

From Industry 5.0 to 6.0: Future Skills for Human–Technology Collaboration in Sustainable Manufacturing*

Joanna OLEŚKÓW-SZŁAPKA

Poznan University of Technology, Department of Engineering Management,
Institute of Logistics, Poznan, Poland

Correspondence should be addressed to: Joanna OLEŚKÓW-SZŁAPKA, joanna.oleskow-szlapka@put.poznan.pl

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Abstract

The transition from Industry 4.0 through Industry 5.0 toward Industry 6.0 marks a paradigmatic shift from technology-driven automation to sustainable, human–machine symbiosis. While Industry 4.0 emphasized digitalization, cyber–physical systems, and data integration, Industry 5.0 reintroduced human-centricity, sustainability, and resilience as key pillars of industrial transformation. Building on this foundation, Industry 6.0 envisions hyper-connected, autonomous, and adaptive ecosystems where humans and intelligent systems co-evolve within ethically governed and environmentally conscious frameworks. This paper explores how the principles of Industry 5.0 form the conceptual and operational basis for Industry 6.0 and identifies the evolving skill sets necessary for future workforce adaptability.

Using a multidisciplinary approach combining conceptual synthesis and review of recent empirical studies, the paper examines emerging competences required to navigate technological complexity and sustainability imperatives. Findings indicate that technical proficiencies—such as artificial intelligence, quantum computing, and data analytics—must be complemented by meta-skills including adaptability, creativity, ethical reasoning, and systems thinking.

The study concludes that successful transition to Industry 6.0 requires more than technological readiness—it demands a holistic alignment between innovation, human capital development, and systemic sustainability. Preparing engineers and managers for this new paradigm calls for curricula integrating digital literacy with social, environmental, and ethical dimensions, enabling them to act as mediators between technological progress and sustainable societal transformation.

Keywords: Industry 6.0, Industry 5.0, Industry 4.0, Future skills, Sustainability and Resilience, Workforce transformation, Transdisciplinary Innovation, Hyperconnectivity

Introduction

While Industry 4.0 was primarily focused on the integration of cyber–physical systems, automation, and data-driven technologies, it has often been criticized for its strong technological determinism and insufficient attention to human and environmental dimensions. As a response, Industry 5.0 emerged, positioning human-centricity, sustainability, and resilience as the three main pillars of the next stage of industrial transformation. This paradigm shift reflects a growing recognition that technological innovation should not only enhance efficiency but also support ecological responsibility and societal well-being, while addressing vulnerabilities exposed by global disruptions such as the COVID-19 pandemic. Building on this foundation, Industry 6.0 is increasingly discussed in the academic literature as the next stage of evolution, moving beyond human–machine collaboration toward a vision of human–machine symbiosis within autonomous, hyper-connected, and adaptive ecosystems. Industry 6.0 expands the scope of industrial transformation beyond manufacturing, incorporating healthcare, education, and urban development, and is often associated with advanced technologies such as generative artificial intelligence, quantum computing, and decentralized autonomous systems. Within this context, the development of future skills

emerges as a critical factor, ensuring that workers and organizations can navigate technological complexity while safeguarding sustainable, ethical, and human-oriented industrial progress.

The objective of this paper is to highlight the ongoing transition from Industry 4.0 to Industry 6.0 and to define the conceptual boundaries of these terms. Furthermore, the paper aims to provide insights into the skills required in an era where humans are expected to collaborate with robots, adapt to dynamic technological and societal changes, and simultaneously maintain a sustainable transition.

Specifically, the study aims to (1) examine how Industry 5.0 principles of human-centricity, sustainability, and resilience provide the foundation for Industry 6.0; (2) identify and discuss the future skills required to enable human-machine symbiosis within hyper-connected and autonomous industrial ecosystems; and (3) analyse conceptual and empirical contributions that illustrate how education, training, and policy frameworks must evolve to prepare the workforce for this paradigm shift.

Industrial Paradigm Shift: From 4.0 to 6.0

The Transition from Industry 4.0 through Industry 5.0 toward Industry 6.0

The concept of Industry 4.0 emerged around 2011, emphasizing cyber-physical systems, smart factories, and integration across digital value chains (Meindl & Mendonça, 2021). Its focus was largely technological, often criticized for underplaying human and environmental dimensions (Margherita & Braccini, 2021).

The industrial sector had only just begun to adapt to the concept of the Fourth Industrial Revolution when new visions of the next stage of transformation emerged, referred to as Industry 5.0. The term was first introduced in 2017 by Esben H. Østergaard (2018) CEO of REInvest Robotics.

