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HUMAN CAPITAL DEVELOPMENT IN THE TRANSITION FROM INDUSTRY 4.0 TO INDUSTRY 5.0: ETHICAL, EDUCATIONAL, REGULATORY PERSPECTIVES

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Abstract. This *study focuses* on the transition of European industry from Industry 4.0 to Industry 5.0, examining the role of trustworthy artificial intelligence (AI), human–machine collaboration and the regulatory and socio-economic requirements of sustainable development. Key enabling technologies – such as artificial intelligence, the Internet of Things (IoT), big data analytics, blockchain, and additive manufacturing – are examined, as well as their role in ensuring the transparency, accountability, and adaptability of production value chains. *Methodology.* This study employs a systematic review of the current academic literature on Industry 4.0/5.0 technologies, EU regulatory frameworks and practical implementation cases. Based on this analysis, it develops a conceptual framework of trust in AI within the context of Industry 5.0, integrating the dimensions of ethics, safety and governance. The main challenges and opportunities for technology integration in industrial ecosystems are synthesised and presented. The research also proposes a set of measurable indicators for evaluating the adaptability, data transparency, security, accountability and human oversight of industrial systems. The *objective* of the present article is twofold: firstly, to identify the fundamental requirements for the implementation of integrated technologies within the European industrial sector; and secondly, to develop a recommendation framework for the realisation of Industry 5.0. The latter is defined as the combination of technological innovation with the social, ethical and legal dimensions of industrial transformation. *Results.* The study identifies the main barriers to effective integration as being data governance, process explainability, trust in AI systems and accountability for automated decisions. It proposes a multi-level trust framework encompassing the following dimensions: data transparency, explainability and auditability, security and privacy, human control and accountability, and standardisation and certification. The findings demonstrate that integrating AI with the Internet of Things (IoT), edge computing and big data analytics enhances the adaptability and product quality of manufacturing systems, but this requires robust change management processes, workforce training and appropriate regulatory support. If implemented through practical monitoring instruments and applied industrial cases, EU regulatory frameworks can drive this transformation. *Conclusion.* A resilient transition to Industry 5.0 requires a comprehensive approach that combines technological modernisation with social and ethical norms, human capital development and robust legal regulation. Institutionalising and adhering to the principles of AI trust, explainability and accountability is crucial for achieving sustainable industrial growth and maintaining the global competitiveness of European manufacturing in the new industrial era.

Keywords: Industry 4.0, Industry 5.0, trustworthy artificial intelligence, AI trust, Internet of Things (IoT), big data analytics, blockchain, additive manufacturing, sustainable industrial development.

JEL Classification: J24, O33, L26, I21

1. Introduction

The industrial ecosystem is currently experiencing a significant evolutionary transformation. This paradigm shift is characterised by a transition from the integration of cyber-physical systems and digital platforms, which underpin the current Industry 4.0 framework, towards a novel paradigm known as Industry 5.0 (Akhavan, 2025). The concept of I

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ndustry 4.0 places significant emphasis on the implementation of automation, enhanced productivity, and optimised efficiency through the integration of smart factories, interconnected machines, and advanced analytics. In contrast, Industry 5.0 aspires to establish a symbiotic relationship between humans and machines (Adel, 2024). This industrial model, representing a new generation of such entities, prioritises not only economic performance but also social responsibility, ethical considerations, and sustainable practices (Xu et al., 2025). In essence, Industry 5.0 redefines the purpose of technological advancement, emphasising the creation of value that benefits both organisations and society at large (Priyadarshini, 2024).

