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Challenges of industrial systems in terms of the crucial role of humans in the Industry 5.0 environment

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Abstract
The fourth industrial revolution (4IR) means the ubiquitous digitization of economic processes using more economical and efficient production technologies. Orientation to productivity, flexibility and low production costs results in a slow process of dehumanization of industry and concentration only on implementing Industry 4.0 (I4.0) digital technologies. A natural consequence of this trend is the concern of governments, employees and communities about new challenges and the importance of man in the economic ecosystem. The hope is the emergence of a new industry concept suggested by the European Commission (EU), which expands the components of the existing I4.0 concept to include human-centric, environmental and resilience aspects. Industry 5.0 (I5.0) is an excellent alternative to the development of today's digital and dehumanized world.
The article aims to identify the key research areas related to the formation of the role of the human being and the safe work environment in implementing the I5.0 concept. The article analyzes the research areas related to implementing the I5.0 concept based on a systematic review of the literature indexed in the Web of Science and Scopus databases. Identifies key issues related to the role of humans in the I5.0 environment. In addition, the priority directions for developing the identified research areas and their impact on forming a safe work environment are determined based on the knowledge of experts with experience in implementing digital technologies of the 4IR.

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1. Introduction

The industries transformed during the 4IR radically impacted society. This is incredibly accurate for industrial workers, whose roles may be changing or even at risk. The increasing dependence on complex technologies will require the development of new work environments and skills. It is already certain today that there will be more significant changes in the way the workforce is organized, challenging the traditional industrial work model. The currently observed trend of combining automation and digitalization of various processes in the economy may have a significant impact on the social role of industry as a current supplier of jobs and a catalyst for economic growth. These changes and issues associated with technological advancement require the industry to re-examine its position and significance in society. A significant threat is adapting the work environment to new conditions resulting from digital transformation (Chiabert et al., 2018).

Awareness of the dangers of global warming and the high energy cost is pushing for the principles of sustainability, sustainable production and consumption, and the evolution to a circular economy approach. It is crucial to increase our dependence on sustainable resources, particularly renewable energy. A priority for Europe, especially the European Union, is becoming the widespread digitization of economic processes and the use of more economical and efficient production technologies. The excessive focus on adopting I4.0 technologies has led to the dehumanization of the workforce. This has raised concerns among employees, governments, and societies regarding the impact on work conditions and the future of human involvement in the smart industry (Breque et al., 2022).

The European Commission has proposed a new approach to 4IR called Industry 5.0, which constructs upon and expands the defining characteristics of I4.0. This concept emphasizes critical aspects that will play a vital role in positioning the industry for the European society of the future (EC 2021). These factors are not only economic or technological but also have significant environmental and social dimensions. Equally important is the search for solutions to improve the well-being of workers.

It has been shown through various scientific studies that the role of human beings is crucial in shaping the future of industry. The humanization of the technologically-built environment was a fundamental factor in the evolution of I4.0 to I5.0 (Barata and Kayser, 2023). Technology use must not violate Workers' fundamental rights, including privacy, independence, and human dignity. The combination of the speed and accuracy guaranteed by automation with the critical thinking, creativity and cognitive skills of humans is expected to guarantee the success of I5.0. New concept of 4IR focuses on the interaction between humans and machines. The new approach will inspire the development of advanced human-machine interfaces supported by AI algorithms. This means faster and better automation with human intelligence for better integration. It also creates new opportunities and risks to worker's health and safety (Melnyk et al. 2023).

Hence, research is needed for human safety in Industry 5.0's digital environment. Based on the above considerations, the following research questions can be defined:

RQ1: Which research areas are currently addressed in the literature on the role of humans in the 4IR and the formation of a safe work environment?

RQ2: Which skills and competencies must employees possess to implement the Industry 5.0 concept successfully?

Thus, the article's aim is to identify key research areas connected to the formation of the role of man and the safe work environment under the conditions of I5.0 implementation. The article analyses research areas related to Industry 5.0 implementation based on a systematic literature review indexed in the WoS and Scopus databases. It identifies the most critical problems and research areas related to man's role in the I5.0 environment.

Moreover, based on the knowledge of experts with experience in implementing the I4.0 concept, priority directions for developing research areas that influence forming a safe work environment were determined. Attention was given to work organization and the necessary skills of human resources.

The presented results are dedicated to researchers and practitioners interested in a safe work environment while implementing the I5.0.

2. The Industry 4.0 concept versus the Industry 5.0 concept

The I4.0 concept has overhauled the manufacturing sector with the following technology: Industrial Internet of Things (IoT), Artificial Intelligence (AI), Big Data, Cyber-Physical Systems (CPS), Cloud Computing and Augmented Reality (AR). The main feature of cyber-physical systems design is smart production by interconnecting intelligent machines supported by many sensors that can communicate in real-time within the production process (Xu, 2020; Lasi et al., 2014). The creators of the I4.0 concept assumed that the main priority of the smart factory is the autonomy and full automation of machines, equipment, and processes, thereby reducing man's intervention in the manufacturing process (Aceto et al., 2019; Xu et al., 2018). The reduction of production costs and increasing competitiveness of manufacturing production in Western Europe has led the I4.0 concept to focus on enhancing mass productiveness and efficiencies by ensuring intelligence between equipment and software using machine learning (ML) (Azeem et al., 2021; Lemos et al., 2022).

Furthermore, the rapid advancement of technology and the increasing reliance of humans on technology have raised researchers' interest in technological trust. Lippert was one of the first researchers to define trust in technology. According to him, trust in technology refers to an individual's willingness to be influenced by technology, which is based on the technology's expected predictability, credibility, usefulness, and the individual's preference for the technology (Lippert, 2001). Ejdys added that trust in technology is influenced by the perceived properties of the technology and environmental factors. The inclination to use technology despite the potential risks associated with its use determines an individual's future intentions regarding the use of a particular technology. This implies that the tendency to use technology is primarily determined by its expected functionality, reliability, and support system (Ejdys, 2017).

Even though the idea of I4.0 was implemented a decade ago, in 2011, research is already underway to introduce the new I5.0 concept (Maddikunta et al., 2022; Nahavandi, 2019). The I5.0 concept responds to the industrial worker community's current demand and concerns against the industry's widespread dehumanisation. The idea of Industry 5.0 further develops the I4.0 concept in a more broad and forward-thinking way (Breque et al., 2022). I5.0 focuses on mass personalisation through sustainability, resilience and human collaboration with CPS, mainly collaborative robots. I5.0 is currently being conceptualised to use the unique ingenuity of humans their empathy in partnership with powerful, clever and precise engines and artificial intelligence. The creators of the Industry 5.0 concept believe it will bring humanity back to the manufacturing industry (Nahavandi, 2019).

So far, manufacturing systems have mainly focused on efficient large-scale production, while the I5.0 idea draws more focus on increasing customer satisfaction. In the future, fewer products should be produced, and more attention should be paid to customisation. Products should not be characterised by a short life cycle or be engineered in a way that they cannot be simply and cheaply repaired. An interesting advantage of I5.0 is to deliver a greener solution to existing manufacturing solutions (Demir et al., 2019).