In 2021, the European Commission published the first comprehensive framework for the Fifth Industrial Revolution in its report Industry 5.0. The document identifies three main pillars that define the new approach to production: (1) human-centric orientation, (2) sustainability, (3) resilience of industrial systems.

Industry 5.0 emerged as a response to a purely technology-driven approach, bringing back the focus on human needs, environmental responsibility, and system resilience.

Human and social centrality is widely recognized as the defining feature of Industry 5.0. On the industrial level, this approach emphasizes reskilling and upskilling of employees, aligning technological development with human needs, and improving workplace safety and ergonomics. From a socio-political perspective, it supports social protection measures aimed at mitigating labor market disruptions and preventing workforce polarization. Industry 5.0 builds on synergies among its technological foundations—such as cyber-physical systems, adaptive robotics, and intelligent software workers—which through real-time integration improve both human well-being and overall productivity, thereby contributing to inclusive sustainability (Ghobakhloo et al., 2023).

“Instead of asking what we can do for technology, we ask what technology can do for us” write Maija Breque, Lars De Nul, and Athanasios Petridis. In elaborating on the pillar of sustainability, the experts reiterate well-established principles related to the circular economy, ecology, green energy, and the fulfillment of human needs without compromising the ability of future generations to meet their own. They also emphasize the potential of artificial intelligence in optimizing resource consumption. Regarding resilience, the experts refer to geopolitical shifts, crises such as the COVID-19 pandemic, and the challenges arising from the vulnerability of globalized production systems.

The debate on sustainable development has gained growing attention in both public and academic discussions. The concept highlights the need to balance social, economic, and environmental aspects of human activity. Although it has been present in academic discourse for several decades, its importance has recently increased. Within this approach, it is crucial to seek long-term solutions in the economy that respond to current societal needs while protecting the ability of future generations to meet theirs, thus ensuring fairness between generations and supporting a comprehensive view of development (Kozar, Matuszewska-Kubicz, 2022). Human-machine collaboration is becoming increasingly important in a rapidly evolving world. To address complex challenges and harness the full potential of technology, it is essential that humans and machines work together seamlessly. “In order to support effective and productive cooperation between humans and machines, it is crucial to invest in the development of the necessary skills and knowledge.” (Kozłowska et al., 2021).

In recent years, scholars have begun to explore Industry 6.0 as the next evolutionary stage in industrial paradigms, extending beyond the human-centric and sustainable orientation of Industry 5.0. According to Verma et al. (2025), Industry 6.0 is defined as a form of ubiquitous, hyper-customer-driven, virtualized, and sustainable manufacturing, wherein factories are hyperconnected, highly autonomous, and responsive to individualized demand, with minimal human intervention.

Other authors (Roshid et al., 2025) characterize Industry 6.0 more broadly as the convergence of human-centric automation, hyperconnectivity, and cognitive manufacturing, driven by advances in artificial intelligence, quantum computing, and edge computing. The concept also encompasses quantum breakthroughs, advanced biotechnologies, neural integration, and decentralized autonomous systems, all within a framework emphasizing sustainable production and adherence to planetary boundaries (AEC Sector, 2025). Industry 6.0 is articulated around several strategic pillars that extend beyond the technological focus of its predecessors. These include technological convergence—such as the integration of artificial general intelligence, Human Digital Twins, quantum computing, and the Industrial Internet of Everything—as well as ethical governance, which emphasizes fairness, transparency, and explainability in AI systems. Complementary pillars highlight inclusive transformation, ensuring equitable access across societies; organizational agility, supporting foresight-driven adaptive structures; and sustainability, embedding circular economy principles and regenerative design within industrial systems (Gomaa, 2025).

Because Industry 6.0 is still nascent, its usage in peer-reviewed literature is limited but growing. A bibliometric and systematic review titled “Industry 6.0 as an Emerging Field of Research” treats it as a merging paradigm of human-centric automation and cognitive manufacturing (Roshid et al., 2025). The same research traces its usage in Scopus-based studies and maps the developmental trajectory of “Industry 6.0” as a field of inquiry. Further, an ASME chapter “Industry 6.0 Transformation: Conceptual Transition” describes I6.0 (Industry 6.0) as a futuristic industrial revolution surpassing the prior five, and outlines its proposed benefits, opportunities, and challenges (Machado, Davim, 2025).

Table 1 presents the key differences and extensions that distinguish Industry 6.0 from its predecessor. Table compares the two paradigms across their core orientation, levels of autonomy, technological enablers, scope, and stakeholder interplay. The comparison highlights how Industry 6.0 aspires to move beyond collaborative human–machine interaction toward more autonomous, intelligent, and ethically governed socio-technical systems.

