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Digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms in the Industry 4.0-based Slovak labor market

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Abstract

Research background: On the basis of an analysis of the current situation and expectations in the field of implementation of the elements of the Industry 4.0 concept, the purpose of this paper is to identify the effects on the labor market in large manufacturing enterprises in the Slovak Republic.
Purpose of the article: The presented work has a theoretical-empirical nature and consists of a theoretical section and a practical section, which includes statistical indicator analysis and quantitative research. In the theoretical section, the paper discusses the issue of Industry 4.0 in general, with a focus on its impact on the labor market, thus laying the groundwork for future research on the subject.
Methods: The output of this work is an analysis of selected indicators of the manufacturing industry sector in the Slovak Republic, based on the most recent employment data analysis in the first stage and quantitative research survey in the second stage, with the respondents being manufacturing industry companies operating in the Slovak Republic, and whose primary objective is to determine the current status of the implementation of the elements and technologies of Industry 4.0 in production companies in the Slovak Republic, as well as the factors influencing this situation, such as digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms.
Findings & value added: The research findings indicate that the degree of digitization adopted by businesses in the Slovak Republic is comparatively less robust and more sluggish to adapt. This is primarily attributable to the underdeveloped educational system, population reluctance, self-actualization, and inadequate state support. Recommendations for the Slovak market aim to increase the digital proficiency of businesses and of the general populace through various means, such as reforming legislation, enhancing state support for entrepreneurs, and modifying the education system, constituting the added value of the work.

Introduction

The terms "Industry 4.0" and "the fourth industrial revolution" are designations used to describe substantial changes occurring in the realm of manufacturing and related commercial operations, which are rooted in the process of digitalization (Turek *et al*., 2023; Lewandowska *et al*., 2023). The subject of Industry 4.0 is frequently debated among both professionals and the general populace, since the process of digitization is progressively permeating various aspects of our existence. The genesis of the Industry 4.0 idea can be traced back to Germany, where it emerged as a response to the diminishing output levels within the industrial sector. This decline prompted the relocation of manufacturing facilities to more cost-effective nations outside of Germany.

The industrial sector has experienced substantial transformations since its origin, commencing with the advent of the initial industrial revolution (Schoeneman *et al*., 2022). This pivotal period marked the ascendance of industry's significance, coinciding with the invention of the steam engine, which emerged as a distinguishing characteristic of this transformative industrial era. During the period known as the second industrial revolution, there was a notable emergence of electrical energy use, a significant focus on the electrification of production processes, and the invention of the internal combustion engine (Poliak *et al*., 2021).

During the progression of the third industrial revolution, there was a progressive integration of robotics and information and communication technology into deep reinforcement learning-based production processes (Sultana & Fernando, 2022), resulting in a significant surge in productivity. The preceding industrial revolutions are distinguished by a notable advancement in industrial sector and output, marked by significant development and innovation (Modibbo *et al*., 2022; Machova *et al*., 2023). The contemporary period is distinguished by swift transformations and advancements in the realm of technology, accompanied by the emergence of the Internet of Things and artificial intelligence by use of digital twin-based cyber-physical production systems, environment mapping algorithms, and immersive metaverse technologies (Cerna *et al*., 2022). These breakthroughs have given rise to the fourth industrial revolution, sometimes referred to as Industry 4.0 (Pugliese *et al*., 2019). The labor market has been significantly influenced by earlier industrial revolutions, and these implications will be examined in greater depth within the present study.

The initial industrial revolution witnessed a significant surge in productivity, prompting corporations to prioritize profit maximization, a factor that subsequently contributed to worker discontent (Mugge, 2020). During the era of the Second Industrial Revolution, there was a notable limitation on workers' rights, coupled with suboptimal working conditions (Kliestik *et al*., 2022a). The third industrial revolution was distinguished by the substitution of human labor with computer technology, leading to the emergence of novel employment opportunities. Consequently, it is anticipated that the labor market will be influenced by the fourth industrial revolution, namely the integration of Industry 4.0 principles into corporate operations (Cramarenco *et al*., 2023; Dabija & Vatamanescu, 2023) in terms of techno-economic assessment (Lăzăroiu *et al*., 2020).

The primary objective of this study is to ascertain the effects on the labor market in major manufacturing enterprises in the Slovak Republic by analyzing the current state and anticipated developments in the implementation of Industry 4.0 elements in terms of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, remote sensing data fusion techniques (Nagy & Lăzăroiu, 2022) and virtual machine and cognitive computing algorithms. Due to a long history of expertise in the technical sector, the Slovak Republic has a large pool of employees with high-quality digitization adaptability potential. However, it is difficult to predict to what extent the country can withstand the acceleration of the current Industry 4.0 trend, which will also be highly dependent on government support and citizen motivation to adopt this trend as soon as possible (Valaskova *et al*., 2022).