The literature contains many definitions that characterize the I5.0 concept, some of which are shown in Table 1.

Table 1. Selected definition of the I5.0 idea

Definition of Industry 5.0	Author/source
Definition 1. I5.0 is the first human-led industrial evolution based on the 6R (Recognise, Reconsider, Realise, Reduce, Reuse and Recycle) rules of industrial upcycling, a regular landfill waste prevention technique and logistics efficiency design to value living standards, innovative creations and produce high-quality customized products.	(Rada, 2020)
Definition 2. I5.0 will primarily focus on human-machine collaboration, thus bringing the human touch or element into the industry again. It has to be noted that I5.0 aims to exploit the synchronous advantages of machines with human capabilities of cognition and decisiveness.	(Pillai et al., 2021)
Definition 3: I5.0 returns human workforce to the manufacturing plant, where people and machines are pared down to improve the efficiency of the process by leveraging human brainpower and ingenuity through the integration of workflows with intelligent systems.	(Nahavandi, 2019)
Definition 4: I5.0 implies consideration of people factors incorporated into processes, systems and technological facets.	(Friedman and Hendry, 2019)
Definition 5: I5.0 is interpreted as the combination of the power of cyber-physical production systems (CPPS) and human smarts to develop synchronous manufacturing factories.	(Longo et al., 2020)

Based on a review of the above definitions, it can be concluded that Industry 5.0 will be defined by a renewed and broadened purpose beyond the production of commodities and benefits for profit. This broader purpose consists of three essential elements: human-centric, sustainability and resilience. For an industry to get a source of real wealth, social, environmental and community considerations must be a priority in its development. This includes responsible innovation that aims to increase cost efficiency or maximise investor returns and enhance the well-being of all stakeholders, including employees, consumers, society and the environment (EC, 2022). Generally speaking, the idea of I5.0 stretches the ideas of I4.0 in a more human- and social-friendly way (Maddikunta et .al., 2022; Prassida and Asfari, 2022).

I5.0 is based on three fundamental approaches (EC, 2022):

- The Human-centric approach means using human potential in machine learning or close cooperation between humans and cobots. The industry's widespread use of digital technologies must prioritize human characteristics for optimal synergy. I5.0 combines the best features of two worlds: technology, which guarantees productivity, flexibility and accuracy, and a human being with cognitive skills and critical thinking. I5.0 is not a threat to employees like I4.0 (Martynov et al., 2019; Amor, 2023).
- The sustainability means the approach is greatly suitable for the 'fit for 55' package adopted by the EC on July 14 2021. The EC is adapting existing climate and energy legislation to reach the EU's new target of cutting emissions of greenhouse gases (GHG) by at least 55% by 2030. The "fit for 55" package is embedded in the European Green Deal, which seeks to put the EU on a climate-neutral path by 2050 (EC, 2021). This means the need for more excellent orientation to applying the principles of sustainable production and consumption and using CPSs using renewable energy in the I5.0 concept. Therefore, the I5.0 concept forces us to apply the principles of a closed digital economy and limit the industry's negative impact on the natural environment (Voulgaridis et al., 2022).
- Resilience means the approach is an essential aspect of designing production and logistics systems and processes due to the geopolitical situation and the experience related to the COVID-19 pandemic. The over-development of global supply chains and the focus on globalisation has resulted in numerous supply disruption issues for production. In addition, the widespread digitisation and virtualisation of production spheres carry the risk of disruption in the flow of information. Hence, the need to focus on developing cybersecurity of processes and data sets that are the basis for the communication of intelligent resources, smart factories and entire supply chains. The resilient industry is the challenge of the modern world today (Romero et al., 2021).

The European Commission has established 6 areas of technological developments that are realisations of sustainability, human orientation and resilience (EC, 2020):

1. Human-machine integration - This field should include technologies for identifying speech, and gestures and predicting behavioral intentions. Additionally, it should include technologies to manage employee stress and strain. Functional will also include technologies for composite, cyber or blended reality, cooperating robots, exoskeletons, etc. Also within the scope of this area are aspects of ensuring the safety of cooperation with intelligent machines, including ML and AI algorithms for recognising the idiosyncrasies of the operator. Working together with collaborative robots can have several implications, such as altering the role of human resources, ethical considerations associated with cobots, training humans to work alongside cobots, regulatory challenges, psychological concerns related to human adjustment to a new form of work and examining job dynamics for both humans and cobots (Sheridan, 2016).
2. Biologically inspired technologies and smart materials - Industry 5.0 requires a focus on environmental protection and even some kind of imitation of nature and the use of natural physical processes and chemical reactions, e.g. in biogas generation or waste disposal, fermentation, etc. Therefore, manufacturing raw materials from waste, the prevalence of recycling, using biosensors, etc., will become standard in I5.0. Interest is also increasing in the use of intelligent materials with sensors and highly up to date features that can be cycled and re-used.
3. Digital twins (DT) and real-time simulation - the technologies streamline manufacturing, testing products and operations, and identifying potential adverse impacts on work safety and production system efficiency. Most

relevant is the possibility to simulate the collaboration between a man and a robot cooperating in the digital equivalent of the production system. In addition, combining the digitized double of CPS with multi-dimensional dynamical modeling and simulation enables measurement of the environmental and social impacts.

4. Cybersecurity represents technologies for securing the transmission, storage and analysis of data necessary for proper functioning cyber-physical systems throughout the value chain. This technology area includes scalable multi-layered cyber security, protected IT infrastructure, and data operating in cloud computing technology. In addition, cybersecurity technologies include machine learning processes to prevent intelligent machines from taking over. A form of security protection from digital asset attack is the increasingly successful Edge Computing technology, which reduces communication expenses and provides better performance of the application in distant areas with reduced network access. Edge Computing technology provides a paradigm for distributed processing at the data source, improving network throughput performance and response time.
5. Artificial intelligence - Nowadays, the highest expectations for the growth of artificial intelligence come from the technology based on causality, not only correlation. Artificial intelligence algorithms are essential to ensure the safety of humans interacting with intelligent machines, respond quickly to unconventional operator behavior and reduce the risk of accidents during human-machine interaction.
6. Energy efficiency technologies aimed at developing the integration of revolving energy sources - One of the critical areas of Industry 5.0 is sustainability which is an excellent excuse to prepare companies for the fit-for-55 package. Regardless of their level of digital sophistication, today's companies must start using energy-efficient technologies and demonstrate t using energy from sustainable resources. The motivator for such action is the currently observed increase in energy prices, especially those derived from fossil fuels.

I5.0 represents an evolution of the I4.0 concept priorities, not a new revolution. The conversion of the I4.0 idea towards the I5.0 requires consideration of a number of problems related to the importance of using human resources in smart factory. Particularly important are aspects of organising human-machine cooperation, ensuring occupational safety when operating collaborative robots, and personnel requirements related to the knowledge and skills of workers employed in I5.0 smart factories. To achieve all I5.0 goals, digital technologies must be implemented comprehensively due to their different impacts on the individual pillars of Industry 5.0, i.e. achieving human orientation, system resilience and sustainable production.

