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INTEGRATING INDUSTRY 4.0 TECHNOLOGIES INTO HUMAN CAPITAL MANAGEMENT: A CONCEPTUAL FRAMEWORK*

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Abstract. Industry 4.0, together with its elements, represents a new challenge for companies in human capital management (HCM). The article aims to provide an overview and comparison of the research published so far regarding the intersection of the Industry 4.0 elements with HCM and to point out their impact. It provides a conceptual basis for other authors and researchers and is a source of ideas for future research. The study applies a narrative literature review and conceptual synthesis approach to identify Industry 4.0 technologies applicable to HCM and to develop a conceptual framework linking these technologies with HCM phases. The findings identify cloud computing, social media, chatbots, virtual and augmented reality, blockchain, Big Data, artificial intelligence, and business intelligence as the most relevant Industry 4.0 technologies applicable to HCM. If these elements are implemented correctly, labour productivity, process efficiency, performance, and competitiveness of the enterprise on the market can be increased. The benefit of the theoretical overview is also the suggestion of areas of managerial implications that could help in the effective integration of Industry 4.0 technologies into human capital management processes.

Keywords: human capital management; education; Industry 4.0; Industry 4.0 elements digitalization

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JEL Classifications: M12, M14, M15, M53

1. Introduction

The current era is influenced by using digital technologies, which are meant to make people's personal and work lives easier. On the one hand, such technologies bring positives in the form of speeding up and facilitating work and business processes, reducing the risk of accidents at the workplace, or increasing the competitiveness of companies on the market and increasing the quality of services and products provided. On the other hand, it is possible to register risks that consist of higher initial costs for the acquisition of digital technology, the need to employ highly qualified personnel, which will often lead to retraining or layoffs.

Digital technologies can be used in various economic spheres and in various business processes (Lojda et al., 2020). Personnel processes are no exception, i.e., those processes in the company that concern people - employees. It is possible to digitize all activities, from the acquisition and selection of employees, through the remuneration of employees to their release or reassignment to another job (Blstakova et al., 2020).

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In this paper, the term Human Capital Management (HCM) is used instead of Human Resource Management (HRM), because HCM emphasizes employees as strategic assets whose knowledge and competencies create organizational value, while HRM traditionally focuses on administrative and operational personnel processes. A more detailed explanation is provided in Section 2.2. Due to the changes brought about by digital technologies, it will be necessary to pay more attention to people and their human capital (HC), i.e., their knowledge, skills and competences. Businesses should avoid mass layoffs and rather, if possible, invest in the education of their employees.

Despite the growing body of literature on Industry 4.0 and human resource management, limited attention has been paid to the systematic integration of Industry 4.0 technologies across all phases of human capital management. Existing studies usually focus on individual technologies or selected HR processes, while a comprehensive framework linking Industry 4.0 elements with HCM phases remains underdeveloped. Therefore, this paper addresses this research gap by proposing a conceptual model integrating Industry 4.0 technologies into the HCM framework.

The aim of this paper is to develop a conceptual model linking Industry 4.0 technologies with the individual phases of human capital management based on a narrative literature review. The proposed model integrates dispersed knowledge on digital technologies applicable to HCM and provides a structured framework for future empirical research.

The article was inspired by several previous surveys in other countries and business areas that focused on digitalization in various areas, such as small and medium-sized industrial enterprises in Austria (Ranacher et al., 2023), agriculture in Azerbaijan (Valiyev et al., 2022), processes in the food industry in the European Union (Kosior, 2022), waste management in Germany (Borchard et al., 2022), education (Mabungela et al., 2025) small and medium enterprises in Ukraine (Shevtsova et al., 2020), use of HRIS in Europe (Barisic et al., 2019). Likewise, the article is an extension of knowledge from the conclusions obtained in the article Pandya and Wang (2024), Ghosh et al. (2024), Pereira et al., (2021), PB (2019), Ndamase et al. (2026).

We see the further direction of the article in the framework of the investigation of relationships, factors, opportunities and threats of the connection of human capital management with digitalization in economic entities in Slovakia. This would contribute to the expansion of knowledge in the field of human capital management (HCM), human resource management (HRM) and digitalization, and would follow on from studies such as digitalization and development of HC in EU countries, HC during digital transformation in Ukraine (Rodchenko et al., 2021).