The first section of the study is dedicated to the establishment of the present condition of the issue both domestically and internationally. This involves an examination of the historical progression of industrial revolutions and their influence on the labor market. Furthermore, it entails a characterization of Industry 4.0, with particular attention given to its principles, components, and technologies, such as digital twin-enabled industrial Internet of Things, event modeling and forecasting tools, and virtual immersive technologies. The general impacts of Industry 4.0 are highlighted, with a specific focus on its effects on the labor market. Additionally, the concept of Industry 4.0 is explored in selected European Union countries, along with an analysis of its manifestation in the Slovak Republic. This analysis encompasses an evaluation of employment trends and future projections.

In the second section, the authors elucidate the objective of the study as well as the subsidiary objectives that contribute to the attainment of the primary goal. Additionally, the authors outline the formulation of research inquiries, the attributes of the research sample, the delineation of the used methodologies, and the materials employed for data analysis in the study.

The subsequent phase of this study focuses on examining the influence of Industry 4.0 on the labor market within the manufacturing sector in the Slovak Republic. This phase encompasses an evaluation of specific indicators pertaining to the manufacturing industry in the Slovak Republic from 2016 to 2022. Additionally, it presents the outcomes of a quantitative research study conducted through the distribution of an online questionnaire to prominent hyper-connected manufacturing companies operating in the Slovak Republic.

The final section of the study comprises a discussion, in which the research questions are assessed, the findings derived from the investigation are debated upon, and practical recommendations are put forth with the objective of enhancing the present condition of the subject matter in relation to the influence of Industry 4.0 on the labor market by integrating spatial computing technologies, interactive 3D geo-visualization systems, and virtual machine algorithms for 3D digital twin factories.

The authors of this study assert that the presented research provides a comprehensive perspective on the contemporary subject matter concerning the implementation of the Industry 4.0 concept and its implications for the labor market. They suggest that this work can serve as a foundation for future endeavors aimed at resolving and exploring the matter of Industry 4.0 in relation to its influence on the labor market in the Slovak Republic by use of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms.

Literature review

The field of industrial production has experienced substantial transformations during the past several centuries, resulting in noteworthy impacts on both enterprises and individuals' livelihoods. The notion of Industry 4.0 is built upon the foundations laid by the three preceding industrial revolutions, with each revolution's principles mutually influencing the others (Gavurova *et al*., 2020).

The inaugural industrial revolution transpired during the latter part of the 18th century until the conclusion of the 19th century. During this era, there was a notable shift in the significance of industry, which surpassed agriculture as the predominant sector. This transition occurred due to the recognition that the fundamental ingredient for the development of civilizations was largely the accessibility of food. Prior to the advent of the initial industrial revolution, the concentration of industrial activity was mostly observed in major urban centers, with little overall representation (Siekelova *et al*., 2020). One defining aspect of the initial industrial revolution was the introduction of the steam engine, a development that resulted in a significant augmentation in worker efficiency. The advent of the first industrial revolution led to the establishment of factories, which in turn facilitated the development of novel innovations like vehicles. However, it is worth noting that, during this period, automobiles were primarily accessible to those belonging to the higher echelons of society (Lyons & Lăzăroiu, 2020).

The temporal span of the second industrial revolution extends from the latter part of the 1880s to around the midpoint of the 20th century. During this era, there was a notable emergence of electrical energy use in industrial settings, with a particular emphasis on the electrification of manufacturing processes. Additionally, the invention of the internal combustion engine took place. The second industrial revolution brought about notable changes in the sectoral composition of production and its energy sources. Additionally, it led to an elevation in the intellectual capacity of society and exerted a substantial influence on the intensity and progression of global economic development (Savova, 2021). These factors collectively had a profound effect on enhancing output in production processes.

The onset of the third industrial revolution occurred throughout the latter part of the 20th century. During this particular era, the integration of robotics and information and communication technology into manufacturing processes led to a notable surge in productivity through virtual modeling technologies, cyber-physical production systems, and cognitive artificial intelligence algorithms (Chang *et al*., 2019).

The third industrial revolution is commonly referred to as the "computer revolution" in academic discourse. The United States is closely linked to this phenomenon due to its significant contributions in scientific and engineering endeavors, substantial investments in research, and the presence of a huge and concentrated pool of talent. This may be attributed to the considerable influx of migrants to the United States during that period. Throughout the era of the third industrial revolution, there was a growing interdependence between science and technology, leading to increased spending in research, development, and teaching (Markarian & Santalo, 2014). One notable feature involves the implementation of electronic systems for the purpose of automating manufacturing processes, alongside the advancements in cybernetics, such as computers and electronics. The utilization of steam machines was superseded by the introduction of electric and motorized devices, resulting in a significant expansion of infrastructure in industrialized nations. Notable advancements have occurred in the domains of nuclear power plants and medicine (Montenegro & Rodrigues, 2020).