At the core of this transformation is the field of artificial intelligence (AI), which has emerged as a critical enabler for Industry 5.0 (Dmitrieva, 2024). The utilisation of artificial intelligence facilitates real-time decision-making across production chains by means of comprehensive data analysis from interconnected systems. When integrated with the Internet of Things (IoT), edge computing, and big data analytics, AI enhances the flexibility and adaptability of manufacturing processes (Fraga-Lamas et al., 2022). To illustrate this point, consider the potential of AI-driven predictive maintenance. This technological advancement enables machinery to anticipate failures and schedule repairs in a timely manner, thereby minimising downtime and reducing costs (Adel, 2024). In a similar manner, AI has the capacity to enhance the efficacy of supply chains through the dynamic adjustment of production schedules, a process that is informed by fluctuations in demand, the availability of resources, and environmental considerations (Lupi, 2023). These capabilities have been demonstrated to enhance operational efficiency and to reduce waste, energy consumption, and carbon emissions, thereby aligning production practices with sustainability objectives (Rejeb et al., 2025).

Nevertheless, the integration of AI into industrial processes gives rise to a number of novel challenges. As machines and algorithms assume greater decision-making responsibilities, issues of transparency, explainability, and accountability become increasingly important (Xu et al., 2025). It is imperative that organisations and stakeholders demand AI systems that are interpretable, in order to ensure that the rationale behind automated decisions is comprehensible to humans (Dmitrieva, 2024). This requirement is particularly critical in safety-sensitive areas such as autonomous robotics in manufacturing, where errors could have serious consequences (Fraga-Lamas et al., 2022). Furthermore, the deployment of AI raises ethical concerns such as fairness, bias and data privacy, necessitating the establishment of robust governance frameworks (Pant et al., 2025). Addressing these concerns promotes a culture of trust in Industry 5.0, ensuring that employees, managers and end users can rely on AI technologies with confidence (Xu et al., 2025).

The transition towards Industry 5.0 also necessitates a re-evaluation of the workforce and organisational structures. As digital technologies become more integrated into everyday operations, employee roles are shifting away from routine manual tasks towards more cognitively demanding, creative and collaborative functions (Sima et al., 2020). This shift requires significant investment in training and development to provide workers with the necessary new skills. Digital literacy is becoming a fundamental requirement, enabling employees to navigate complex software platforms, interpret data insights and interact effectively with AI-assisted systems (Akhavan, 2025). Analytical thinking and problem-solving skills are also becoming more important, as employees need to be able to evaluate AI recommendations, make informed decisions and find innovative solutions to new challenges (Pant et al., 2025). Given the proliferation of connected devices and the growing vulnerability of digital infrastructure, data management and cybersecurity skills are also essential (Priyadarshini, 2024).

Whilst automation can offer significant efficiency gains, it also has social implications that organisations must carefully manage (Xu et al., 2025). Trust in algorithms is a central concern; employees need to feel confident that AI systems operate reliably and fairly (Adel, 2024). The cultivation of this trust can be facilitated by transparency measures, including explainable AI models, user training, and the implementation of accountability mechanisms (Dmitrieva, 2024). By fostering a collaborative human-machine environment, organisations can ensure that technology enhances human capabilities rather than replacing them (Fraga-Lamas et al., 2022). Such an approach has been demonstrated to support employee well-being, maintain motivation, and encourage active participation in innovation processes (Rejeb et al., 2025).

Another defining feature of Industry 5.0 is its emphasis on sustainability and societal impact (Akhavan, 2025). The paradigm of industrial decision-making has evolved to encompass not only economic metrics but also environmental and social considerations (Lupi, 2023). In the contemporary business landscape, enterprises are progressively held responsible for their ecological impact, resource utilisation, and societal contributions (Grünewald, 2025). AI and other digital tools have the potential to support sustainability initiatives by monitoring energy usage, optimising resource allocation, and predicting environmental impacts (Fraga-Lamas et al., 2022). Furthermore, organisations can utilise AI to enhance worker safety, ensure compliance with regulatory

standards, and promote inclusive practices, thereby creating an industrial ecosystem that is more ethical and socially responsible (Xu et al., 2025).

The evolution from Industry 4.0 to Industry 5.0 marks a significant shift in industrial and organisational thinking. Rather than focusing purely on efficiency and productivity, it adopts a more holistic approach that values human-machine collaboration, ethical responsibility, sustainability, and trust in technology (Priyadarshini, 2024). Artificial intelligence is a key part of this change, as it enables real-time, data-driven decision-making, improves adaptability and supports sustainable practices (Pant et al., 2025).