3. Materials and methods

To explore the role of humans in the 4IR, and to identify the knowledge and skills required to deployment the I5.0 concept, we conducted an in-depth analysis of scientific articles from the WoS and Scopus databases. Our methodology included a literature analysis, an expert survey, and discussions to draw conclusions. Figure 1 presents the used research methodological framework.

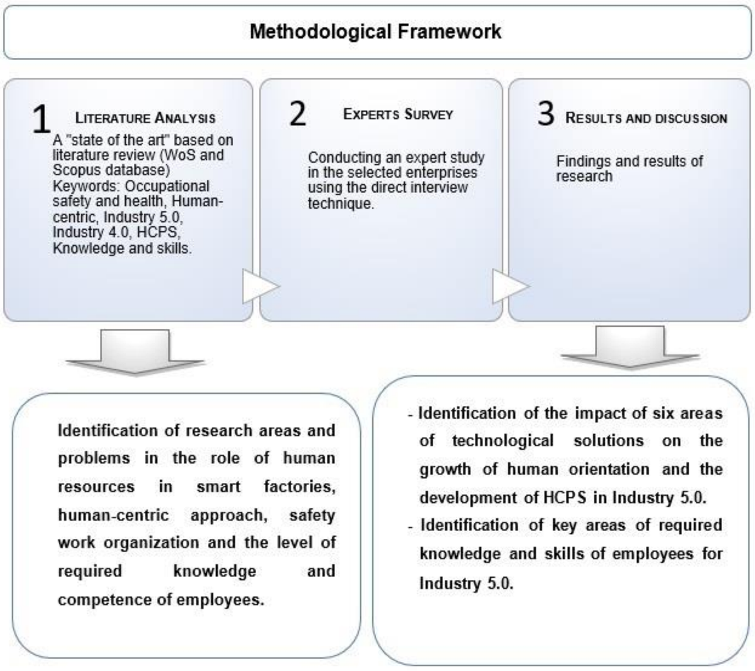

Fig. 1. Methodological framework

Additionally, we focused on creating a safe work environment in this new era of Industry 5.0. The following search criteria were adopted:

Search period: from January 01 2011, to December 31 2022 (2011 is the beginning of I4.0, which is the basis for I5.0 concept - hence this search start date);

- the WoS and Scopus databases were searched for the words I4.0 AND/OR I5.0 AND Occupational safety and health in titles, abstracts and keywords of publications;
- in the WoS and Scopus database, searching for the words I4.0 AND/OR I5.0 AND Human-centric in titles, abstracts and keywords of publications;
- the WoS and Scopus database searched for the words I4.0 AND/OR I5.0 AND knowledge and skills in the titles, abstracts and keywords of publications;
- the WoS and Scopus database was searched for the words I4.0 AND/OR I5.0 AND HCPS in the titles, abstracts and keywords of publications;
- the result was narrowed down to scientific articles published in English.

The expert survey helped collect the necessary responses to achieve the goal of the paper. The experts represented the required knowledge and experience from Industry 4.0/5.0 technologies. The questionnaire was standardized and was validated among five independent European experts. The survey questionnaire consisted of 10 questions (5 closed and 5 semi-open). 79 experts were interviewed between February 1 and March 15, 2023. The experts represented companies that implemented technologies related to cyber-physical production systems and represented the automotive and food industries. The study was conducted using the survey questionnaire method and Computer-Assisted Web Interview (CAWI) data collection technique.

4. Results and discussion

4.1 The role of humans and occupational safety in the I5.0 environment

To determine the role of humans and occupational safety in the I5.0 environment, the content of papers found in the Web of Science (WoS) and Scopus databases was analysed. Details of the search are described in the Materials and Methods section. The quantitative results of the search are shown in Table 2. Very similar results were obtained in both databases.

Table 2. Quantitative results of search phrases in WoS and Scopus database

Search phrases	No. of articles in Wos	No. of articles in Scopus
I4.0 AND Occupational safety and health	12	7
I5.0 AND Occupational safety and health	1	1
I4.0 AND Human-centric	37	48
I5.0 AND Human-centric	26	32
I4.0 AND knowledge and skills	29	34
I5.0 AND knowledge and skills	3	4
I4.0 AND HCPS	7	1
I5.0 AND HCPS	1	2

As can be noticed from the data summarized in Table 2, the searched areas of health and safety, Human-centric, knowledge and skills, and HCPS in the I5.0 environment are still poorly researched. The articles indexed in the WoS database are usually the same papers as those searched in the Scopus database. Due to their small number, a detailed content analysis of all the papers was carried out and based on this, research areas were identified, which are presented as a Venn diagram in Figure 2. A cluster showing the most frequently occurring concepts in the analyzed articles (Figure 3).

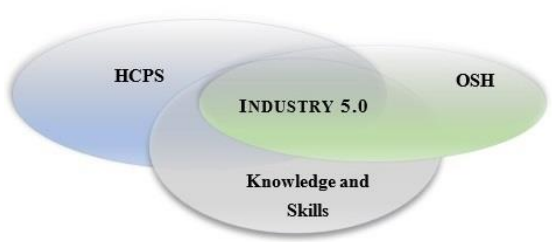

Fig. 2. Venn diagram illustrating the relationships between the areas of Industry 5.0, OSH, Knowledge and Skills, HCPS

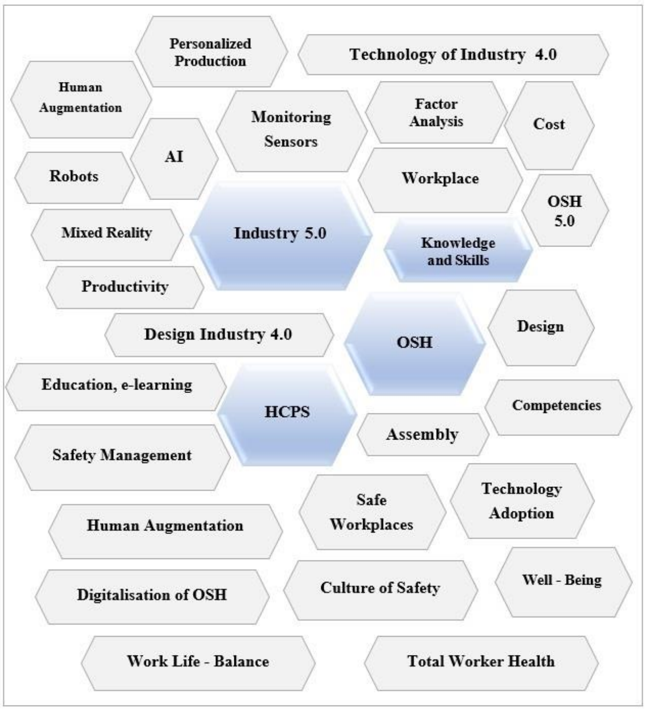

Fig. 3. The cluster of areas of interest to researchers in Industry 5.0, OSH, Knowledge and Skills, and HCPS

Analyzing the literature and Figure 2, it can be concluded that the studied areas of Industry 5.0, OSH, Knowledge and Skills, and HCPS intermingle together. However, Figure 3 presents the most common areas of interest related to Industry 5.0 implementing. These include:

- In the area of I5.0 - Human-Centric, Sustainability, Resilient, Technology of I4.0;
- In the area of HCPS - Human Augmentation, AI, Machine Learning, Robots, Productivity, Factor Analysis, Designing A Smart Factory, Human Augmentation, Industrial Internet, Cloud platform, Value creation, Hybrid human-machine, augmented intelligence;
- within OSH - Personalized Production, Mixed Reality, Monitoring Sensors, Safety Management, Safe Workplaces, Technology Adoption, Well - Being, Digitalization of OSH, Smart Culture of Safety, Well-Being, Work-Life Balance, Total Worker Health, Modification of work processes, Multifactorial risks, Mobile work, Privacy, Personal data protection, Smart working environment, Exoskeletons, Smart workwear, Intelligent risk assessment, Autonomous personal protective equipment, New psychosocial challenges;
- Knowledge and Skills - Lifelong Learning, E-Learning, New Competencies, Competencies of the future, Digital competencies, cognitive load.
- The seamless integration of human and machine intelligence characterizes Industry 5.0. The new approach is closely related to I4.0 technologies, and the effective collaboration humans and machines is essential for the success of this concept. The development of I5.0 requires the utilization of human creativity, intelligence, and empathy

within a cyber-physical system. These qualities are critical features of intelligent machines that can augment human capabilities and lead to more efficient production processes. Hence, developing a category of systems called Human-Cyber Physical Systems (HCPS) provides an application environment for all areas of technology related to human centricity, sustainability and resilience. An HCPS is an intelligent complex system which consists of relevant humans and AI-supported cyber-physical systems striving to achieve specific production goals optimally. In this case, the physical systems that execute the material flows of production operations and carry out production tasks function as the "executive". CPSs supported by AI are the core of information flows in production activities. They support humans in necessary perception processes, cognition, analysis, decision-making and control of physical systems. In the CPSs, humans play the role of "masters". Humans are the creators of these systems, meaning that even the most intelligent cyber-physical systems owe their intelligence to humans. Additionally, humans are the ones who operate and use these systems, which means that they hold the highest position and have the ultimate right to make decisions and control. In the HCPS cyber system, the industrial Internet and cloud platform are two key components that connect various cyber and physical systems, and people. These components serve as integration tools, enabling information sharing and coordinated and integrated optimization - two essential features of HCPS (Wang et al. 2022).

Today, people constitute a networked community that shares common goals for value creation. This community consists of representatives of enterprises representing suppliers, producers, sellers, customers, etc. It means a transformation from a product-centric model to a customer-centric model and from a production model to a production-service model (Zhou et al., 2019). The key issue in I4.0 is neglecting the role of human resources and focusing on improving productivity through technologies that eliminate humans from the value-creation process. This problem will grow and may meet with excellent resistance from politicians and trade unions of industrial workers if such a modus operandi continues. In Industry 5.0, it is still essential to digitize processes and use efficient manufacturing technologies focused on increasing productivity while emphasizing the role of humans and using their specific features that intelligent robots and artificial intelligence will not replace. It is about creativity, creative thinking and the ability to make empathy decisions and a simple human approach. Chen et al. (2020) focused on HCPS systems for I5.0 in the production of wind turbines. The authors proposed a conceptual model that includes crucial human assistive technology features such as health condition monitors, information translators, and predictive damage models. It can be accomplished through human cooperation and by combining the IoT and AI. Longo et al. (2020) drew attention to emerging problems in HCPS systems. The article proposes that ethical matters involving technology and human rights values in a factory environment are not properly represented. They proposed a design technique that takes into account human values in designing the future factories.

The main feature of HCPS systems is the creation of hybrid human-machine assisted intelligence, which provides a full range and synergistically incorporates the advantages of human and machine intelligence. This allows the innovative potential of people to be released and a significant increase in the innovativeness of the manufacturing industry to be achieved (Zhong et al., 2017).

An exciting area of research covered in the articles is the development of hybrid human-machine intelligence, which involves integrating and cooperating biological intelligence systems with machine intelligence systems. These evolutions will typically lead potentially to increased problem-solving and decision-making capabilities through humans and machines collaboration. Among the potential uses are collaborative machines (cobots), machine learning, assisted education, and human-machine integration products (Pan, 2016).

The design of today's and tomorrow's HCPS systems requires considering Human-Robot Collaboration (HRC) or cobots, which allow humans and collaborative robots to work closely together while performing tasks. Special sensors and vision systems allow for immediate reactions caused by human behavior. The future research will be centered on this particular direction: better understanding human behavior, the environment, and task completion status. Researchers primarily propose using a more significant number of sensors supported by advanced artificial intelligence algorithms. Submitting appropriate interfaces for information exchange between humans and machines is also essential. By their very nature, these systems should be oriented towards ensuring greater security. Unexpected movements of robots will be minimized, translating into greater trust and acceptance of cooperation in the human-cobot system. Many available solutions come from various research areas, such as robotics using demonstration techniques, hands-on guidance or simulation techniques, computer science, ML and AI, etc. This will allow the robot to be taught to perform complex tasks and will also contribute to progress in the area of computer vision and machine learning in the field of object recognition and semantic mapping (Matheson et al., 2019).

The human orientation of the Industry 5.0 concept requires particular concern for ensuring human safety, especially in human-smart-machine collaboration. Safety workers, also known as occupational health and safety (OSH) professionals, are responsible for ensuring a safe work environment through policies, procedures, and equipment. Applied digital technologies, artificial intelligence, dematerialization, cyclicality and efficiency as drivers of change in HCPS must allow consideration of worker safety. Important areas currently receiving attention are:

- Smart working environment - Sources of value for transformational elements include a set of sensors that acquire data processed with the support of artificial intelligence to learn about working conditions, recognize risky situations and develop reactions to them. Virtualization and intelligent cyber-physical systems assist users in simulating, predicting and resolving issues. The initial indications of digitization and its integration with smart work environments are the inclusion of monitoring devices in work clothing and exoskeletons, which act as extensions of intelligently connected work equipment and personal protective gear. The basis for achieving a safe, healthy and effective future work is connecting sensory devices to the work environment, allowing information to be processed through artificial intelligence techniques. Big Data, on the other hand, enables the continuous collection and processing of data, which makes it possible to monitor and control OSH in real-time (Simonetto et al., 2022; Lopez et al., 2021; Balissone et al., 2018; Chiabert et al., 2018; Ramos et al., 2022, Nickel 2023).

- Intelligent risk assessment - Using simulations and virtual models in decision-making to assess risks, identify safety and control standards and using proactive management, the ability to identify unsafe situations, analyze data and transform it into preventive information transferred to CPSs, expand the capabilities of threat and risk management. In addition, real-time dashboards based on key performance indicators (KPIs) and panels of hazards and health and safety measures are being created for management. The development of autonomous PPE as intelligent components, rather than just sensors and interpretive signal transmitters for preventive services, is another step in the digitization of OSH (Ávila-Gutiérrez et al., 2022, Campero-Jurado et al., 2020). Industry 5.0 technology enables real-time data collection and prevention of potential threats. This leads to continuous improvement of work safety. For instance, installing a set of devices and sensors can detect and report any operator behavior that may threaten workplace safety (Pistolesi and Lazzerini, 2020; Sun et al., 2019; Małysa, 2022; Colim et al., 2022).