The field of information technology has emerged as a fundamental pillar of several industries. It has been estimated that around 80% of innovative advancements rely on computerization (Laksmana & Yang, 2015). The advent of telecommunication and information technologies has laid the foundation for the emergence and growth of the network economy. From a labor market perspective, three key drivers have played a crucial role. These determinants include the economic dimension, which is centered around the productivity of a skilled workforce and is based on knowledge and the value generated by such personnel. The social dimension encompasses the challenges faced by society in addressing new realities related to social issues, in conjunction with increased performance, labor productivity, employment, demographic concerns, changes in the nature of creative and innovative processes, complex revitalization changes, and global competitiveness (Li, 2019). Lastly, the philosophical-educational dimension pertains to the emergence of a new societal division and its associated values, particularly in terms of aesthetic and intellectual perception (Durana *et al.*, 2020). The accelerated rate of technological advancements, particularly in the field of information technology, has resulted in notable transformations characterized by substantial improvements in productivity and quality through immersive holographic imaging technologies, blockchain-based decentralized metaverse systems, and 3D space mapping algorithms.

The advancement of technology is accompanied by a corresponding growth in customer demands (Fialova & Folvarcna, 2020). The 21st century has witnessed a reduction in the duration of product life cycles, accompanied by an increasing customer demand for intricate and distinctive items in larger quantities. This phenomenon has presented a formidable challenge for the industry, prompting the advent of the fourth industrial revolution, also known as Industry 4.0 (Cho *et al.*, 2012). The fourth industrial revolution is distinguished by the integration of intelligent systems that are interconnected through networks, enabling communication between humans and machines in terms of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms (Thanh *et al.*, 2020).

The concept of Industry 4.0 revolves around the integration of the Internet of Things, computer systems, and artificial intelligence. This integration is anticipated to bring about substantial transformations in human intellectual activity, thus leading to noteworthy effects on the labor market (Susanto *et al*., 2019). The impact of each industrial revolution on individuals, society, and national economies was profound. The fourth industrial revolution is unlikely to deviate from this pattern. Numerous organizations are progressively integrating its constituent aspects and technology to align with prevailing trends and enhance their competitive edge in the market. The notion of Industry 4.0 is founded upon the process of digitalization, facilitating a substantial overhaul of industrial methods. The optimization of informatization from the era of the third industrial revolution is achieved via the implementation of this concept (Clayton & Kral, 2021; Kolupaieva & Tiesheva, 2023).

The notion of Industry 4.0 lacks explicit definitions of standardized protocols, communication interfaces, or technical specifications for the design and assembly of machinery and equipment. Furthermore, it does not offer particular guidelines or directives. Industry 4.0 refers to a pan-European initiative led by executives of prominent European companies and government officials from the European Union. The primary objective of this initiative is to foster societal demand for innovative consumer and industrial technologies, thereby facilitating the rapid adoption of robotics and advanced automated control systems that reduce reliance on human labor (Ruttimann & Stockli, 2016; Durana *et al*., 2021; Sony, 2020).

The primary and fundamental conceptual objective of Industry 4.0 was to facilitate the reindustrialization of manufacturing in Germany using advanced technologies that can effectively compete with low-cost labor, and then the concept was generalized. Simultaneously, it is anticipated that the emergence of new employment opportunities would necessitate the engagement of individuals possessing advanced qualifications (Kolade & Owoseni, 2022; Smaldone *et al*., 2022). The objective is moreover to substantially augment the scope of research and development, enhancing competitiveness, a goal that can be attained through various means (Hoffmann, 2019). These include establishing a secure market position for industry subsectors, fostering innovation, advancing industrial information technologies, cultivating a skilled and motivated workforce, strengthening collaboration between industry sectors and their suppliers as well as customers, and providing support to executive institutions and facilities involved in research, development, education, and training (Minarik *et al*., 2022; Zavadska & Zavadsky, 2020; Said *et al*., 2021).

The fundamental principles behind the notion of Industry 4.0 encompass the digitalization of many elements, such as product, processes, equipment, and services, alongside the integration and utilization of exponential technologies such as digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms. The fundamental concept is the reciprocal exchange and collaboration among machines, individuals, logistical systems, and commodities (Zhong *et al*., 2021; Kliestik *et al*., 2023). Simultaneously, work engages with a substantial volume of information that has hitherto proven challenging to document or remains undocumented. This capability facilitates expedited decision-making processes that are more effective. The establishment of a strong correlation between products, equipment, and employees is expected to yield enhanced operational efficiency of machinery employed in the manufacturing process, leading to cost reduction and resource conservation (Hatzigeorgiou & Lodefalk, 2021; Lăzăroiu *et al*., 2022; Andronie *et al*., 2023).