2. Human Capital Development in Industry 4.0/5.0

In the digital era, human capital refers to the collective knowledge, skills and competencies that allow organisations to adapt to rapid technological change and remain competitive in increasingly complex industrial and economic landscapes (Sima et al., 2020). Human capital is no longer limited to basic education and technical proficiency; it also includes digital literacy, problem-solving skills, critical thinking, creativity and ethical awareness. The accelerated integration of sophisticated technologies, including artificial intelligence (AI), the Internet of Things (IoT), edge computing, robotics, and cyber-physical systems, has profoundly transformed conventional workplace dynamics, thereby necessitating a re-evaluation of human capital strategies. The development and reproduction of human capital, therefore, is a multidimensional process that involves continuous learning, skill enhancement, and adaptation to technological and organisational shifts (Xu et al., 2025).

The following key theoretical constructs are of particular relevance in this context: trust in AI systems, algorithmic explainability, and risk management in automated production environments (Xu et al., 2025). Trust in AI is a prerequisite for effective human-machine collaboration, and employees must have confidence in the fairness, reliability and transparency of AI systems. Algorithmic explainability is defined as the process of ensuring that the decision-making processes performed by AI are comprehensible to humans. This enables managers and employees to evaluate and validate outcomes. In the context of smart manufacturing, for instance, predictive algorithms have the capacity to recommend production adjustments or maintenance schedules. Should these recommendations be opaque, employees may hesitate to implement them, resulting in reduced efficiency and the potential for operational errors. Transparent AI systems have been shown to facilitate comprehension of the reasoning behind decisions, thereby fostering confidence, ethical accountability, and responsible adoption of advanced technologies (Dmitrieva, 2024).

It is evident that risk management constitutes a pivotal element within the framework of human capital development in high-tech workplaces. The integration of automation and artificial intelligence (AI) has been demonstrated to reduce specific operational risks, such as human error in repetitive tasks. However, it has also given rise to new risks, including those related to cybersecurity, data privacy, algorithmic bias, and system reliability (Fraga-Lamas et al., 2022). Consequently, it is incumbent upon organisations to furnish their employees with the requisite knowledge and skills to identify, assess, and mitigate these risks. This encompasses training in cybersecurity awareness, adherence to data protection regulations, and the ethical evaluation of algorithmic outcomes. Employees must possess the capability to not only operate sophisticated digital systems, but also to interpret data conscientiously, assess potential impacts, and intervene when anomalies or ethical concerns emerge (Pant et al., 2025).

An effective response to these challenges requires a multidisciplinary approach. Developing human capital in Industry 4.0 and 5.0 involves more than just technological skills; it also requires the integration of psychological, managerial and social dimensions. Employees, for example, may experience cognitive overload or stress when adapting to highly automated work environments. Therefore, organisations must consider ergonomic and psychological factors when designing training programmes and operational plans. Effective leadership and management strategies are crucial for guiding teams through transitions, motivating employees and fostering a culture of continuous learning and innovation (Pant et al., 2025). Furthermore, cross-functional collaboration between IT specialists, engineers, HR professionals and organisational psychologists ensures that technology is implemented in a way that aligns with human capabilities and organisational goals.

Digital platforms and Internet of Things (IoT) systems are reshaping workforce requirements and redefining organisational structures (Sima et al., 2020). The increasing number of connected devices enables real-time monitoring of production processes, predictive analytics and dynamic decision-making. Consequently, employees are expected to possess advanced digital competence, including the ability to analyse data, interpret complex dashboards, and act on AI-generated insights. Routine manual tasks are increasingly being automated, meaning that employees must now focus on cognitive, creative and strategic functions. In a production setting, for instance, human operators may no longer carry out manual assembly, but instead supervise collaborative robots (cobots),

optimise workflows based on real-time data and develop innovative solutions to improve operations (Xu et al., 2025).

