaced by an interconnected network of plug-and-play industrial entities. Consequently, future engineers cannot limit their understanding to isolated local instrumentation; they must be trained to manage fluid, dynamic shop-floor environments where every individual sensor and actuator possesses an operational digital identity and interacts directly with cloud environments.

Complementing this structural breakdown, Lihui Wang provides the definitive analytical link regarding the operationalization of Cyber-Physical Systems (CPS) and Digital Twins within contemporary manufacturing setups (Wang et al., 2015). Wang argues that the true value of Industry 4.0 does not stem from pure automation, but from the deep bidirectional synchronization between physical manufacturing assets and their virtual, cloud-based counterparts. By collecting real-time sensor streams across Zühlke's modular shop floors, these cloud-embedded Digital Twins run continuous simulations, monitor structural behaviors, and execute predictive optimizations. For engineering education, Wang's research highlights an imperative shift: training can no longer rely on static laboratory assignments. Educational models must pivot toward cloud-manufacturing platforms where students interact with high-fidelity digital twins, learning to govern systems where algorithmic outputs directly control physical machinery across distributed networks.

To orchestrate the massive stream of operational information running through these systems, the 5C architecture developed by Jay Lee provides a systematic, step-by-step framework for integrating intelligence into industrial platforms (Lee et al., 2015). Lee's model structures the deployment of industrial artificial intelligence and predictive analytics across five distinct layers:

1. Connection Level (accurate data acquisition from sensors),
2. Conversion Level (transforming raw data into meaningful clinical information through analytics),
3. Cyber Level (the central hub where the Digital Twin aggregates all data to understand the machine's state),
4. Cognition Level (applying Machine Learning to generate diagnostic insights and predictive maintenance recommendations for expert decision-making), and

5. Configuration Level (the feedback loops that autonomously adjust physical systems based on cyber insights).

Integrating Lee's 5C framework into the curriculum ensures that future engineers do not view data analytics as a separate computer science module, but as a core, continuous, closed-loop architecture that drives industrial resilience, asset optimization, and autonomous self-configuration.

To evaluate how these cyber-physical frameworks, operate on a macroeconomic scale, the following sections analyze the digital readiness and human capital strategies of diverse international scenarios, specifically Ireland and Colombia.

4.3. Ireland: Digital Maturity and Human Capital

The case of Ireland evidences the relationship among connectivity, human capital, and digital competitiveness. The country occupies leading European positions in digital transformation indicators thanks to a strategy based on technological entrepreneurship, connectivity infrastructure, and specialized training. Among the most relevant factors, the availability of qualified talent, the presence of hyper scale data centers, and the articulation with global corporations such as Amazon and Microsoft stand out. Likewise, the existence of stable and attractive regulatory and fiscal frameworks has favoured sustained technological investments. The Irish model would indicate that digital transformation requires a simultaneous integration of public policies, infrastructure, and advanced education.

4.4. Colombia and the Digital Economy Agenda

Colombia (Duque, 2023) appears as a regional reference in Latin America for its strategy oriented toward connectivity, entrepreneurship, and the development of digital human capital. The goal of training 100,000 programmers in two years constitutes an indicator of state recognition regarding the centrality of human talent in the digital economy. Additionally, the deployment of fibre optics, 5G pilot projects, and migration toward cloud services strengthen the national technological ecosystem. Nonetheless, the analysis also identifies situations to be resolved related to informality, intellectual property protection, and the need to consolidate ethical frameworks for artificial intelligence.

4.5. Generative Artificial Intelligence and New Business Models

The expansion of GAI represents one of the central pieces of evidence of the study. According to Gartner, by 2026, nearly 80% of organizations will integrate AI models into their operations. GAI substantially modifies the praxis of engineering by automating tasks related to programming, simulation, generative design, and predictive analysis. The engineer evolves from a technical operator toward a strategic supervisor and architect of human-machine interaction. Currently, GAI serves as an effective cognitive amplifier or a collaborative tool for ideation and synthesis. This transition implies a curricular redefinition where competencies associated with ethical validation, problem formulation, critical thinking, and contextual interpretation capacity acquire relevance.

5. Discussion and Analysis of Results

We developed ideas regarding the convergence of paradigms that define the best professional profile in Industry 4.0. To this end, the educational trends toward 2030 (Kamp, 2016), the ethical framework of stakeholder capitalism (Schwab, 2018; Roberts, 2019), and the ontological distinction between education and instruction (Callaos, 2015, 2018) were articulated. A joint vision of the three aforementioned authors is analyzed, amalgamating the profile of the "T-Shaped" engineer, whose mission transcends algorithmic efficiency to become an engine of "Engineering for Development". An attempt was made to advance from the theoretical intersection of the authors, coincidences, and contradictions, to the proposal of an educational ecosystem that balances scientific rigor with systemic wisdom and social commitment.