Industry 4.0 is further distinguished by the progressive integration of biotechnologies and nanotechnologies, in addition to geolocation data mining and tracking tools, machine intelligence technologies, and remote sensing algorithms. A corporation that adopts this notion is referred to as an "intelligent company" due to its utilization and integration of several advanced technologies, including CAD systems for design, ERP systems, 3D scanning and printing, extended reality, sustainable cyber-physical production systems, and artificial intelligence-based decision-making algorithms (Kumar *et al*., 2020; Horvath & Szabo, 2019; Gray & Kovacova, 2021; Andronie *et al*., 2021). By integrating these emerging technologies into its operational procedures, the organization undergoes a digital transformation. Digitization plays a crucial role in various aspects of production, including production processes, the creation and manufacturing of new products, production lines, logistics, warehouse systems, shipping, customer service, complaint resolution processes, and recycling (Vaidya *et al*., 2018; Ye *et al*., 2020). The emergence of the Industry 4.0 trend is rooted in the extensive integration of information technology and associated data processing within the industrial sector (Umiński *et al*., 2023). This integration is characterized by four fundamental attributes:

1. Vertical integration refers to the integration of production systems, which involves connecting information across various systems within the entire organizational structure of a company. This integration en-

compasses smart production systems, connected logistics systems, and marketing strategies that are tailored to meet the individual needs and specific requirements of customers, thereby emphasizing personalization (Sierra-Perez *et al*., 2021).

2. Horizontal integration refers to the establishment of connections along the supply chain, encompassing suppliers, customers, and the flow of goods from manufacturers to consumers, as well as associated services. This phenomenon represents a novel form of global connectivity, characterized by value-added networks that involve the integration of partners and customers.
3. The integration of engineering processes encompasses the seamless incorporation of several stages throughout the life cycle, including planning, development, implementation, testing, and sales.
4. The acceleration of exponential technologies leads to their increased accessibility and utilization. Their primary function is to facilitate the adoption of personalized solutions, enhance flexibility, and reduce costs in the industrialization process (Sierra-Perez *et al*., 2021; Zabojnik, 2015).

The idea of Industry 4.0 is characterized by a number of fundamental characteristics, which serve to differentiate production under the implementation of Industry 4.0 from traditional production methods by use of predictive geospatial modeling and simulation tools, image processing computational algorithms, and multi-sensor fusion systems in simulated 3D extended reality environments. The foundation is on expedited processes, which are facilitated by smart (intelligent) technology through vertical integration of production processes, horizontal integration utilizing advanced iterations of the value chain, and seamless production flow over the entirety of the value chain (Yang & Gu, 2021). The approach is thus centered around intelligent processes, representing a substantial departure from conventional manufacturing methods. The fundamental premise of this approach is around the establishment of what smart factory (Ionescu, 2021) in terms of deep learning-based object detection technologies and remote big data management tools (Andronie *et al*., 2023).

Hence, digitalization emerges as the central focus of Industry 4.0. In practical terms, this implies that various items, equipment, gadgets, and even some spaces will be equipped with their own microchips, enabling remote control and operation through internet connectivity (Kovacova & Lewis, 2021). The term "smart factory" is commonly used to describe the concept of the "factory of the future," a fundamental aspect of the fourth industrial revolution (Ionescu, 2021; Kovacova & Lewis, 2021; Markarian & Santalo, 2014). The primary focus of Industry 4.0 is the optimization of production processes rather than the generation of new ideas. Therefore, the central tenet of the Industry 4.0 paradigm is centered around the notion of optimization (Bonab, 2017; Lăzăroiu & Harrison, 2021).

The concept of Industry 4.0 is predicated around the integration and advancement of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms. In this study, the authors will provide a concise overview of the technologies related to smart city sustainability (Brioschi *et al*., 2021), earnings management adoption (Mongrut & Winkelried, 2019), value creation and capture across the automotive field (Pavlínek & Ženka, 2016), knowledge capitalism (Peters, 2022), big data-driven cognitive automation and smart manufacturing (Rogers & Zvarikova, 2021), process innovation in smart factories (Sjodin *et al*., 2018), transformative changes in innovative systems (Schot & Steinmueller, 2018), digital twin-based cyber-physical systems (Tao *et al*., 2019), and enterprise digital transformation (Verhof *et al*., 2021; Piotrowski & Orzeszko, 2023).

The prevailing corporations leading the way in the adoption of Industry 4.0 are Delmia and Technomatix, both of which are products of Dassault Systems (France) and Siemens (Germany), prominent technical firms. CEIT Zilina holds a relevant position within the Slovak Republic and has been actively implementing transformative measures since 2011 to facilitate the digitization process of the Matador Group (Galbraith & Podhorska, 2021).

Industry 4.0 represents a manifestation of societal transformation achieved through the integration of the physical, virtual, and social realms. This transformation exerts a profound influence on various domains, including industry, technical standardization, safety protocols, education, legislation, research, social systems, labor market dynamics, working conditions, and the prerequisites for work qualifications. The employment sector and economic development will see the most pronounced effects as a result of the fourth industrial revolution (Galbraith & Podhorska, 2021).