In this context, continuous learning is a cornerstone of human capital development. The rapid pace of technological evolution means that skills can quickly become obsolete. To support lifelong learning, organisations must implement ongoing training programmes, workshops, e-learning platforms and mentorship opportunities (Fraga-Lamas et al., 2022). Educational initiatives should address technical skills such as programming AI models, managing IoT networks and interpreting big data analytics, as well as soft skills including critical thinking, collaboration, ethical decision-making and adaptability. For instance, an AI ethics workshop could educate employees on recognising potential algorithmic bias, evaluating fairness in automated decision-making processes, and ensuring that their actions align with organisational values.

The transition to robotic and AI-assisted work requires robust human oversight and ethical regulation to prevent dehumanisation and maintain trust in automated systems (Fraga-Lamas et al., 2022). Human workers actively participate in shaping, guiding and supervising AI and automated processes, rather than being passive recipients of technology. Ethical governance structures are necessary to ensure technology enhances, rather than replaces, human judgement and well-being. Transparent reporting systems, clear accountability mechanisms and participatory decision-making processes are essential in creating a trustworthy work environment. Employees who understand the purpose, limitations and rationale of technological interventions are more likely to accept and collaborate effectively with AI systems (Pant et al., 2025).

Human capital development involves preparing employees for the regulatory and compliance responsibilities associated with emerging technologies. Given the growing global focus on AI ethics, data protection and workplace safety, it is crucial that employees are familiar with the relevant legal frameworks, international standards and organisational policies. For instance, familiarising oneself with the EU AI Act and pertinent labour regulations enables employees to comply with legal requirements and contribute to organisational risk management strategies (Xu et al., 2025). This knowledge safeguards the organisation and empowers employees to act confidently and responsibly within highly automated environments.

Furthermore, Industry 5.0 places significant emphasis on human-centred innovation, wherein the primary function of technology is to enhance human creativity, decision-making and problem-solving capabilities, as opposed to the complete automation of these processes (Adel, 2024). Human capital, therefore, encompasses not only technical expertise but also ethical awareness, social intelligence, and strategic thinking. Employees are expected to collaborate with machines, evaluate AI recommendations critically, and consider the environmental, social, and ethical consequences of industrial decisions. In the field of manufacturing, for instance, human operators may intervene in AI-generated production schedules with a view to minimising waste, reducing energy consumption, or enhancing worker safety (Lupi, 2023). The integration of technological and human capabilities is pivotal in ensuring the sustainability, resilience, and social responsibility of production systems.

Finally, it is incumbent upon organisations to measure and enhance human capital systematically. As Sima et al. (2020) assert, metrics pertaining to employee well-being, engagement, skill utilisation, and innovation capacity are imperative for the effective monitoring of human capital development strategies. By evaluating these factors, organisations can identify skill gaps, design targeted training programmes, and optimise workforce allocation in line with technological advancements. The implementation of continuous evaluation and feedback loops has been demonstrated to foster a learning culture, thereby encouraging employees to adapt proactively to technological changes while maintaining high levels of motivation, ethical awareness, and professional growth (Pant et al., 2025). Human capital development in the context of Industry 4.0 and 5.0 is a multidimensional and ongoing process that integrates technical skills, psychological readiness, ethical awareness, and managerial oversight. To ensure workforce readiness and sustainable performance, organisations must adopt a comprehensive approach combining continuous education, human-machine collaboration, risk management and ethical governance. Investing in human capital enables organisations to successfully navigate technological transitions, foster innovation and gain a competitive advantage in an ever-changing industrial landscape (Fraga-Lamas et al., 2022; Xu et al., 2025).