The results obtained confirm the convergence among the theoretical approaches of Kamp (2016), Schwab (2018), and Callaos (2015, 2018) regarding the necessity to transform engineering education in the face of technological acceleration. Schwab (2018) maintains that the Fourth Industrial Revolution integrates physical, digital, and biological dimensions. The results show that this convergence is already materializing through cyber-physical systems, digital platforms, and intelligent architectures capable of operating over large volumes of data. Kamp (2016) posits that contemporary engineering must be oriented toward competencies in complex problem solving and continuous adaptability. The analyzed evidence confirms that rigid professional profiles prove insufficient in the face of technological ecosystems characterized by accelerated innovation and dynamic obsolescence. Likewise, Callaos's approaches acquire special relevance in the face of the expansion of GAI. The abundance of information does not guarantee knowledge generation or sustainable social development. Higher education faces the challenge of training professionals capable of exercising critical discernment and ethical responsibility in environments dominated by cognitive automation.

The reinvention of talent and, therefore, of the human capacities required to form part of and compete according to Roca (2012) in the Fourth Industrial Revolution, could be satisfied by the authorial triad composed of Aldert Kamp (2016), Klaus Schwab (2018), and Nagib Callaos (2015, 2018), whose visions converge on the need for a new professional ethos; this would derive in a change that surpasses what is simply known as technical efficiency. It will be a change in behaviour, character, and labour values toward a more humane, responsible, and socially committed approach. The automation figures and the skills profile announced annually at the Davos World Economic Forum (WEF) seem to validate the curricular restructuring or the change in the teaching-learning methodology proposed by Kamp for the year 2030.

The transition from analogue models toward the cyber-physical hybridization established by the Fourth Industrial Revolution or Industry 4.0 forces the articulation of three axes: the taxonomic distinction of digital processes (digitalization vs. transformation), the systemic attributes of the current era (interconnectivity and convergence), and the change or disruption that value models entail. Furthermore, the Knowledge Society, under the lens of Peter Drucker, establishes knowledge as the sovereign resource of modern production. The path toward the digital era is not limited to an update of instrumental endowment and algorithmic codes; it proposes a paradigm shift, according to McKinsey (2023), both in organizational culture and in complex problem solving.

The analysis of digital readiness indicators according to Ribas (2017) in regions such as Ireland, Colombia, and the specific case of Peru, reveals that technological maturity depends on integrated hierarchical ecosystems, whose components display dense interoperability and synchronization across distinct structural and operational scales. The cases of Ireland and Colombia reveal that digital transformation does not depend exclusively on technological infrastructure. The decisive factor would lie in the institutional capacity to articulate human talent, connectivity, legal certainty, and innovation ecosystems.

A transcendent milestone is the evolution of initiatives such as DeepMind, which symbolize the transition "from gaming to science," where deep learning algorithms optimize the frontier of scientific knowledge, with a great impact on pharmacology and medicine. Additionally, the code used was made open source (Haas, 2024). As an example to follow, two axes are appreciated: reinforcement learning or the trial-and-error method to reach a second axis, of another level, related to a General Purpose AI; all of this to derive in the materialization of solving the problem of decoding proteins through AlphaFold. This advance not only constitutes a technical achievement but perhaps also a paradigm shift in the relationship between algorithmic modelling and experimental sciences.

Technological integration post-2023 necessarily demands a high-quality connectivity infrastructure as a sine qua non condition for the digital economy, according to Abasolo (2019). The irruption of GAI also introduces a relevant epistemological tension. While classical automation replaced repetitive physical tasks, GAI intervenes directly in cognitive activities traditionally considered exclusive to the human intellect. This would force a redefinition not only of professional competencies but also of the pedagogical foundations of engineering education. The training of the specialist, in the various disciplines, would be subjected to a dialectical review: is their reinvention necessary? The answer could reside in the capacity to integrate Generative AI tools into business models such as Ash Maurya's Lean Canvas. Twenty-first-century startups operate under the logic of technologies such as Application Programming Interfaces (APIs) as well as value creation supported by intelligent systems. In that sense, digitalization is not an end, but the means for new engineering disciplines and other areas of knowledge to work collaboratively to provide timely responses to innumerable local and global problems, grounding themselves in a robust bibliography and in an ethical and strategic praxis. Said praxis translates into simultaneously acting ethically under solid moral principles in accordance with prior strategic planning with a view to achieving long-term objectives.

6. Conclusions and Final Reflections

The prospective analysis and the review of international scenarios allow for the conclusion that engineering training profiles must be structured under a systemic and flexible approach. In the face of the speed of technological disruption, universities cannot limit themselves to the teaching of isolated tools; on the contrary, it is imperative to prioritize both hard technological skills and transversal competencies, such as adaptive leadership and interdisciplinary communication (Cortes Coss, 2024).

The regional cases evaluated confirm that purely technical development, if it lacks a robust innovation ecosystem, quality enabling infrastructure, and ethical governance, limits the real impact of Industry 4.0 in Latin America. Therefore, the current landscape of higher education in engineering demands a profound curricular reform that transcends disciplinary memorization. The adoption of interactive learning models is required to prepare professionals not only to assimilate emerging technologies and artificial intelligence but to critically lead the socio-technical transformation processes demanded by contemporary organizations within the knowledge society.

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