Table 1: Key differences and extensions between Industry 5.0 and Industry 6.0

Feature	Industry 5.0	Industry 6.0
Core orientation	Human-centric integration (humans and machines collaborate) with sustainability and resilience as core principle	Beyond collaboration toward symbiosis and autonomy, with machines that can self-optimize and human input being minimal
Autonomy level	Humans still participate in decision loops; machines assist or augment	High degree of autonomy: systems anticipate demand, self-configure, self-heal, or self-govern
Technological enablers	AI, IoT, robotics, digital twins, human–machine interfaces	More advanced: quantum computing, edge/ubiquitous AI, neural integration, bio-interfaces, decentralized autonomous systems
Scope	Focus on production, human-machine workspaces, sustainable circular value chains	Extends beyond manufacturing to ecosystem-wide integration (e.g. smart cities, healthcare, biosystems) and an emphasis on planetary boundaries
Interplay of stakeholders	Stakeholder integration with emphasis on social inclusion, ethics, regulation	Greater machine agency, but still embedded in socio-technical governance with stronger demands on oversight and ethical frameworks

Source: Own elaboration based on Verma et al. (2025), Fernández-Miguel et al. (2024), Roshid et al. (2023), and Chaudhuri, Sarvaiya & Sharma (2023).

Verma et al. (2025) position Industry 6.0 as a paradigm where factories are virtualized, hyper-connected, and sustainable. In contrast, studies on Industry 5.0 treat it as a corrective evolution to Industry 4.0, adding human-centricity, sustainability, and resilience components to previously technology-driven systems (Barata, Kayser, 2023).

In summary, while Industry 5.0 builds upon Industry 4.0 by embedding human-centricity, sustainability, and resilience into production systems, Industry 6.0 aspires to a further leap—toward autonomy, intelligent symbiosis, and system-wide integration that goes beyond the factory floor. The concept is still under conceptual development, and further empirical research will be needed to concretize definitions, frameworks, and use cases.

Chaudhuri, Sarvaiya, and Sharma (2023) analyze how workforce transformation shapes value creation across the stages of Industry 4.0, 5.0, and 6.0. The authors demonstrate that leadership vision, digital investment, and continuous upskilling represent the most critical enablers of adaptability, while barriers such as financial constraints, technological immaturity, and organizational resistance significantly slow down transformation. By applying AHP and TOPSIS methodologies, their research reveals that adaptability levels vary across sectors: industries such as IT, manufacturing, and healthcare show relatively high readiness, while construction and retail remain less prepared for systemic change. Importantly, their findings highlight that Industry 5.0 reinforces the importance of human-machine collaboration, requiring creativity, problem-solving, and interdisciplinary teamwork, whereas Industry 6.0 will depend on aligning advanced technologies—including artificial intelligence, quantum computing, and nanotechnology—with resilient workforce strategies and sustainable value creation.

The transition from Industry 5.0 to Industry 6.0 is not only a technological shift but also a profound transformation of workforce requirements, placing future skills at the center of sustainable and human-machine symbiotic manufacturing systems. Recent research emphasizes that beyond digital and technical competences such as artificial intelligence, data analytics, and cybersecurity, so-called meta-skills—including adaptability, resilience, creativity, and systems thinking—are becoming equally critical (WEF, 2025, Skill-Up Project, 2024)

Future Skills in the Era of Artificial Intelligence and Industry 6.0

The transition from Industry 4.0 through 5.0 and toward 6.0 illustrates how successive industrial paradigms increasingly integrate advanced technologies with human-centric and sustainable principles. Within this evolution, artificial intelligence emerges as a pivotal driver of change, reshaping both the structure of employment and the nature of professional tasks. Its growing influence underscores the necessity of redefining the skill sets required in the evolving labour market, where technical competences must be complemented by adaptability, creativity, and ethical awareness.

Artificial intelligence is increasingly influencing the labour market, introducing changes both in the structure of employment and in the way professional tasks are carried out. One of the key aspects of this evolution is the automation of processes, which makes certain routine and repetitive tasks more susceptible to replacement by AI systems. As a result, this may lead to the restructuring of occupations and the reduction of certain job positions, particularly those based on repetitive activities.

At the same time, however, artificial intelligence creates new opportunities for both companies and employees. The use of AI enables the analysis of vast amounts of data within a short period of time, which translates into greater efficiency and precision in task execution. Furthermore, the introduction of artificial intelligence into the workplace opens new domains of application, leading to the emergence of novel professional roles and an increasing demand for new skills.