2. Theoretical background

2.1 Industry 4.0 and its elements

Industry 4.0 is characterized by the rapid pace of technological progress, the speed of the emergence and spread of digital technologies and innovations, which changes the previously used ways and paradigms of the functioning of people and businesses (Zhang et al., 2023). Although it is a concept that was originally developed mainly for manufacturing companies, its elements are increasingly becoming part of other areas, such as marketing, finance, HR, education.

Industry 4.0 is a concept of the fourth industrial revolution that originated in Germany around 2011 and is based on the systematic digitization and integration of modern digital technologies (especially the Internet of Things, cyber-physical systems and cloud solutions) into production and business processes. Its goal is to increase efficiency, speed and safety of work, optimize production processes, improve the quality of products and services and strengthen the competitiveness of companies by enabling new business models and a higher degree of interconnection of devices and systems (Zakharov et al., 2020; Sima et al., 2020; Pilichowska, 2021; Neumann et al., 2021; Raddi-Mira et al., 2024; Hawaou et al., 2024).

Industry 4.0, i.e., the fourth industrial revolution, represents one of the relatively new concepts that was introduced in Germany in 2011 and whose goal is to connect all devices in the company via the Internet of

Things and thus create smart devices out of them. Its typical feature is also the use of information systems and information and communication technologies (ICT) in industrial areas. The challenge in this area is the use of this concept in other than production areas of the company.

The fourth industrial revolution is based on various pillars, such as digitalization, internet of things, additive manufacturing, Big Data analysis, autonomous robots, simulations, horizontal and vertical system integrations, additive manufacturing (3D printing), cloud systems, augmented reality, cyber data protection, sensors, artificial intelligence, or Business Intelligence (Dragičević & Bošnjak, 2019; Kurt, 2019; Machado et al., 2020; Oztemel & Gursev, 2020; Jamwal et al., 2021).

Digitalization (Figure 1) is one of the tools of Industry 4.0, which is very important for companies operating in different areas and different spheres of the national economy. It is about the possibility of optimizing various business parameters, such as performance, efficiency, or competitiveness (Slusarczyk, 2018; Lachvajderová et al., 2021). Managers must respond effectively and quickly to changes related to the arrival of digital technologies, because this is the only way to ensure the competitiveness of businesses. One form of digitalization is the digitization of analog data through a Human Resources Information System (HRIS). This system ensures the collection, analysis, and storage of information about employees throughout their entire life cycle in the organization (Tursunbayeva, 2019). Research confirms that HRIS positively affects the efficiency of HCM processes and supports the fulfillment of corporate strategy (Akoyo & Muathe, 2017; De Silva & Da Silva Lima, 2017; Barisic et al., 2019). Its main benefits include more efficient planning and decision-making, reducing administrative burden, employee development, and strengthening the strategic importance of HCM. Although HRIS is mainly used in large enterprises, solutions for small and medium-sized enterprises are also available (Baswardono et al., 2019).

Another form is the digitization of biometric data, which uses human characteristics such as face, voice, eyes or fingerprints for identification and access control purposes (Royakkers et al., 2018). Biometric technologies also enable the analysis of emotions through non-verbal communication. However, their use raises questions about the protection of privacy and personal data.