An important significance for building an Industry 5.0 environment is the use of human characteristics as Resilient Operator 5.0. The vision of "Resilient Operator 5.0" focuses on creating a "self-resistant" workforce. Self-resilience - refers to physical, biological, worker safety and psychological health, as well as the productivity of each worker on the production floor. According to Romero and Stahre, in terms of "self-resistance," we are dealing with physical resilience, cognitive resilience, biological resilience and psychological resilience. Biological resilience refers to the operator's ability to maintain industrial health and safety hygiene, which may be supported by smart wearables and smart PPE. Exoskeleton technology can support an operator's physical resilience by providing additional muscle strength, protection, and endurance. Cognitive resiliency is achieved through the operator's ability to maintain their mental agility under pressure and avoid human mistakes by augmented reality (AR) technology operating as a digital support system. Mental resilience pertains to the operator's capacity to emotionally cope with crises, aided by VR technology that offers a safe (virtual) workplace to manage risks and crises (Romero and Stahre, 2021). The work of Operator 5.0 in an Industry 5.0 environment becomes safe through the use of adaptive automation, a feature of which is the prevention of errors and undesirable events by combining data analytics technology and intuition of the operator with an intelligent machine (cobot) equipped with an agent with predictive and health management abilities. Such a system constitutes a common cognitive system centered on enhancing the predictive abilities of the human-machine systems. The two components inform and alert each other of potential risks and support the system's resilience to disturbances (Vogl et al., 2019; Jones et al., 2018).

An important area of interest for researchers in the human-machine system is Modeling and simulation (MS) and Human Digital Twin (HDT). In particular, the MS of people is of tremendous importance in the design of HCPS systems. MS aims to define and extract critical characteristics of people to create virtual models of human-machine cooperation. The integrated virtual models reflect physical units' and humans' key features and dynamic movement. Detection devices or smart sensors that are discrete and miniaturized record human movement and physiological and psychological data better to design a safe human-machine system in HCPS systems. Inertial measurement units (Zhou et al., 2020) and optical technology (Bilberg and Malik, 2019; Laurent 2023) are used to record human motion. Human motion data can support the creation of virtual models and control and interact with the physical system. The ability to receive biological signals (pulse, electrocardiogram, body temperature) makes it possible to monitor the physical condition and diagnose the operator in real-time (Wang et al., 2022). Soon, the much-interested HDT built on advanced technologies for reading data about a person's physiological and mental states will allow more accurate modelling of human-machine cooperation in a real system that mirrors the virtual system built in the digital equivalent of the HDT.

Deployment of digital technologies supporting the work environment in Industry 5.0 means the need to consider new knowledge and new competencies of employees working in smart factories. The development of future competencies is due to the intensification of the advancement of the I5.0 idea, which is a great technological challenge and a psychosocial one. This is because modern technologies require continuous learning and improvement of digital competencies. They cause a heavy cognitive load associated with the huge amount of data coming quickly. This increases the already high-stress levels among employees. And this is compounded by a reduction in job stability (temporary, on-call, remote work, independent job search, retraining, etc.). Digitalization also burdens a high dependence on others (clients, colleagues, partner networks, etc.), a significant factor in the company's success (Brauners and Ziefle, 2022; Neumann et al., 2022).

The skills necessary to realize the concept of I5.0 are mostly concerned with digitizing the production environment, collecting and analyzing big data, ensuring data security (cybersecurity) and effectively creating cyber-physical systems. It is expected that there will be new theoretical knowledge and practical skills for industrial workers and executives. Traditional skills are being replaced by machines, and the emergence of new expected skills requires adaptation to new technologies (Santos et al., 2021; Melnyk et al., 2023).

The standard of production technologies applied (intelligent machinery and equipment, autonomous transportation, etc.) requires the employment of highly skilled personnel, knowledge transfer skills, teamwork and openness to change. Lifelong learning is growing in importance. Production companies need to drive a culture of innovation and learning, and change the culture of learning, which involves shifting values and priorities. Industry 4.0 technologies are automating many processes in companies, making it possible to build more efficient and "lean" work teams, but still requiring a completely new approach to developing employee talent. The increasing demand for new skills is mainly due to the growing need for seamless integration and transparency of information within organizations. The production systems are becoming more automated, and operations are getting more autonomous, which requires factories to make self-managed and autonomous decisions. The workforce is expected to be much more flexible with the rise of digital connectivity (Rojko et al., 2020; Lee and Med, 2021; Adepoju and Aigbavboa, 2021; Li et al., 2021;Sony and Mekolth, 2022).

According to the literature on the knowledge and skills of human assets to deploy the I5.0 concept, the field under study can identify the following problems:

- employees need specialized knowledge and a whole new skills regimen arising from digitization, which is expected to lead to an increase in the general productivity of production systems, the efficiency of operations leadership, and the productivity of production and ancillary processes (Saniuk et al., 2021);
- there is a demand for high-skilled employees characterized by receptiveness to new technologies, knowledge transfer and teamwork (Ahrens and Spottl, 2015; Mohelska and Sokolova, 2018; Shamim et al., 2016; Pfeiffer et al. 2016);
- in an I4.0 environment, it is crucial to merge expertise in information and manufacturing technologies with management skills. This is especially vital in strategy development, case analysis, networking by collaboration with business partners, new business models, change management and use of leadership (Graczyk – Kucharska et al., 2018; Kazancoglu and Ozkan-Ozen, 2018; Schneider, 2018);
- the importance of life-long education in an I5.0 environment is definitely growing, which requires: promoting a culture of innovation and learning, changing modes of learning (e.g., remote learning), and a new approach to developing workforce talent (Luthra and Mangla, 2018; Shamim et al., 2016).

Research by S. Saniuk and S. Grabowska (2022 a, b), shows that employees of smart enterprises implementing the I5.0 should possess the following skills:

- general technical knowledge. Have skills related to the application of the principles of mathematics, physics, chemistry and other sciences necessary to solve engineering problems;
- the ability to plan, conduct experimental research and analyse and interpret the results;
- skills to design systems, components, and processes that meet economic, social environmental, health, ethical, feasibility, safety and sustainability constraints and conditions;
- the ability to work in multidisciplinary teams;
- kills to find, formulate and solve engineering problems;
- complete understanding of professional, ethical norms, principles and responsibilities;
- verbal and non-verbal communication skills;
- the necessary knowledge to understand the impact of engineering solutions and decisions in the global, economic, social and environmental context;
- the need for lifelong learning;
- knowledge and understanding of contemporary world problems;
- technology skills and modern methods used in current engineering practice.

4.2. Expert findings

In the next phase of the research, experts were invited to give their opinion on the strength of the impact of implementing I5.0 technology areas (designated by the EC) on the humanization of industry. Experts rated the strength of impact on a five-point Likert scale (where 1 meant no impact and 5 meant very high impact). The distribution of responses is provided in Figure 4.