In summary, artificial intelligence is reshaping the professional landscape, creating both opportunities and challenges for companies and employees. Effective management of these transformations requires adequate preparation and adaptation to the new market conditions (Wang, Lu, 2025).

Digital transformation is a process to which the majority of manufacturing enterprises are intentionally open. Only 5% of respondents indicated that their companies had not planned changes in the use of data and processes, communication methods, and other areas aimed at fully leveraging the opportunities offered by digital technologies. At present, engineers do not perceive digital transformation as introducing radical changes at the level of individual requirements or challenges they will be expected to meet. They generally do not feel that the changes associated with transformation significantly affect the expectations of employers regarding, for example, digital competences. On the one hand, this may suggest confidence in the skills currently possessed or the belief in the ability to acquire new ones easily and quickly. On the other hand, it cannot be excluded that some engineers may not be fully aware of the types of new qualifications that will become indispensable in the context of a comprehensive digital transformation. Scholarly studies estimate that the integration of artificial intelligence into enterprises can raise employee productivity growth by an average of around 3 percentage points. The magnitude of this effect, however, varies considerably depending on methodological assumptions, with reported estimates ranging from 1.7 to 6.9 percentage points (Borowski et al., 2024).

The portal Bank.pl, in the article “How Artificial Intelligence Will Influence Economic Growth and the Labour Market”, presents a chart and three scenarios of productivity development following the implementation of artificial intelligence.

Scenario 1 assumes the absence of AI adoption, which would result in productivity growth remaining at a constant rate (for example, 1% annually).

Scenario 2 assumes that the implementation of AI would contribute to a temporary increase in productivity growth (for example, by 3 percentage points over a 20-year horizon). According to the analysis, “the difference in annual GDP between these two scenarios after 20 years would amount to 80%.” In this context, it is necessary to consider Scenario 3, in which the so-called technological singularity is reached. This refers to a situation in which artificial intelligence surpasses human intellectual capabilities and is able to generate even more advanced forms of artificial intelligence, thereby triggering an exponential technological acceleration. In such an extreme case, productivity growth—and consequently economic growth—would continuously accelerate.

Scenario 3 assumes that after an initial surge in productivity, the growth rate would continue to increase by 1% annually. In this case, GDP after 20 years would be 94% higher than in Scenario 1 and 8% higher than in Scenario 2. However, over a 75-year horizon, GDP would be 35 times higher than in Scenario 1 and 20 times higher than in Scenario 2 (Borowski et al., 2024).

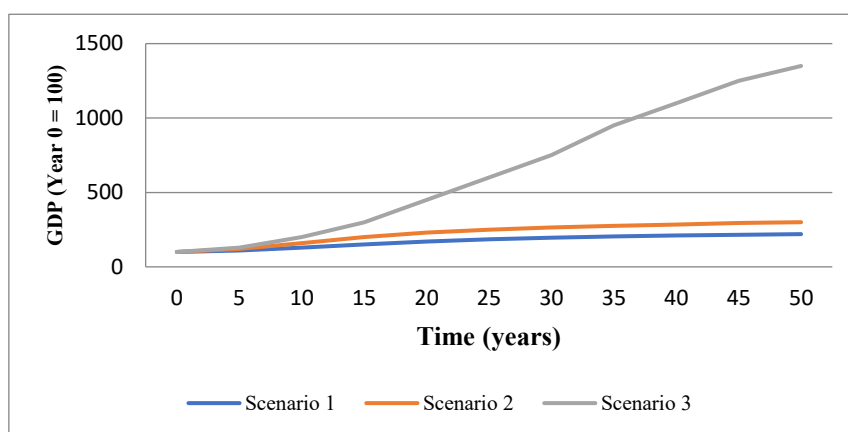


Fig 1. Productivity Growth Scenarios after AI implementation

Source: Borowski et al., (2024)

The potential achievement of technological singularity remains highly uncertain in terms of both timing and feasibility. Should such a phenomenon occur, it could lead to a substantial reduction in employment relative to current levels, with only occupations resistant to automation by artificial intelligence remaining intact. This scenario would pose a profound societal challenge, necessitating regulatory and policy responses. Possible interventions might include moderating the pace of technological development, restricting AI applications in selected sectors, or introducing taxation schemes for enterprises employing advanced automation technologies. Recent studies indicate that the skill requirements of the labour market in 2025 and beyond will increasingly combine advanced digital competences with human-centric capabilities. According to the Future of Jobs Report 2025 (World Economic Forum, 2025), analytical thinking, resilience, flexibility, and agility are among the most sought-after core skills, while expertise in artificial intelligence, big data, cybersecurity, and digital networks continues to expand rapidly. Complementary findings from the World Manufacturing Forum (2025) emphasize the persistence of hybrid skill sets, where technical knowledge such as robotics, automation, and data analytics must be integrated with creativity, teamwork, and entrepreneurial thinking. Moreover, recent labour market research highlights that AI adoption often increases demand for complementary human skills—particularly problem-solving, communication, and adaptability—suggesting that future workforce strategies should align technological competences with broader social and cognitive abilities.