The implementation of the Industry 4.0 concept is expected to have a positive impact on enhancing enterprise competitiveness through industrial Artificial Intelligence of Things, visual perceptive systems, and bio-inspired computational intelligence algorithms. This can be achieved through the improvement of production flexibility, leading to a stronger market position for enterprises due to increased process efficiency (Dávid

& Dadkhah, 2023). The anticipated beneficial effects can be succinctly outlined as follows:

- Higher productivity refers to the ability to achieve greater output levels while minimizing mistakes and hazards, increasing the quantity of items produced, and reducing the duration of working hours.
- Enhanced flexibility is observed in several aspects, including the customization of goods to meet individual needs, improved manufacturing efficiency, and a broad range of control procedures with significant variations.
- Enhanced competitiveness is achieved through several means, such as reducing manufacturing costs, adopting innovative solutions and technologies, and maintaining flexibility in responding to swings in demand.
- Enhanced profitability through strategies such as mass manufacturing, process optimization, reduced inventory, and cost-effective production methods.

The first aspect to consider is safety, which encompasses the prevention of faults and mistakes in software as well as the safeguarding of worker safety through the utilization of sensors. Additionally, it involves the implementation of prompt reactions and interventions to address any potential safety concerns. Ecology encompasses practices such as deactivating unwanted objects, adopting environmentally friendly solutions, and utilizing renewable energy sources (Fernando & Lăzăroiu, 2023). Advocates of the Industry 4.0 concept anticipate that the enhanced functionalities and streamlined procedures of a medium-sized facility would result in a substantial annual revenue growth of several million dollars. However, this transformation is also expected to have a notable impact on workforce reduction (Krulicky & Horak, 2021; Grofcikova, 2020). The adoption of Industry 4.0 may lead to the displacement of high-paying employment and to a shortage of skilled and experienced personnel (Kubickova *et al*., 2021; Lanier *et al*., 2019).

The evolving demand for skilled labor is undergoing a transformation due to the advent of Industry 4.0. Consequently, the workforce will require new proficiencies and competencies, necessitating a paradigm shift in workforce certification (Popescu *et al*., 2022). There will be a notable surge in the need for individuals with education in technical and natural scientific disciplines, a population that has witnessed growth within university settings in recent times (Vinerean *et al*., 2022).

Workers engaged in repetitive regular operations should learn additional skills in response to the advent of Industry 4.0. Furthermore, it is important for individuals to actively participate in ongoing educational endeavors. Consequently, this will need the formulation of market-oriented policies that focus on cultivating the requisite talents and skills essential for sustaining competitiveness within a progressively dynamic economic landscape (Hamilton, 2022).

The assertion that Industry 4.0 does not inherently entail widespread job loss and the subsequent substitution of human labor with automated systems is further substantiated by the empirical evidence from Germany, that, in 2016, reported a mere 6% unemployment rate. The statistical data pertaining to the Republic of Korea also indicates shifts in the composition of employment opportunities. The proportion of employed individuals working in the service industry had a notable growth from 9.1% in 2011 to 15.7% in 2017. There was a notable rise in the proportion of individuals working shifts between 2011 and 2017. Specifically, the percentage of people engaged in shift work rose from 6.5% in 2011 to 15.1% in 2017 (Johnson & Nica, 2021).

It is imperative to acknowledge the counter perspective, namely that certain businesses have long grappled with labor shortages due to digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms. Consequently, the adoption of the Industry 4.0 paradigm stands to offer substantial advantages to these companies, without entailing workforce reductions or dismissals. One instance that exemplifies this phenomenon is the Czech Republic, with a particular focus on its automotive industry. In this context, the implementation of automation and robotization technologies serves as a means to effectively compensate for the scarcity of available labor (Klingenberg *et al*., 2019). This approach is particularly relevant given the country's relatively low unemployment rates and the absence of substantial projections for a substantial increase in the workforce due to demographic trends.

The fourth industrial revolution is expected to have several noteworthy implications, which can be succinctly stated as follows (European Commission, 2022; Lyons, 2022; Mondejar *et al*., 2021):

– The rise in the proportion of capital and revenue resulting from the substitution of human labor with automated machinery and robots has led to a decline in the proportion of labor and its associated benefits for employees.

- There has been a decrease in the demand for labor, which is perceived as favorable given Europe's current scarcity of trained employees. This scarcity is mostly attributed to a fall in population, with Germany's working-age workforce projected to diminish by almost 20% by the year 2030.
- The primary focus will be on individuals' talents rather than on financial resources, resulting in the segmentation of labor markets into distinct categories based on skill levels, where low skills correspond to low pay and high skills correspond to high salaries. Consequently, this division may exacerbate societal conflicts.
- The substitution of individuals with technological advancements will ultimately result in enhanced safety and cleanliness inside work environments, hence rendering occupations more purposeful.
- The proliferation of digital technologies can lead to an increasing sense of discontentment as a result of the mechanisms of information dissemination via social media that may generate and perpetuate unrealistic expectations, as well as facilitate the dissemination of extreme ideas and ideologies in relation to the concept of Industry 4.0.