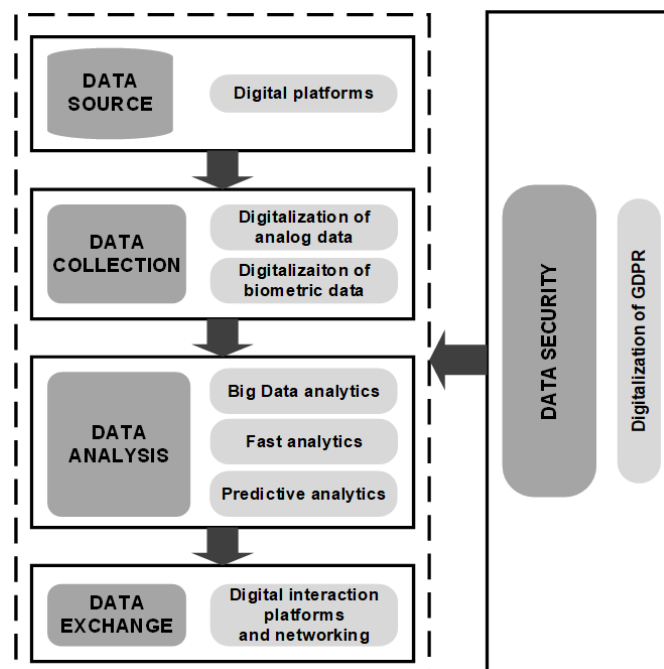


Figure 1. Forms of digitalization towards company employees

Source: own processing

A significant area of digitization is Big Data, which enables the processing of large volumes of diverse data characterized by the volume, speed of creation and diversity of data (Kubina et al., 2015). In the field of HCM, it is used, for example, in the analysis of employee motivation or in smart factories (Polat & Erkollar, 2021; Koman et al., 2018). It is important not only to collect data, but also to evaluate it effectively. Also related to Big Data is rapid analytics, which allows for the analysis of smaller data sets in real time and supports operational decision-making, for example when providing feedback to employees or job applicants (Eva et al., 2019). Predictive analytics uses Business Intelligence technologies to identify relationships between data and predict future events, thereby supporting the optimization of business processes.

Digitalization is also reflected in the use of digital interaction platforms and network solutions, such as intranets, which enable effective communication and information sharing within an organization. These tools increase work productivity, speed up communication, and improve data availability. An integral part of digitalization is data security. In the European Union, the processing of personal data must be in accordance with the GDPR, which regulates the protection of personal data and the free movement of data (Jakobi et al., 2020; Trocin et al., 2021). The GDPR was adopted by the European Parliament in 2016 (Eur-lex, 2023). The importance of data protection increased especially during the COVID-19 pandemic, when companies digitized processes related to the recording of employee health data (Beňová, 2021).

2.2 Human capital, human capital management and its connection with Industry 4.0

Human capital management differs from traditional human resource management by emphasizing the strategic value of employees and the contribution of human capital to organizational performance and value creation. While HRM focuses primarily on administrative and operational personnel processes, HCM considers employees as strategic assets whose knowledge, competencies and capabilities contribute directly to achieving organizational objectives (Kianto et al., 2017; Debrah et al., 2018).

The basis of the concept of human capital management (HCM) is human capital (HC), which represents the sum of an individual's knowledge, skills, abilities and experiences acquired during life. According to Goldin (2016), it also includes education, health, expertise, talent and creativity. Human capital is also understood as a set of abilities, skills and motivation that enable the practical use of knowledge and the creation of value (Zhang, 2023). Its level is mainly influenced by education, health, working conditions and lifelong learning (Pilichowska, 2021; Sultana et al., 2022; Khalid & Syed, 2024).

Human capital management is a modern approach focused on the development and effective use of human capital to increase the performance of the organization and support its long-term development (Kianto et al., 2017). An important part of HCM is the education of employees and the development of their competencies, while continuous education should be a natural part of the corporate culture (Vochozka et al., 2018; Tuncdogan, 2021; Chang, 2023; Mugunzva & Manchidi, 2024).

HCM includes the processes of planning, acquisition, adaptation, development, evaluation and retention of employees. It consists of seven interconnected phases: identification of key knowledge and skills, quantification of the value of human capital, measurement of its effectiveness, analysis of impacts on performance, identification of shortcomings, adoption of corrective measures and reporting.

The importance of human capital has become even more pronounced in connection with digitalization and Industry 4.0, as it is employees who, with their knowledge, skills and competencies, decide on the success of the implementation of digital technologies (Stachová et al., 2020; Adams, 2018; Debrah et al., 2018). Digitalization contributes to increasing productivity, competitiveness and efficiency of processes (Bayram & İnce, 2017; Valiyev et al., 2022), but at the same time it changes the nature of work, work habits and requirements for employees (Renn et al., 2024).

The introduction of digital technologies may lead to the disappearance of some jobs, especially routine administrative and production activities, while the importance of retraining and further education of employees is growing (Pak et al., 2023; Radosavljević et al., 2020; Gonzalez Vazquez et al., 2019; Kicová, 2019; Lourcing

& Jonasson, 2023). Industry 4.0 requires qualified workers with digital and ICT competencies, which are a prerequisite for the effective use of modern technologies (Polat & Erkollar, 2021; Woerkom et al., 2023; Agolla, 2018; Pereira et al., 2020).