Figure 2 presents the results of a labour market screening of job advertisements conducted in the second quarter of 2025. The dataset included approximately 200 postings collected from major recruitment platforms (Pracuj.pl, No Fluff Jobs, Inzynio, Indeed, Jooble, Praca.pl, and RobotAutomatyka.pl). The analysis shows that in Industry

5.0, employers most frequently demand technical competences such as PLC programming, data analysis, Python programming, and knowledge of automation systems. At the same time, the presence of skills related to machine learning, vision systems, and cybersecurity highlights the increasing convergence of classical automation with advanced digital technologies.

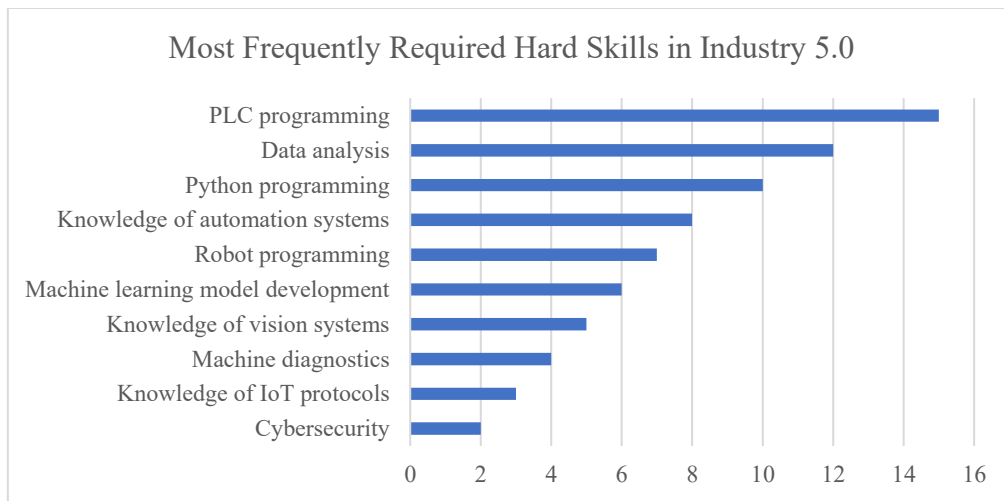


Fig. 2. The most frequently required hard skills in Industry 5.0 appearing in job postings

Source: Elaborated based on current job offers on such websites as Pracuj.pl, No Fluff Jobs, Inzynio, Indeed, Jooble, Praca.pl, RobotaAutomatyka.pl

The numbers in the figure 2 represent the number of job postings in which a given skill was required. An analysis of job offers indicates that in Industry 5.0 both technical and soft skills are of key importance. The most frequently sought competences include PLC programming, data analysis, and knowledge of automation systems. Employers also value analytical thinking, teamwork skills, and effective communication.

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The Future of Jobs Report 2025 (World Economic Forum, 2025) highlights a marked divergence between rapidly growing and at-risk occupations (see table 2). Professions associated with artificial intelligence, sustainability, data analytics, and robotics are projected to expand most dynamically, while routine clerical and transactional roles face progressive decline. This polarization underscores the urgency of re-skilling initiatives that align human capital with evolving technological ecosystems.

Table 2: Fastest Growing vs. Most At-Risk Occupations

Fastest Growing:	Most At-Risk:
1. Specialists in artificial intelligence and machine learning	1. Bank tellers and related clerks
2. Sustainable development specialists	2. Postal clerks
3. Business intelligence analysts	3. Cashiers and ticket sellers
4. Information security analysts	4. Data entry clerks
5. Fintech engineers	5. Administrative and executive secretaries
6. Data analysts and scientists	6. Material recording and stock-keeping clerks
7. Robotics engineers	7. Accountants, bookkeeping and payroll clerks
8. Big data specialists	8. Legislators and officials
9. Agricultural equipment operators	9. Statistical, financial, and insurance clerks
10. Digital transformation specialists	10. Direct sales workers, street vendors and related workers

Source: Own study based on the WEF, 2025

According to the Future of Jobs Report 2025 (WEF, 2025), by 2030 around 22% of current jobs are expected to undergo structural transformation, with 170 million new positions projected to emerge and 92 million to be displaced, resulting in a net increase of 78 million jobs.