In order to address the implications of Industry 4.0 on the labor market, the authors' investigation is concentrated on examining the present circumstances in the Slovak Republic. Specifically, the authors analyze the progression of the unemployment rate and employment trends across various sectors of the economy. This analysis is based on the statistical data available from 2016 to 2022. Given the prominence of the manufacturing industry sector in the economy of the Slovak Republic, this study will primarily examine the employment aspect of this sector. The practical component will involve conducting an extensive analysis of the Slovak manufacturing industry, with a specific focus on employment. This analysis will be complemented by the findings of a questionnaire survey conducted in selected industrial enterprises. The survey will specifically investigate the impact of Industry 4.0 trends on employment within these enterprises. The analysis findings and theoretical framework will be examined in conjunction with the outcomes of the questionnaire survey.

Research methods

The aim of this research is to analyze the influence of Industry 4.0 principles on the labor market of major manufacturing companies in the Slovak Republic, specifically focusing on their impact on large-scale organizations. This will be accomplished by analyzing the current state of affairs and expected advancements in the implementation of Industry 4.0 concepts, such as cloud-based digital twin manufacturing systems, acoustic environment recognition algorithms, and decision intelligence tools in the immersive industrial metaverse. Objectives of the research:

- Determine the extent to which major industrial enterprises in the Slovak Republic have implemented or intend to carry out components of the Industry 4.0 concept.
- Examine the observed effects on employment and job dynamics within large Slovak enterprises resulting from the implementation of Industry 4.0 elements, as well as the anticipated impacts.
- Assess how large Slovak enterprises evaluate the readiness of their workforce for the demands of Industry 4.0 and the measures they undertake to ensure adequate preparation.

In accordance with the objective of this study, a set of research inquiries has been created. These inquiries will be addressed through the analysis of a questionnaire survey conducted within a specific sample of prominent industrial production firms in the Slovak Republic.

RQ 1: *What is the degree of implementation or planned implementation of Industry 4.0 features among large industrial production businesses in the Slovak Republic?*

RQ 2: *What is the observed influence on employment and work dynamics within major industrial production firms in the Slovak Republic, and what are the anticipated outcomes resulting from the deployment of the various components of the Industry 4.0 concept?*

RQ 3: *What methods do major industrial production firms in the Slovak Republic employ to assess and assure the readiness of their personnel to meet the demands of Industry 4.0?*

In order to ensure a comprehensive understanding of the resolved issue, this research encompassed not only a survey conducted among manufacturing companies, but also an examination of various statistical indicators pertaining to the manufacturing industry in the Slovak Republic. Specifically, the analysis placed particular emphasis on employment data, with the objective of identifying key characteristics of the manufacturing sector in the Slovak Republic in relation to its workforce. The process of analyzing the data obtained from the questionnaire survey is conducted prior to the interpretation of the results.

The research sample for quantitative analysis consisted of large industrial production enterprises in the Slovak Republic. The selection was based on the categorization of enterprises according to their size, specifically including those with more than 249 employees.

A total of 500 organizations were selected from the aforementioned database to participate in the research — the selection was strongly affected by the availability of the contact data and willingness to participate in the research. These companies represent a diverse range of sectors, including the automobile industry, wood and paper, apparel and footwear, food industry, metal industry, chemistry and plastics, as well as engineering and other manufacturing areas (according to SK NACE categories — C — production; D — electricity and gas; F — construction industry; G — wholesale and retail; H – transportation). Within the selected industries, organizations were subsequently chosen based on their employee count falling within the database categories of 250–499, 500–599, 1,000–1,999, and 2,000–2,999 workers. Following the completion of the study, a total of 500 organizations were chosen for participation. Subsequently, an online questionnaire was distributed to these selected companies on July 12, 2023, and the data gathering process concluded on September 12, 2023. The questionnaire survey lasted around 2 months. The questionnaire consisted of 15 questions, of which 5 were open-ended, while respondents provided their answers by selecting one of the options for the remaining questions. The main objective of the questionnaire was to assess the digital adaptability of companies operating in the Slovak Republic, determine the financial status of these companies (average amount of assets, equity, short-term and long-term liabilities, EBIT) using the Orbis database from Bureau van Dijk (a Moody's Analytics Company), and identify the regions with the highest level of digitalization implementation, among other things. A total of 413 firms participated in the questionnaire survey, resulting in a response rate of 82.6% for the given questionnaires, which can be considered a representative sample.

Based on the geographical distribution of operations (Figure 1), the predominant portion of the study sample was comprised of firms situated in the region of Trencin (20.41%), followed by enterprises in the region of Nitra (17.35%) and enterprises in the region of Zilina (16.33%). The research findings indicate that the enterprises located in the region of Kosice had the lowest level of representation, accounting for just 7.14% of the total sample. These facts may be verified by the presence of automobile companies in the regions with the largest share, which play a crucial role in the economy of the Slovak Republic. Additionally, these locations are experiencing the highest degree of digitalization.