The most important competencies in Industry 4.0 are digital skills, including information and data literacy, communication and collaboration, digital content creation, security and problem solving (Flores et al., 2020). Alongside them, the importance of emotional skills and emotional intelligence is growing, which represents one of the main competitive advantages of a person over technology and affects his professional development (Pirsoul et al., 2023).

3. Research objective and Methodology

The article is based on a qualitative research design using a narrative literature review and content analysis of scientific publications focused on Industry 4.0 technologies and human capital management (HCM).

The first phase was a systematic literature review in Web of Science (Table 1). The search was based on combinations of keywords “Industry 4.0”, “fourth industrial revolution”, “human capital management”, “human resource management”, “human”, “digitalization”, “content analysis”, “performance”.

The search was conducted in several iterations. The initial search focused on the combination of “Industry 4.0” and “human capital management” identified only 8 publications, with only one being a review study. Due to the low number of relevant results, the search terms were subsequently expanded to include broader terms related to digitization and content analysis, identifying over 400 publications. After reviewing the titles, abstracts and methodology, empirical studies unrelated to the aim of the work were excluded and publications focused on the use of Industry 4.0 technologies in the field of HCM/HRM were retained. The last search was focused on the connection between human capital management, digitalization and performance, from which 14 additional relevant studies were identified.

Table 1. Results of literature search

Search query	Records found	Relevant after screening	Focus
Industry 4.0 + Human capital management	8	1	Literature review
Industry 4.0 + Human + Content analysis	405	4	Industry 4.0 & HCM
Human capital management + Digitalization + Performance	48	14	HCM digitalization
Industry 4.0 + Human capital + Digitalization + Fourth industrial revolution	378	202	Industry 4.0 & HCM
Human capital management + Human resource management	660	7	HCM vs. HRM

Overall, the literature review confirmed that research linking Industry 4.0 technologies with all phases of human capital management is still limited and most publications focus on individual technologies or selected HR processes, which supports the existence of the identified research gap.

In the second phase, the identified publications were subjected to content analysis. The analysis focused on identifying Industry 4.0 technologies applicable to human capital management and examining their impacts on individual HCM activities. Special attention was paid to recruitment, training and development of employees, performance appraisal, communication, workforce planning and decision-making processes.

In the third phase, the findings obtained from the literature review were synthesized and used to develop a conceptual model illustrating the relationships between selected elements of Industry 4.0 and the phases of human capital management. The model also includes the influence of the external environment and key stakeholders influencing the implementation of digital technologies in organizations. The proposed model represents a conceptual framework that can serve as a basis for future empirical research aimed at verifying the relationships between Industry 4.0 technologies and human capital management practices in enterprises.

Subsequently, the identified technologies were categorized according to their potential application within the seven phases of human capital management. The categorization served as the basis for developing the conceptual framework presented in Figure 2.

4. Results

Figure 2 presents the conceptual model linking Industry 4.0 technologies with the individual phases of human capital management. The model consists of three interconnected components: the HCM process supported by HCMS, the Industry 4.0 technologies applicable across HCM phases, and contextual factors represented by stakeholders and the external environment.

The model consists of three interconnected blocks. The core of the model is business itself. Its functioning is based on a defined mission, vision, goals, strategy and corporate culture. These elements determine the direction of the organization and create the prerequisites for effective human capital management. The HCM concept is therefore closely linked to the overall strategy of the business and supports the achievement of its long-term goals.

The proposed model covers all phases of human capital management. In the phase of identifying key knowledge and skills, digital technologies support competency mapping and workforce planning. During the phase of quantification and measurement, Big Data, Business Intelligence and HCMS enable data collection, analysis and performance measurement. The analysis phase is supported by artificial intelligence and predictive analytics, which facilitate trend identification and decision-making. The identification of deficiencies and the implementation of corrective measures are improved through analytical tools, digital learning platforms and virtual or augmented reality. Finally, the reporting phase is supported by HCMS and Business Intelligence, which provide real-time visualization and reporting of human capital indicators.