In the context of Industry 5.0, the skills palette has already been expanded to include digital human work, resilience, and sustainability competences (Pinzone et al., 2024). Industry 6.0 is expected to reinforce these capabilities and extend them further toward areas such as AI governance, ethical awareness, and the supervision of autonomous, self-optimizing systems (Verma et al., 2025). Case-based studies, for example in welding robotization, also show how manual and perceptual skills remain indispensable for hybrid industrial ecosystems, even in highly automated contexts (Lénat et al., 2024).

The World Economic Forum forecasts that 39% of core skills required for jobs will change by 2030, underlining the urgency of re-skilling and up-skilling initiatives that link educational curricula with industrial needs.

Some conceptual work highlights the term “twenty-first century competencies” as necessary for Industry 5.0, arguing that emerging economies must proactively cultivate skills oriented toward social stability, resource preservation, and climate resilience (Ikenga & van der Sijde, 2024). Meanwhile, recent literature on Industry 6.0 frames it as a nascent research field that blends human-centric automation, hyper-connectivity, and cognitive manufacturing, providing a basis for identifying the next generation of skills (Roshid et al., 2023). In this view, future skills include not only digital and meta-skills, but also competences for oversight, adaptation, and ethical governance in autonomous systems.

In addition to technological and organizational drivers, the transformation of future skills is also shaped by policy and regulatory frameworks. Initiatives such as the European Union’s Pact for Skills (Pact for skills, 2023) emphasize lifelong learning and structured re-skilling pathways, aligning workforce development with industrial and digital priorities. Furthermore, the adoption of the EU Artificial Intelligence Act creates demand for new professional roles, including specialists in ethical oversight, algorithmic auditing, and legal compliance. Sectoral studies further suggest that adaptation to AI is highly uneven across industries: while information technology and financial services demonstrate rapid uptake, manufacturing and logistics adopt more gradually, and education as well as public administration remain comparatively slower in reconfiguring skill profiles.

A central implication of this shift is the reconfiguration of workforce skills. Industry 4.0 was largely underpinned by technical literacy, while Industry 5.0 expanded the scope to include creativity, resilience, and emotional intelligence. Industry 6.0 further raises expectations, requiring transdisciplinary professionals capable of combining ecological awareness, ethical reasoning, and collaboration with emotionally intelligent AI. Future skills are therefore not limited to technological competences but increasingly encompass the ability to navigate moral dilemmas, foster systemic thinking, and co-create solutions in symbiotic human–machine ecosystems (Gomaa, 2025).

Taken together, these insights allow us to conceptualize a skills continuum: Industry 5.0 emphasizes human-centricity, sustainability, and resilience, while Industry 6.0 builds on this foundation to achieve human–machine symbiosis, demanding both advanced technical competences and higher-order cognitive and ethical skills.

Preparing Human Capital for the Transition from Industry 5.0 to 6.0

The transformation from Industry 5.0 to 6.0 not only involves technological convergence but also requires a profound reconfiguration of education, training, and policy. While Industry 4.0 emphasized technical literacy, and Industry 5.0 expanded the focus toward sustainability, resilience, and human-centric collaboration, the emerging Industry 6.0 paradigm calls for even broader competencies. These include the ability to navigate ethical dilemmas, manage autonomous and symbiotic technologies, and design systemic solutions that extend beyond manufacturing into healthcare, education, and urban ecosystems. Consequently, both higher education institutions and policymakers face the challenge of aligning curricula, training strategies, and governance frameworks with these evolving demands.

It is increasingly emphasized that engineers and technical staff must acquire a blend of technical, methodological, and social competences to effectively implement Industry 5.0 strategies. One study proposes a multi-criteria decision-making methodology for selecting appropriate reskilling and upskilling paths in organizations transitioning to Industry 5.0, highlighting that generic digital trainings alone are insufficient (Leon, 2023). Moreover, a conceptual framework for workforce skills in Industry 5.0 integrates labour shortages, eco-digital shifts, and human centricity, suggesting that bridging the gap between policy and firm-level practice is critical (Oeij et al., 2024).