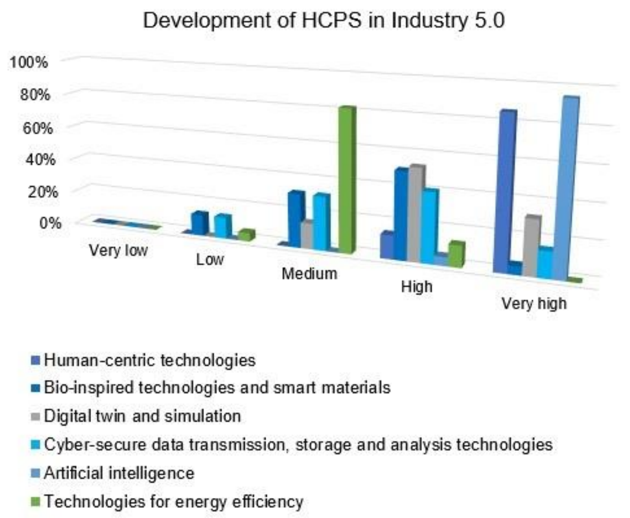

Fig. 4. The influence of technology on the growth of human orientation and the development of HCPS in Industry 5.0

Experts rated the impact of I5.0 technology areas on the humanization of the industry as follows:

- Human-centered technology solutions and human-machine interface solutions - very high impact of 68 experts, high impact of 11 experts;
- Biology-inspired technologies and smart materials - high impact 40 experts, medium 25, low 10, very high 4;
- Digital twins and simulations - high influence 42 experts, very high influence 25, medium 12;
- Artificial intelligence - very high impact 75, high 4;
- Technologies for energy efficiency - medium influence 65 experts, high 10, low 4.

From the literature analysis, it is clear that Industry 5.0 is a transformation in the knowledge and competencies of employees. Therefore, the opinion of experts on the skills and competencies needed to create human-centered systems of Industry 5.0 was surveyed. The response breakdown is presented in Figure 5.

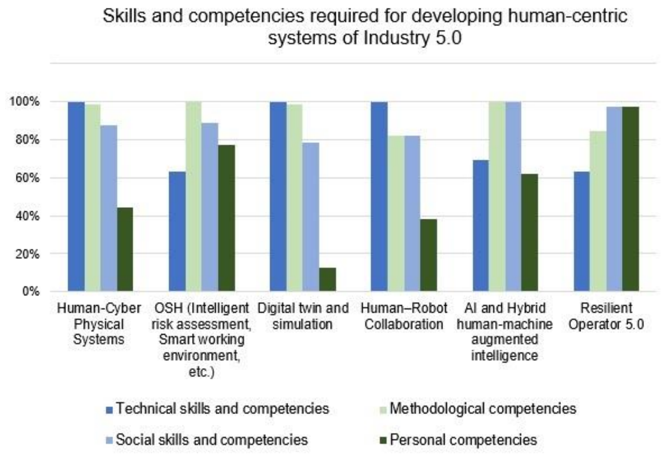

Fig. 5. Skills and competencies required for developing human-centric systems of Industry 5.0

Experts indicated what group of competencies and skills will be necessary to create human-centered areas of Industry 5.0. In their opinion, creating:

- HCPS - Human-Cyber Physical Systems will require employees to have: Technical skills and competencies (79), Methodological competencies (78), Social skills and competencies (69), Personal competencies (35);
- OSH (Intelligent risk assessment, Smart working environment, etc.) will require employees to have: Methodological competencies (79), Social skills and competencies (70), Personal competencies (61), Technical skills and competencies (50);
- MS and HDT will require employees to have: Technical skills and competencies (79), Methodological competencies (78), Social skills and competencies (62), Personal competencies (10);
- Human-Robot Collaboration (Cobots): Technical skills and competencies (79), Methodological competencies (65), Social skills and competencies (65), Personal competencies (30);
- AI and Hybrid human-machine augmented intelligence: Methodological competencies (79), Social skills and competencies (79), Technical skills and competencies (55), Personal competencies (49);
- Resilient Operator 5.0: Personal competencies (77), Social skills and competencies (77), Methodological competencies (67), Technical skills and competencies (50).

To implement Industry 5.0 technologies focused on sustainable development, human orientation, and system resilience, a new approach is required, particularly in the development of new employee competencies. This means that employees with technical skills, combined with methodological and social ones, will be the most valuable resource. Therefore, enterprises should prepare their employees for the transformation in this area, training them to a great extent and combining social and technical competencies in both managerial and engineering positions.

5. Conclusion

Industrial companies are still pondering what Industry 4.0 means for their businesses and what technologies to implement , meanwhile, the European Commission-driven Industry 5.0 is looming on the horizon. So companies are facing a correction in the direction that Industry 4.0 has been taking. According to the I5.0 concept, production is to be not only competitive, but also resilient to disruption, as well as sustainable. Unlike the industry developed according to the 4.0 concept, it should go beyond the purely financial gains from digitization and automation.

Enterprises today recognize the importance of adapting to changing times, especially with modern technologies and the digitization of processes. It is crucial to leverage the new knowledge, creativity, and competencies of employees to stay ahead in the market. To gain a competitive edge, it's essential to have expertise, market flexibility, and a human-centric approach, not just in the market but also in creating a safe work environment.

The Industry 5.0 concept seeks to create connections based on trust and interaction between humans and machines. It enables HCPS systems to benefit more significantly from intelligent machines and devices and 5.0 operators equipped with new skills and gadgets (exoskeletons, augmented reality glasses, etc.). To enter new efficiency, productivity and resilience levels human systems nor machines can achieve. A factory operating under the principles of I5.0 would potentially create a totally separate and far more complex mix of issues. The reconfiguration of production areas, involving very rapid tool changes and even physical equipment movement, can create a number of occupational safety issues. The vast number of potential customer configurations may require risk assessments to be conducted separately for each.

I5.0 concept, characterized by its human orientation, further intensifies the need to develop employees' knowledge and competence. The application of intelligent interfaces, augmented reality and collaborative robots are changing the interaction: human-CPS. Today's employees must understand the need to collaborate and manage systems composed of intelligent machines and devices. According to conduct research and analysis of the literature, recent trends in sustainability and systems resilience are necessary for improving the modern workforce. In addition, technical capabilities are required due to widespread digitization, which results in more efficient and flexible manufacturing systems and requires close human-machine cooperation. There is a demand to recruit high-skilled workers with an ability to be open to transformation and to transfer knowledge and work as part of a team. Experts emphasize combining different competencies (technical, methodological, social and personal). This poses a challenge to the education system, highlighting the priority of fostering interdisciplinarity in engineering teaching and the need to create lifelong learning that enhances workforce creativeness and talent building.

In summary, from the analysis of the publication's content, there are many significant challenges related to human orientation, the part of humans in smart factories, and the formation of a safe working environment in Industry 5.0. In-depth research is needed to establish an successful work division and interaction between people and intelligent machines. Determination of models for the use, mutual inspiration and development of unique human and machine intelligence advantages. Especially in the development of human-machine hybrid intelligence. An exciting challenge is to address security, privacy, mental health and work ethics issues in the new environment imbued with artificial intelligence. The development of artificial intelligence and the use of cognitive technologies in human-machine cooperation is one of the most apparent trends likely to develop soon because human-machine cooperation requires human intelligence and perception. In continuation of further research, it would be worthwhile to broaden the research to include issues related to: sociology of technology, management or psychology seems.