3. EU Employment and Skills Policies in Digital Era

The European Union is actively implementing upskilling and digital education programmes to prepare its workforce for the demands of a rapidly evolving technological landscape. These programmes focus on enhancing digital literacy, analytical thinking and technical competencies, ensuring that employees in all sectors can collaborate effectively with advanced technologies such as AI, robotics and IoT systems (Pant et al., 2025). In addition, the EU supports labour mobility, enabling skilled professionals to work across member states and facilitating the diffusion of

knowledge, best practices and innovation. Policies that promote responsible AI regulation, such as the AI Act, aim to ensure transparent, explainable and accountable AI deployment, thereby fostering trust between humans and machines while mitigating ethical, legal and social risks (Xu et al., 2025). These measures lay the groundwork for developing human capital in the digital economy, emphasising the importance of continuous learning, ethical competence, and technical skills.

Although Ukraine possesses significant human capital potential, it faces multiple challenges in aligning with EU digital and industrial standards. Modernising vocational education and professional training systems is essential in order to equip the workforce with the necessary skills for operating in highly automated, AI-driven industrial environments (Sima et al., 2020). Furthermore, institutional capacity must be strengthened to encompass the integration of emerging digital technologies into production processes, the establishment of effective regulatory oversight, and the implementation of continuous professional development frameworks. Ukraine must also prioritise the adoption of AI auditing and transparency mechanisms to make algorithmic decisions more explainable and trustworthy to employees, managers and end users (Priyadarshini, 2024). Aligning with EU practices requires technological modernisation, as well as embedding ethical and regulatory principles into education and enterprise management systems to foster a culture of responsible innovation (Pant et al., 2025).

The practical implementation of these priorities requires coordinated efforts across multiple domains. Educational transformation should include flexible, modular programmes that address AI ethics, data literacy and digital innovation. These programmes should offer employees and students opportunities for lifelong learning and upgrading their skills (Sima et al., 2020).

Trust and accountability mechanisms are crucial, such as enterprise-level AI monitoring systems and national-level oversight frameworks that ensure algorithmic fairness, safety and transparency (Dmitrieva, 2024). Furthermore, it is necessary to harmonise regulations, aligning national legislation with the EU AI Act and adopting human-centred design standards that prioritise safety, ethical compliance and social responsibility (Pant et al., 2025). Ultimately, collaborative governance between universities, industries and public institutions is essential for fostering research and innovation, as well as the practical implementation of Industry 5.0 technologies. This ensures that human capital development remains closely linked to technological and industrial transformation (Fraga-Lamas et al., 2022). This comprehensive approach will enable Ukraine to strengthen its workforce, boost productivity, and develop a resilient, ethical, and digitally competent economy.

In the long term, Ukraine's integration into the European digital ecosystem hinges on successfully creating an adaptive and innovative human capital model that can respond to global industrial trends. The establishment of centres of excellence in AI, robotics and sustainable manufacturing could accelerate this transformation by providing platforms for research, training and technology transfer. Strengthening international partnerships and expanding public-private co-operation are also critical for bridging the gap between academic knowledge and industrial practice. Ukraine can position itself as an active contributor to Europe's transition towards Industry 5.0 – a future defined by technological excellence, human well-being, and social responsibility – by fostering a skilled, ethical, and innovation-oriented workforce.

4. Conclusions

A successful transition from Industry 4.0 to Industry 5.0 requires a comprehensive, integrated strategy balancing technological advancement with human-centred principles, education and legal accountability (Xu et al., 2025). Industry 4.0 has primarily focused on automation, efficiency and optimising production processes through cyber-physical systems, the Internet of Things (IoT), big data analytics and artificial intelligence (AI) (Adel, 2024). While these developments have significantly increased productivity, the next industrial paradigm, Industry 5.0, emphasises integrating human creativity, ethical responsibility and social sustainability into technological ecosystems (Priyadarshini, 2024). This transition requires a fundamental rethink of organisational culture, workforce skills, regulatory frameworks and societal objectives, not just an upgrade of machinery or adoption of new software (Pant et al., 2025).