Based on the data provided in the industrial sector (Figure 2), authors have classified the participating firms into distinct industries according to SK NACE. The dominating industry in the Slovak Republic was primarily C — production, accounting for 46% of the GDP. This sector included car businesses, which play a vital role in the country's economy and are also leaders in developing digital solutions. Sector D, which accounts for 24% of the total, represents power and gas. Following that, sector F, accounting for 14%, is the building industry.

Based on the data pertaining to the number of employees (Figure 3), the firms involved in the study were classified into several groups based on the Fin Stat database. The majority of firms consisted of a significant proportion of workers ranging from 250 to 499 (52.04%), with the subsequent highest representation being enterprises with employee counts ranging from 500 to 599 (37.76%). A total of 8.16% of firms falling within the employee range of 1,000 to 1,999 participated in the research, while the proportion of enterprises with the number of workers ranging from 2,000 to 2,999 was found to be the lowest at 2.04%.

In order to address the theoretical aspect of the study, the research employed the methodologies of analysis, synthesis, and comparison. These approaches were applied to expert sources from both domestic and international scholars who have extensively studied the subject matter of Industry 4.0 and its implications for employment and the labor market by integrating spatial data mining algorithms, process simulation and modeling technologies, and ambient sound recognition tools in realistic 3D simulation environments.

Subsequently, the study of specific indicators pertaining to the industry sector in the Slovak Republic was conducted, utilizing the latest data provided by the national Statistical Office. The present study employed methods of analysis, synthesis, and comparison to handle this particular aspect of the research:

1. A quantitative research study was carried out using a questionnaire survey, since it allows for the collection of a substantial quantity of data within a shorter time period. The surveyor's duty included analyzing 500 enterprises operating in the Slovak Republic across 5 sectors. The study focused on 15 comprehensive questions aimed at assessing the digital preparedness and proficiency of these firms. Subsequently, the financial indicators of these enterprises were determined based on the responses obtained and analyzed using the Orbis database. The questionnaire was built utilizing the Survio online platform, which allows for the direct dissemination of the questionnaire to email contacts or sharing via different social networks. Respondents find it easier to complete the questionnaire in this specific format compared to utilizing an alternate electronic form, such a fillable PDF document. The research mostly uses graphical depictions to comprehend the gathered data and discoveries from the questionnaire.
2. The quantitative research findings underwent comparison analysis and were thereafter displayed via graphic representation and tabular presentations.
3. In the last phase of the study, a thorough analysis will be conducted to integrate and evaluate the research findings. Furthermore, the study's findings lead to the formulation of practical suggestions.

Results, discussion and policy recommendations

This section of the study presents the findings from the analysis of specific indicators within the manufacturing industry in the Slovak Republic, covering the time frame from 2016 to 2022. Subsequently, the research outcomes obtained through a questionnaire administered to a sample of industrial production enterprises in the Slovak Republic are interpreted.

Figure 4 depicts the progression of the unemployment rate in the Slovak Republic from 2016 to 2022. There was a noticeable overall decrease in the unemployment rate, except for the period from 2020 to 2021, which had a higher unemployment rate. The unemployment rate fluctuated between 5% and 6%. The COVID-19 pandemic, which impacted almost all industries, including the Slovak Republic, may account for this predicament. Over the next several years, the unemployment rate is steadily decreasing.

Based on the graphical representation provided, it can be observed that the industrial production sector witnessed the highest workforce participation across various industries throughout the timeframe spanning from 2016 to 2022. The workforce within the industry was relatively stable from 2016 to 2022.

Analysis of selected indicators of the manufacturing industry of the Slovak Republic for the period 2016–2022

The Statistical Office of the Slovak Republic clearly indicates that industrial output significantly contributes to the generation of gross added value in the national economy. Figure 5 data demonstrates a consistent upward trend from 2016 to 2022. In 2022, the gross added value of industrial output reached a peak of around 6,195,000 euro.

Three subsectors consistently dominate individual economic activity in the realm of industrial production (SK NACE C — production). These industries include the production of transportation vehicles, the production of metals and metal structures (excluding machinery and equipment), and the production of rubber, plastics, and other non-metallic mineral products.

Figure 6 aims to display the overall number of firms in this sector, in relation to the total number of enterprises in the Slovak Republic over the observed period. The production businesses reached the largest proportion in 2022, indicating a favorable trend of increasing firms during the monitored period. According to the Statistical Office of the Slovak Republic, the number of production-oriented firms in 2022 was roughly 80,600.