The article “Preparing Students for Industry 5.0: Evaluating the Industrial Engineering and Management Education” emphasizes that the transition from Industry 4.0 to Industry 5.0 represents a shift from a purely technology-driven paradigm toward one that prioritizes sustainability, resilience, and human centrality. The research was carried out by Koch, Volker et al. (2024) from Graz University of Technology. An online survey was conducted in 2022 by the Austrian Association of Industrial Engineers (WING), targeting three groups: students, graduates, and human resource professionals. The sample included 9,758 invited participants (7,478 students and 2,280 professionals), resulting in 1,219 responses, of which 803 were fully completed. The findings reveal that more than 80% of respondents agree that current Industrial Engineering and Management (IEM) curricula require substantial updates to align with the demands of Industry 5.0. Participants identified an optimal competence distribution of 39% technological, 28% methodological, and 33% social skills, highlighting the necessity of balancing technical expertise with soft skills. The study also underscores the importance of lifelong learning, flexible and interdisciplinary curricula, and the integration of sustainability and human-machine collaboration. The authors conclude that higher education institutions must adopt new teaching strategies to ensure that graduates are equipped not only to meet technological challenges but also to act as leaders in ethics, innovation, and social responsibility.

A major contribution of the study Fernandez-Miguel et al. (2024) is the integration of geanthropology as a transdisciplinary framework for understanding human-environment-industry interactions. Looking ahead, the concept of Industry 6.0 is presented as an evolution of Industry 5.0, moving from human-machine collaboration to human-machine symbiosis, with a broader scope that extends beyond manufacturing to healthcare, education, and urban development. Industry 6.0 is envisioned as an era of sustainable innovation, circular economy practices, and ethically responsible technological development. The study demonstrates that even hard-to-abate sectors can become models of ecological transition when systemic and transdisciplinary approaches are applied. Authors present a holistic systemic sustainability index is proposed as a tool to measure and guide sustainability initiatives, reflecting positive trends and adaptability. Index aggregates a broad set of 24 metrics into seven contingency factors: resource consumption, production dynamics, innovation, environmental impacts, social impacts, market dynamics, and economic impacts. Table 3 presents the analytical framework for assessing the sustainability performance of an industrial district, which constitutes the foundation of the proposed *Systemic Sustainability Index (SSI)*. The framework is structured around seven contingency factors—resource consumption, manufacturing dynamics, innovation, environmental impacts, social impacts, market dynamics, and economic impacts—each operationalized through a set of measurable sustainability metrics. In total, 24 indicators are included, covering technical, economic, social, and environmental dimensions.

Table 3: Analytical framework for assessing the sustainability performance of an industrial district

Contingency factors	Sustainability metrics			
	Resource consumption	Water (m ³ /m ³)	Electricity (m ² /kWh)	Natural Gas (m ² /m ³)
Manufacturing dynamics	Production (m ²)	Production by Employee (m ² /employee)	Production Efficiency (m ² /Ton)	Unsold Merchandise in Stock (mln m ²)
Innovation	Investments (€)	Tangible Fixed Assets (€)	/	/
Environmental impacts	GHG Emissions (m ² /Ton CO ₂)	PMP Emissions (m ² /Ton)	VOCs Emissions (m ² /Ton)	Waste Generation (m ² /Ton)
Social impacts	Employees (N ^o)	Average Firm Size (N ^o Employees)	Turnover by Employee (€)	Share Value by Employee (€)
Market dynamics	Total Turnover (€)	Foreign Turnover Ratio (%)	Average Price (€/m ²)	/
Economic impacts	Goods Expense (€)	Financial Expenses (€)	Net Income (€)	Total Assets (€)

Source: Fernández-Miguel et al., 2024.

From an educational perspective, the introduction of systemic sustainability indices highlights the necessity of equipping future engineers and managers with competences that go beyond technical literacy. The ability to interpret and apply integrated performance frameworks such as the SSI requires proficiency in data analytics, systems thinking, and sustainability assessment. This implies that curricula in the context of Industry 5.0 and 6.0

must prepare graduates not only to manage advanced technologies but also to evaluate their broader ecological and socio-economic implications. In practice, this means that educational programmes should integrate sustainability metrics, interdisciplinary project work, and policy-relevant training, enabling future professionals to act as translators between technological solutions and systemic governance requirements.