The fundamental principle of this transition is that of human-machine collaboration. In contradistinction to the fully automated, efficiency-driven focus of Industry 4.0, Industry 5.0 seeks to create production systems in which humans and intelligent machines complement each other (Xu et al., 2025). Human workers contribute creativity, critical thinking, and ethical judgment, while AI systems and automation handle repetitive tasks, process large datasets, and provide decision-support tools (Dmitrieva, 2024). In the context of manufacturing, for instance, AI can suggest production sequences that have been optimised, with the final decision being made by human supervisors based on ethical, safety or social considerations (Fraga-Lamas et al., 2022). The implementation of such a model has been demonstrated to enhance not only productivity but also job satisfaction, employee engagement, and organisational resilience (Rejeb et al., 2025).

Education and continuous learning are critical enablers of this transformation. As industries adopt advanced technologies, it is imperative that employees develop new competencies to operate effectively in hybrid human-machine environments (Sima et al., 2020). Core competencies encompass digital literacy, data management, analytical thinking, and cybersecurity awareness (Akhavan, 2025). Furthermore, soft skills such as communication, collaboration, problem-solving, and ethical decision-making are becoming increasingly important (Pant et al., 2025). In order to equip their workforce for the evolving industrial landscape, it is essential that organizations invest in structured training programmes, upskilling initiatives and mentorship opportunities (Priyadarshini, 2024).

It is imperative to recognise the significance of legal accountability and governance frameworks in ensuring that Industry 5.0 practices are both responsible and sustainable (Xu et al., 2025). In the context of AI's growing role in operational and strategic decision-making, it is imperative for organisations to establish comprehensive guidelines that address data privacy, algorithmic fairness, and ethical compliance (Dmitrieva, 2024). The transparency and explainability of AI systems are of paramount importance in fostering trust among employees, customers and regulators (Pant et al., 2025). In addition, organisations should implement mechanisms for auditing automated decisions, addressing biases, and ensuring that ethical standards are consistently applied (Fraga-Lamas et al., 2022).

Sustainability is another pivotal component of Industry 5.0. Flexible production systems must consider environmental, social, and economic outcomes simultaneously (Rejeb et al., 2025). In the contemporary business landscape, there is an increasing expectation on the part of companies to reduce energy consumption, minimise waste, and optimise resource usage (Lupi, 2023). The potential of AI and IoT technologies to support these objectives is evident in their capacity to provide real-time monitoring of energy usage, facilitate predictive maintenance to extend machinery life, and simulate production scenarios to minimise environmental impact (Fraga-Lamas et al., 2022). Furthermore, human operators can utilise these data-driven insights to make ethically informed decisions that balance business efficiency with environmental stewardship (Grünewald, 2025).

A successful transition also requires organisations to adopt frameworks for measuring human-centric outcomes, such as employee well-being, job satisfaction, and cognitive load (Xu et al., 2025). Trust in AI systems is critical; employees must feel confident that machine-assisted decisions are fair, transparent, and aligned with organisational and ethical standards (Adel, 2024). The development of AI trust indicators, standardised well-being metrics, and human-centred performance assessments has the potential to assist organisations in the monitoring of the impact of technological integration on workforce engagement and morale (Pant et al., 2025).

It is recommended that future research endeavours focus on empirical case studies that illustrate the socio-economic ramifications of Industry 5.0 practices. Such research can examine industries across different regions, comparing outcomes in EU countries with emerging industrial contexts such as Ukraine (Sima et al., 2020). Key research areas may include the effectiveness of human-machine collaboration, the relationship between ethical AI implementation and employee trust, and the measurable benefits of sustainable production systems (Priyadarshini, 2024).

The transition from Industry 4.0 to Industry 5.0 represents a paradigm shift that integrates technological modernisation with human-centred values, sustainability, and ethical responsibility (Xu et al., 2025). The future of industry is said to lie in production systems that are flexible, transparent, and resilient while prioritising human dignity, safety, and continuous learning (Akhavan, 2025). By allocating resources to the development of organisational skills, cultivating confidence in artificial intelligence, instituting comprehensive governance frameworks, and pursuing sustainability goals, organisations can successfully navigate this transition (Pant et al., 2025).

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