The basis for integrating Industry 4.0 technologies across HCM phases is the HCMS information system, which supports all phases of human capital management. It enables centralized management of employee data, automation of administrative processes, workforce planning, performance management, employee training, benefit management and analytical data processing. This increases the efficiency of personnel processes and improves decision-making.

Cloud computing ensures the connection of individual systems and the sharing of information in real time. Social media supports employee recruitment, communication and performance evaluation. Chatbots streamline communication with applicants and employees. Virtual and augmented reality are used mainly in employee education, training and adaptation. Blockchain enables secure data processing and verification of applicant qualifications. Big Data supports the analysis of large volumes of data and predictions of future developments. Artificial intelligence is used in recruitment, performance evaluation, education and personalization of employee development. Business Intelligence provides aggregation, analysis and visualization of data needed for managerial decision-making.

The created model demonstrates how selected Industry 4.0 technologies can support individual HCM phases and improve organizational performance through more efficient processes, data-driven decision-making and enhanced human capital development.

The selected technologies were identified as the most frequently occurring and practically applicable Industry 4.0 elements in the reviewed literature related to human capital management. Technologies primarily associated with manufacturing processes, such as additive manufacturing, autonomous robotics or cyber-physical systems, were excluded because their direct application to HCM activities is limited.

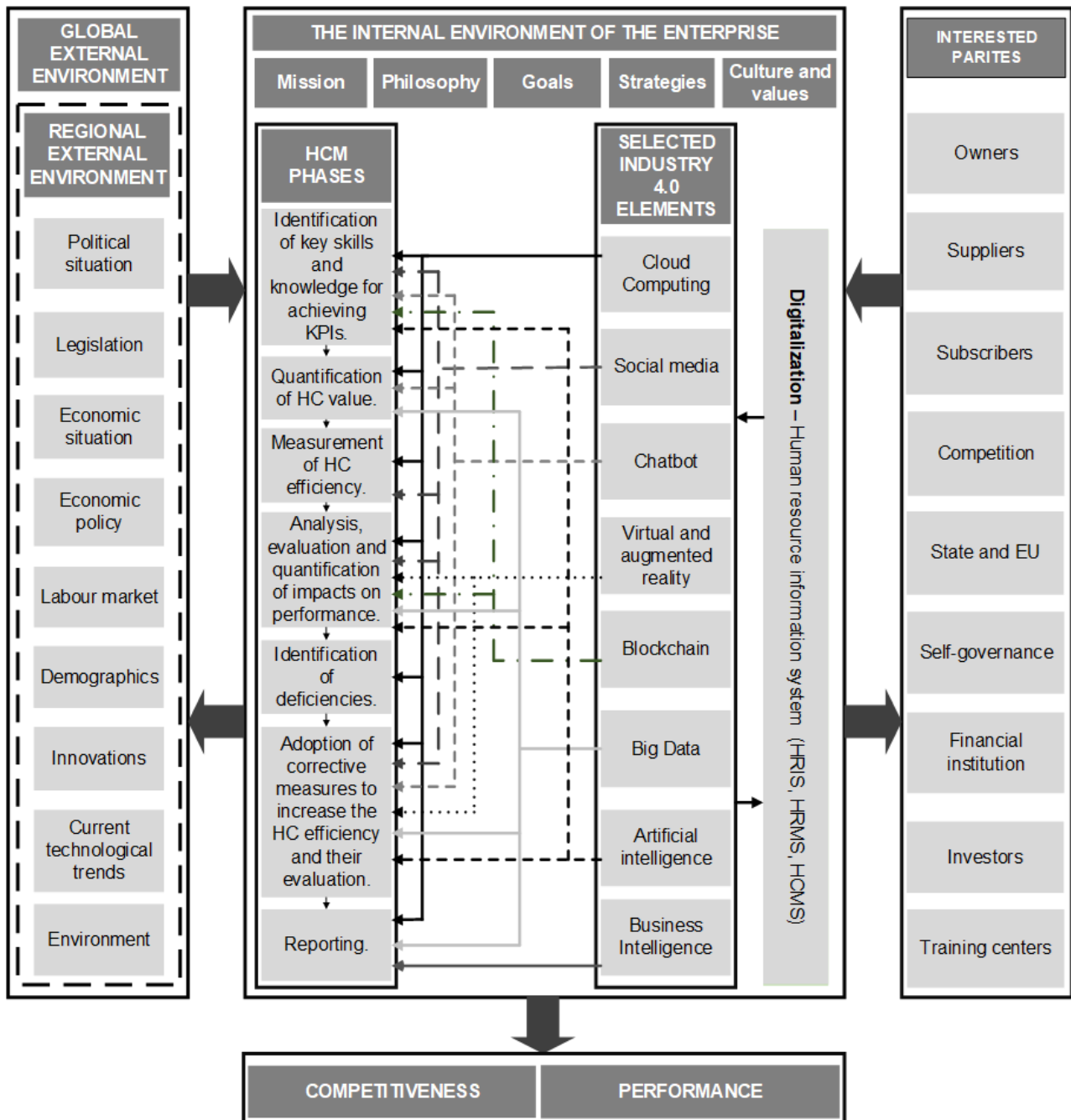


Figure 2. Conceptual model linking Industry 4.0 technologies with Human Capital Management phases

Source: own processing

The second block represents a company implementing Industry 4.0 technologies across human capital management processes. The basic prerequisite for successful implementation is a human capital management information system (HCMS), which ensures effective data management and supports the use of digital technologies. The second block is the external environment of the company, and the third block represents stakeholders who can significantly influence the course and results of the implementation.

The external environment includes factors operating at both regional and global levels. These include the political situation, legislation, economic situation, economic policy, the situation on the labor market, demographic development, technological trends, innovations and environmental requirements. These factors affect the ability of companies to introduce digital technologies, obtain financial resources, develop employees and respond to changing market conditions.

Political stability and the legislative environment create the framework for the functioning of companies and determine the conditions for investments and digitalization of processes. The economic situation and economic policy affect the availability of financial resources and support for modernization projects. European Union initiatives that support digital transformation through grants, funds and other financial instruments also play a significant role.