What makes the index holistic is that it does not analyze these factors separately, but instead integrates them into a unified framework. This allows the assessment to capture the interdependencies and interactions between technological, economic, social, and environmental dimensions. For example, digitalization may simultaneously increase production efficiency (economic factor), reduce emissions (environmental factor), and change workforce structures (social factor). By combining these aspects, the index reflects the overall trajectory of systemic sustainability rather than partial improvements. In practical terms, the holistic systemic sustainability index serves as a key performance indicator (KPI) that managers and policymakers can use to monitor progress, identify weaknesses, and design context-specific sustainability strategies. It thus provides both a measurement instrument and a strategic compass for guiding industrial transformation toward Industry 5.0 and the envisioned Industry 6.0. Chaudhuri, Sarvaiya and Sharma (2023) conduct an empirical investigation into the transformation of the workforce across Industry 4.0, 5.0, and 6.0, focusing on both enablers and barriers of adaptability. Using Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), they rank the relative importance of different drivers of transformation. Their results show that leadership vision (with the highest AHP weight), followed by investment in digital technologies and continuous reskilling, are the most critical enablers of workforce adaptability. Among barriers, the most significant are financial limitations, lack of technological infrastructure, and resistance to change within organizations.

The sectoral analysis further reveals that IT (TOPSIS score 0.82), manufacturing (0.79), and healthcare (0.74) demonstrate strong adaptability to workforce transformation, whereas construction (0.52) and retail (0.47) lag significantly behind. The study also highlights how Industry 5.0 redefines value creation by emphasizing human-machine collaboration, creativity, and interdisciplinary teamwork, while Industry 6.0 extends these requirements toward AI integration, quantum computing, nanotechnology, and systemic sustainability. The authors conclude that sustainable transformation requires sector-specific interventions, robust re-skilling frameworks, and strategic leadership to align human capital with the evolving technological landscape (Kuwar et al, 2025).

These findings collectively underscore that the successful transition from Industry 5.0 to 6.0 cannot rely solely on technological advances. It requires an integrated approach in which education, training, and policy frameworks develop professionals capable of combining technical expertise with systemic, ethical, and sustainability-oriented competences.

Conclusions

The shift from Industry 4.0 through Industry 5.0 to Industry 6.0 represents more than a linear technological progression; it signals a paradigmatic transformation in how manufacturing systems are conceptualized and governed. Whereas Industry 4.0 concentrated on automation and digital integration, and Industry 5.0 introduced human-centricity, resilience, and sustainability, Industry 6.0 envisions manufacturing as a conscious, circular, and regenerative ecosystem. This new paradigm reframes production not only as a site of technological advancement but also as a platform for social innovation, ethical governance, and ecological stewardship (Gomaa, 2025).

Recent research also highlights the dual role of artificial intelligence and big data analytics in reshaping professional landscapes within the transition to Industry 6.0. These technologies not only automate repetitive tasks but also redefine the nature of work, shifting emphasis toward strategic, advisory, and decision-support functions. At the same time, they create demand for new competences, including advanced data analysis, digital governance, and the ethical use of AI, while reinforcing the importance of meta-skills such as critical thinking, adaptability, and communication. This reflects a “technological paradox”: AI and big data simultaneously strengthen professional roles through efficiency and innovation, yet risk eroding traditional skills such as interpersonal interaction or critical evaluation of information. The empirical findings of Deliu and Olariu (2024) illustrate this dynamic, with respondents acknowledging both opportunities and concerns linked to AI adoption.

Beyond technological disruption, the findings of this study underline that the transition toward Industry 6.0 requires profound adjustments in education, training, and policy. Higher education curricula must increasingly integrate interdisciplinary and sustainability-oriented modules, equipping graduates not only with technical proficiency but also with systems thinking, ethical reasoning, and leadership skills. At the same time, re-skilling and up-skilling programmes are indispensable to prepare the existing workforce for new professional demands, especially in sectors with lower adaptability (Chaudhuri et al., 2023). Policy frameworks, including initiatives

such as the EU Pact for Skills and the AI Act, will play a decisive role in aligning labour market needs with societal expectations.

Moreover, systemic assessment tools such as the Systemic Sustainability Index (SSI) provide a strategic compass for Industry 6.0, demonstrating that sustainability cannot be separated from workforce transformation. Understanding and applying such frameworks requires professionals trained not only in engineering but also in data interpretation, socio-environmental analysis, and governance. This highlights the close interconnection between sustainability metrics and the competencies demanded by future industrial ecosystems.

The transition toward Industry 6.0 should thus be understood as a phased and adaptive process rather than a sudden transformation. A realistic roadmap begins with vision alignment across stakeholders, followed by readiness assessments that identify strengths and gaps. Pilot projects, often tested within living labs, provide a foundation for scaling into systemic adoption. Finally, continuous adaptive governance ensures that manufacturing ecosystems remain flexible, resilient, and responsive to changing technological and societal demands (Gomaa, 2025).

Overall, the successful evolution toward Industry 6.0 will depend not only on technological breakthroughs but also on cultivating a workforce equipped for ethical leadership, interdisciplinary collaboration, and systemic innovation.

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