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Reference

Aceto, G., Persico, V., Pescapé, A., 2019. A survey on information and communication technologies for industry 4.0: State-of-the-art, taxonomies, perspectives, and challenges. IEEE Communications Surveys & Tutorials, 21(4), 3467-3501.

Adepoju, O., O., Aigbavboa, C., O., 2021. Assessing knowledge and skills gap for construction 4.0 in a developing economy. Journal of Public Affairs, 21(3), e2264.

Ahrens, D., Spöttl, G., 2015. Industrie 4.0 und Herausforderungen für die Qualifizierung von Fachkräften. In Digitalisierung industrieller Arbeit. Nomos Verlagsgesellschaft mbH & Co. KG.

Amor, A., M., 2023. Reinventing Human Resources Through Digitalization. In Managing Technology Integration for Human Resources in Industry 5.0, IGI Global.

Ávila-Gutiérrez, M., J., Suarez-Fernandez De Miranda, S., Aguayo-González, F., 2022. Occupational Safety and Health 5.0—A Model for Multilevel Strategic Deployment Aligned with the Sustainable Development Goals of Agenda 2030. Sustainability 14, 6741. DOI: 10.3390/su14116741

Azeem, M., Haleem, A., Javaid, M., 2022. Symbiotic relationship between machine learning and Industry 4.0: A review. Journal of Industrial Integration and Management, 7(03), 401-433. DOI: 10.1142/S242486 2221300027

Baldissone, G., Comberti, L., Fargione, P., Maida, L., Nebbia, R., 2018. The role of basic and applied research activities for the improvement of OS&H conditions and the dissemination of the Culture of Safety. Geam-Geoingegneria Ambientale E Mineraria-Geam-Geoengineering Environment and Mining, 154, 32-41.

Barata, J., Kayser, I., 2023. Industry 5.0–Past, Present, and Near Future. Procedia Computer Science, 219, 778-788.

Barata, J., Kayser, I., 2023. Industry 5.0–Past, Present, and Near Future. Procedia Computer Science, 219, 778-788.

Bilberg, A., Malik, A., A., 2019. Digital twin driven human–robot collaborative assembly. CIRP annals, 68(1), 499-502.

Brauner, P., Ziefle, M. 2022. Beyond playful learning–Serious games for the human-centric digital transformation of production and a design process model. Technology in Society, 71, 102140.

Breque, M., De Nul, L., Petridis, A., 2022. Industry 5.0 Towards a Sustainable, Human Centric and Resilient European Industry; p. 14. European Commission, Brussels,

Campero-Jurado, I., Márquez-Sánchez, S., Quintanar-Gómez, J., Rodríguez, S., Corchado, J. M., 2020. Smart helmet 5.0 for industrial internet of things using artificial intelligence. Sensors, 20(21), 6241.

Chen, X., Eder, M. A., Shihavuddin, A., S., M., 2020. A concept for human-cyber-physical systems of future wind turbines towards Industry 5.0. Manuscript submitted for publication.

Chiabert, P., D'Antonio, G., Maida, L., 2018. Industry 4.0: technologies and OS&H implications. Geam-Geoingegneria Ambientale E Mineraria-Geam-Geoengineering Environment and Mining, (154), 21-26.

Colim, A., Carneiro, P., Carvalho, J. D., Teixeira, S., 2022. Occupational safety & ergonomics training of future industrial engineers: A project-based learning approach. Procedia Computer Science, 204, 505-512.

Demir, K. A., Döven, G., Sezen, B., 2019. Industry 5.0 and human-robot co-working. Procedia computer science, 158, 688-695.

EC European Commission, 2021. Revision of the Renewable Energy Directive: Fit for 55 package. Available online: https://www.europarl.europa.eu/Reg-Data/etudes/BRIE/2021/698781/EPRS_BRI(2021)698781_EN.pdf (accessed on 27 March 2023).

EC, European Commission, 2022. Industry 5.0. Towards a Sustainable, Humancentric and Resilient European Industry. Available online: https://op.europa.eu/en/publication-detail/-/publication/468a892a-5097-11eb-b59f-01aa75ed71a1/ (accessed on March 27 2023).

Ejdys, J., 2017. Determinanty zaufania do technologii, Przegląd organizacji, 12 (935, 20-27.

Friedman, B., Hendry, D., G., 2019. Value sensitive design: Shaping technology with moral imagination. Mit Press.

Graczyk-Kucharska, M., Szafranski, M., Golinski, M., Spychala, M., Borsekova, K., 2018. Model of competency management in the network of production enterprises in industry 4.0—Assumptions. In Advances in Manufacturing. Springer International Publishing.

Jones, A. T., Romero, D., Wuest, T., 2018. Modeling agents as joint cognitive systems in smart manufacturing systems. Manufacturing Letters, 17, 6-8.

Kazancoglu, Y., Ozkan-Ozen, Y. D., 2018. Analysing Workforce 4.0 in the Fourth Industrial Revolution and proposing a road map from operations management perspective with fuzzy DEMATEL. Journal of enterprise information management.

Lasi, H., Fettke, P., Kemper, H., G., Feld, T., Hoffmann, M., 2014. Industrie 4.0. Wirtschaftsinformatik, 56, 261-264. DOI: 10.1007/s11576-014-0424-4

Laurent, A., 2023. Towards Process Safety 4.0 in the Factory of the Future. John Wiley & Sons.

Lee, J., J., Meng, J., 2021. Digital competencies in communication management: A conceptual framework of Readiness for Industry 4.0 for communication professionals in the workplace. Journal of Communication Management, 25(4), 417-436.

Lemos, J., Gaspar, P., D., Lima, T., M., 2022. Environmental risk assessment and management in industry 4.0: a review of technologies and trends. Machines, 10(8), 702.

Li, G., Yuan, C., Kamarthi, S., Moghaddam, M., Jin, X., 2021. Data science skills and domain knowledge requirements in the manufacturing industry: A gap analysis. Journal of Manufacturing Systems, 60, 692-706.

Lippert, S., K., 2001. An exploratory study into the relevance of trust in the context of information systems technology. The George Washington University.

Longo, F., Padovano, A., Umbrello, S., 2020. Value-oriented and ethical technology engineering in industry 5.0: A human-centric perspective for the design of the factory of the future. Applied Sciences, 10(12), 4182.

Lopez, M., A., Terron, S., Lombardo, J., M., Gonzalez-Crespo, R., 2021. Towards a solution to create, test and publish mixed reality experiences for occupational safety and health learning: Training-MR.

Luthra, S., Mangla, S., K., 2018. Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. Process Safety and Environmental Protection, 117, 168-179.