An important factor is the situation on the labour market and demographic developments. Digitalization changes the requirements for employees and increases the importance of digital and social skills. At the same time, the aging of the population reduces the availability of the workforce, which increases the need for education, retraining and effective use of human capital.

Technological trends are moving towards the use of artificial intelligence, cloud solutions, virtual and augmented reality, blockchain, Big Data and social media. These technologies contribute to the automation of processes, higher labor productivity and more effective decision-making. At the same time, they support the principles of sustainability and environmental protection through resource savings, reduced paper consumption and process optimization.

The third block of the model consists of stakeholders. Internal stakeholders include business owners and employees. External stakeholders are customers, suppliers, competitors, the state, local governments, financial institutions, investors and educational organizations.

Business owners influence decisions on investments in digital technologies and create conditions for their implementation. Employees represent the bearers of human capital, the quality of which significantly affects the success of the transformation. Suppliers provide technological solutions and support for their implementation. Customers create pressure for innovation and higher-quality products and services. Competition motivates businesses to modernize and introduce new technologies. The state, the European Union and local governments create legislative and financial conditions for the development of digitalization. Financial institutions and investors provide the capital necessary for the implementation of transformation projects. Educational and training organizations ensure the development of employees' competencies in the field of digital technologies.

5. Discussion

The research results confirmed that the connection of the concept of human capital management (HCM) with the elements of Industry 4.0 represents a current and still insufficiently explored area of scientific research. An analysis of professional literature showed that digitalization significantly affects human capital management and gradually changes the way personnel processes are implemented. The importance of digitalization in business practice is also emphasized by Jankelová et al. (2021), who point to the acceleration of the implementation of digital technologies during the COVID-19 pandemic.

The main theoretical contribution of the article lies in the creation of a conceptual framework linking the individual phases of HCM with selected elements of Industry 4.0. Unlike most existing studies that focus on specific technologies or selected personnel processes, the proposed model provides a comprehensive view of the use of digital technologies in the entire human capital management process. The results thus extend the knowledge presented by the authors Pereira et al. (2021), Ghosh et al. (2024), Pandya and Wang (2024) or Podhorcová et al. (2023), who point out the growing importance of digital technologies in the field of human resource management and employee development.