Maddikunta, P., K., R., Pham, Q., V., Prabadevi, B., Deepa, N., Dev, K., Gadekallu, T. R., Liyanage, M., 2022. Industry 5.0: A survey on enabling

technologies and potential applications. Journal of Industrial Information Integration, 26, 100257. DOI: 10.1016/j.jii.2021.100257
Małysa, T., 2022. Application of Forecasting as an Element of Effective Management in the Field of Improving Occupational Health and Safety in the Steel Industry in Poland. Sustainability, 14(3), 1351.
Martynov, V., V., Shavaleeva, D., N., Zaytseva, A., A., 2019. Information technology as the basis for transformation into a digital society and industry 5.0. In 2019 International Conference "Quality Management, Transport and Information Security, Information Technologies"(IT&QM&IS) 539-543, IEEE.
Matheson, E., Minto, R., Zampieri, E., G., Faccio, M., Rosati, G., 2019. Human–robot collaboration in manufacturing applications: A review. Robotics, 8(4), 100. DOI: 10.3390/robotics8040100
Melnyk, L., Kubatko, O., Matsenko, O., Balatskyi, Y., Serdyukov, K., 2023. Transformation of the human capital reproduction in line with Industries 4.0 and 5.0.
Mohelska, H., Sokolova, M., 2018. Management approaches for Industry 4.0–the organisational culture perspective. Technological and economic development of economy, 24(6), 2225-2240.
Nahavandi, S., 2019. Industry 5.0-A Human-Centric Solution. Sustainability, 11, 4371. DOI: 10.3390/su11164371
Neumann, E. M., Vogel-Heuser, B., Haben, F., Krüger, M., Wieringa, T., 2022. Introduction of an Assistance System to Support Domain Experts in Programming Low-code to Leverage Industry 5.0. IEEE Robotics and Automation Letters, 7(4), 10422-10429.
Nickel, P., 2023. Human Factors in Interface Design of Electronic Control Systems for Mechanical Equipment in Stage and Studio Automation. In International Conference on Human-Computer Interaction, 184-193. Cham: Springer Nature Switzerland.
Pan, Y., 2016. Heading toward artificial intelligence 2.0. Engineering, 2(4), 409-413.
Pfeiffer, S., Lee, H. S., Zirnig, C., Suphan, A., 2016. Industrie 4.0: Qualifizierung 2025. Frankfurt am Main: VDMA.
Pillai, S., G., Haldorai, K., Seo, W., S., Kim, W., G., 2021. COVID-19 and hospitality 5.0: Redefining hospitality operations. International Journal of Hospitality Management, 94, 102869.
Pistolesi, F., Lazzerini, B., 2020. Assessing the risk of low back pain and injury via inertial and barometric sensors. ieee transactions on industrial informatics, 16(11), 7199-7208.
Prassida, G., F., Asfari, U., 2022. A conceptual model for the acceptance of collaborative robots in industry 5.0. Procedia Computer Science, 197, 61-67.
Rada, M., 2020. Industry 5.0 definition. Available online: https://michaelrada.medium.com/industry-5-0-definition-6a2f9922dc48 (accessed on March 27 2023).
Ramos, D., Cotrim, T., Arezes, P., Baptista, J., Rodrigues, M., Leitão, J., 2022. Frontiers in occupational health and safety management. International journal of environmental research and public health, 19(17), 10759.
Rojko, K., Erman, N., Jelovac, D., 2020. Impacts of the Transformation to Industry 4.0 in the Manufacturing Sector: The Case of the US. Organizacija, 53(4), 287-305.
Romero, D., Stahre, J., 2021. Towards the resilient operator 5.0: the future of work in smart resilient manufacturing systems. Procedia CIRP, 104, 1089-1094. DOI: 10.1016/j.procir.2021.11.183.
Saniuk, S., Grabowska, S., 2022a. Development of Knowledge and Skills of Engineers and Managers in the era of Industry 5.0 in the light of expert research. Scientific Papers of Silesian University of Technology, 158, DOI:10.29119/1641-3466.2022.158.35
Saniuk, S., Grabowska, S., Grebski, W., 2022b. Knowledge and Skills Development in the Context of the Fourth Industrial Revolution Technologies: Interviews of Experts from Pennsylvania State of the USA. Energies, 15(7), 2677.
Santos, G., Sá, J.C., Félix, M., J., Barreto, L., Carvalho, F., Doiro, M., Zgodavová, K., Stefanović, M., 2021. New Needed Quality Management Skills for Quality Managers 4.0. Sustainability 13, 6149. DOI: 10.3390/su13116149.
Schneider, P. 2018. Managerial challenges of Industry 4.0: an empirically backed research agenda for a nascent field. Review of Managerial Science, 12(3), 803-848.
Shamim, S., Cang, S., Yu, H., Li, Y., 2016. Management approaches for Industry 4.0: A human resource management perspective. In 2016 IEEE congress on evolutionary computation (CEC) (pp. 5309-5316). IEEE.
Sheridan, T., B., 2016. Human–robot interaction: status and challenges. Human factors, 58(4), 525-532.
Simonetto, M., Arena, S., Peron, M., 2022. A methodological framework to integrate motion capture system and virtual reality for assembly system 4.0 workplace design. Safety Science, 146, 105561.
Sony, M., Mekoth, N., 2022. Employee adaptability skills for Industry 4.0 success: a road map. Production & Manufacturing Research, 10(1), 24-41.
Sun, S., Zheng, X., Villalba-Díez, J., Ordieres-Meré, J., 2019. Indoor air-quality data-monitoring system: Long-term monitoring benefits. Sensors, 19(19), 4157.
Vogl, G., W., Weiss, B., A., Helu, M., 2019. A review of diagnostic and prognostic capabilities and best practices for manufacturing. Journal of Intelligent Manufacturing, 30, 79-95.
Voulgaridis, K., Lagkas, T., Sarigiannidis, P., 2022. Towards Industry 5.0 and Digital Circular Economy: Current Research and Application Trends. In 2022 18th International Conference on Distributed Computing in Sensor Systems (DCOSS), 153-158. IEEE. DOI: 10.1109/DCOSS54816.2022.00037
Wang, B., Zhou, H., Yang, G., Li, X., Yang, H., 2022. Human Digital Twin (HDT) driven human-cyber-physical systems: key technologies and applications. Chinese Journal of Mechanical Engineering, 35(1), 11. DOI: 10.1186/s10033-022-00680-w
Xu, L., D., 2020. Industry 4.0—Frontiers of fourth industrial revolution. Systems Research and Behavioral Science, 37(4), 531-534. DOI: 10.1002/sres.2719
Xu, L., D., Xu, E., L., Li, L., 2018. Industry 4.0: state of the art and future trends. International journal of production research, 56(8), 2941-2962.
Zhong, R., Y., Xu, X., Klotz, E., Newman, S., T., 2017. Intelligent manufacturing in the context of industry 4.0: a review. Engineering, 3(5), 616-630.
Zhou, H., Yang, G., Lv, H., Huang, X., Yang, H., Pang, Z., 2019. IoT-enabled dual-arm motion capture and mapping for telerobotics in home care. IEEE journal of biomedical and health informatics, 24(6), 1541-1549.
Zhou, J., Zhou, Y., Wang, B., Zang, J., 2019. Human–cyber–physical systems (HCPSs) in the context of new-generation intelligent manufacturing. Engineering, 5(4), 624-636. DOI: 10.1016/j.eng.2019.07.015.