The novelty of the proposed model lies in its comprehensive integration of Industry 4.0 technologies with all phases of human capital management. Unlike previous studies, which primarily address individual digital technologies or selected HR activities, the proposed framework systematically connects technologies, HCM phases, stakeholders and external environmental factors within a single conceptual model.

A significant contribution to the proposed model is the use of the human capital management perspective instead of traditional human resource management. While HRM primarily focuses on personnel processes, HCM emphasizes the strategic value of human capital and its contribution to the performance and competitiveness of the enterprise. This approach is in line with the views of the authors Kianto et al. (2017), Debrah et al. (2018) and Zhang (2023), who consider human capital to be one of the decisive factors of the long-term performance of the organization.

The literature analysis also identified cloud computing, social networks, chatbots, virtual and augmented reality, blockchain, Big Data, artificial intelligence and Business Intelligence as the most important technologies usable in individual phases of HCM. Their application is most often associated with employee recruitment, training and development, performance appraisal, data management and management decision support. These findings correspond to the results of studies by Bilge et al. (2021), Chang (2023), Polat and Erkollar (2021), Flores et al. (2020) and Stachová et al. (2020), which point to the growing importance of digital tools in the development and effective use of human capital.

An important aspect of the proposed model is also the inclusion of stakeholders and external environmental factors. Many existing studies examine digitalization mainly from the perspective of internal company processes, however, the success of the implementation of Industry 4.0 technologies is significantly influenced by the legislative environment, economic situation, labour market developments, demographic changes, technological progress and availability of financial resources. The importance of external factors in the digital transformation of companies is also emphasized by Rodchenko et al. (2021), Cherenko et al. (2021), Kelchevskaya and Shirinkina (2019), Valiyev et al. (2022), Ranacher et al. (2023), Kosior (2022), Borchard et al. (2022), Shevtsova et al. (2020).

The results further indicate that the implementation of Industry 4.0 technologies is not only a technological challenge, but primarily a managerial and personnel challenge. The success of digital transformation depends on the level of digital competencies of employees, support from management, organizational culture and the willingness of companies to invest in human capital development. This conclusion is also supported by the authors Agolla (2018), Adams et al. (2018), Woerkom et al. (2023), Tuncdogan et al. (2021), Pirsoul et al. (2023) and Khalid and Syed (2024), who emphasize the importance of competencies, continuous learning and emotional skills of employees in a digital environment.

The practical contribution of the article lies in the creation of a framework that can help managers identify appropriate technologies for individual phases of HCM and plan the digital transformation process more effectively. The implementation of the proposed technologies can lead to increased labor productivity, more efficient use of human capital, improved decision-making processes and strengthened competitiveness of the enterprise, which is also confirmed by the results of research by the authors Vetráková and Smerek (2019), Field and Mkrtchan (2017), Bayram and İnce (2017), and Martincevic (2022).

Conclusion

Despite the above contributions, the research has several limitations. The proposed model was created based on a synthesis of knowledge from professional literature and has not been empirically verified in the conditions of specific enterprises. The results therefore primarily represent a theoretical basis for further research. A promising direction for future research is empirical testing of the model in companies of various sizes and sectors, as well as a more detailed examination of the impact of individual Industry 4.0 technologies on specific phases of human capital management. Future research may also compare the applicability of the model across different industries and organisational sizes and examine the contribution of individual Industry 4.0 technologies to specific HCM phases.

The aim of the article was to analyze the possibilities of integrating Industry 4.0 elements into the concept of human capital management and based on the synthesis of knowledge from professional literature, to create a conceptual framework illustrating their mutual connection. The analysis confirmed that digitalization and

Industry 4.0 technologies are gradually becoming an integral part of human capital management and significantly influence the way personnel processes are implemented.

The main contribution of the study is the development of a conceptual model linking Industry 4.0 technologies with all phases of human capital management while considering the role of HCMS, stakeholders and external environmental factors. The proposed framework provides managers with a structured overview of technologies applicable across HCM processes and serves as a basis for planning digital transformation initiatives.

The conceptual nature of the model and the absence of empirical validation represent the main limitations of this study. Future research should therefore focus on empirically testing the proposed model in organizations of different sizes and sectors and on assessing the contribution of individual Industry 4.0 technologies to specific phases of HCM.

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