Figure 7 illustrates a noteworthy pattern of labor productivity per person in industrial production enterprises employing over 20 individuals from 2016 to 2022. During the investigated time period, there was an initial decline in labor productivity, which was subsequently followed by an increase. In historical terms, the Slovak Republic had a significant increase in real labor productivity per person employed, reaching a peak of 12.10% year-on-year in June 2021, while it hit a record low of -7.20% year-on-year in June 2020.

Figure 8 illustrates the observed increase trajectory of the average monthly nominal salary for employees working in industrial production enterprises with a workforce exceeding 20 individuals, throughout the period spanning from 2016 to 2022. The year 2022 had the most substantial rise in the mean monthly nominal pay, with a growth of 7.4% in comparison to the preceding year, 2021.

Our analysis indicate that industrial Artificial Intelligence of Things integrate workplace tracking systems, virtual team performance tools, and haptic and biometric sensor technologies by use of multimodal behavioral analytics and holographic display devices in 3D immersive workspaces. Artificial intelligence data-driven adaptive self-organizing and Internet of Things systems develop on image processing computational algorithms, contextual awareness tools, and behavioral modeling technologies through geolocation data mining and tracking, computer-based teamwork simulations, workplace collaboration software, and wearable augmented reality devices in virtually simulated workspace environments. Generative artificial intelligence technologies optimize workplace monitoring systems, wearable self-tracking devices, and automated employment decision tools by integrating spatial data mining algorithms in immersive work environments. Virtual employee engagement and team performance analytics, workplace tracking and monitoring systems, and remote collaboration and ambient scene detection tools shape immersive coaching and mentorship spaces in sustainable Industry 4.0.

Analysis and interpretation of the findings derived from the questionnaire-based survey

The findings of the study indicate that a significant proportion of firms, namely 41.13% (Table 1), have begun to adopt the various components and technologies associated with Industry 4.0 in a progressive manner. Furthermore, a notable 24.16% of enterprises have already made substantial progress in implementing these aspects. A total of 26.53% of firms are now in the process of gradually addressing the implementation of various elements and technologies. Certain enterprises are actively engaged in assessing their needs and carefully planning the implementation process by use of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms. Additionally, 8.18% of enterprises are currently contemplating the possibility of implementing certain components and technologies.

In the realm of implementation, five distinct categories were established since many firms identified multiple areas of implementation (Table 2):

1. The first category encompasses several aspects of firm operations, including production, technological preparation of production, development and construction, information technology (IT), industrial engineering, maintenance, and predictive maintenance. Among the 413 enterprises that have either adopted or initiated the implementation of this idea, 17.63% have included these activities.
2. The second category encompasses several aspects related to production, including technological preparation, development and construction, IT, industrial engineering, maintenance and predictive maintenance, suppliers, and administration. This category has been implemented by 18.19% of the total 413 firms that have either implemented or initiated the implementation of this idea.
3. The third category, encompassing production, technological preparation of production, IT, and administration, has been implemented by 22.64% of the total 413 firms that have initiated or are in the process of implementing the aforementioned idea.
4. The fourth category, encompassing manufacturing, technological preparation of production, development and building, and IT, is being implemented by 29.43% of the total 413 firms that have initiated or are in the process of implementing this particular idea.
5. The fifth category, which pertains to production and the technological preparation of production, as well as the implementation of IT, is adopted by 12.11% of the total 413 enterprises who have initiated or are in the process of implementing this particular idea.

In the realm of planned implementation, two distinct categories were established to encompass companies that have either commenced or are currently in the process of implementing, while an additional two categories were designated for companies that are contemplating or in the early stages of planning implementation. This categorization was necessitated by the fact that companies have identified multiple areas in which they intend to implement their plans:

– A significant proportion, namely 64.18%, of the 311 organizations that have already embarked on the implementation of Industry 4.0 have expressed their intention to adopt this paradigm in several functional areas. These areas include Finance and Accounting, Human Resources, Industrial Engineering, Maintenance and Predictive Maintenance, Logistics and Warehousing, as well as Customer Services.

- The second group encompasses several sectors such as administration, sales, customer service, logistics, and warehousing. It is projected that around 35.82% of the 102 firms that have already adopted Industry 4.0 in some domains will also apply it in these aforementioned sectors.

Organizations that are considering the implementation of:

- The first category encompasses several aspects such as production, technological preparation of production, development and building, IT, maintenance and predictive maintenance, logistics and warehousing, suppliers, finance, and accounting. The plans entail implementing around 75.28% of the 110 firms that are now contemplating or considering the implementation process.
- The second category encompasses several aspects such as production, technological preparation of production, information technology (IT), development and construction, industrial engineering, maintenance, predictive maintenance, and administration. The intention is to execute about 24.72% of the 110 firms that are either planning or considering the implementation of these initiatives.

In terms of the perception of significant opportunities for the use of Industry 4.0, it was found that companies see opportunities in several areas in which they agree on the level of 3 categories:

- 1st category: application of the Internet of Things to production, increase in performance, efficiency of external processes within the supply-customer chain, increase in performance and efficiency of internal processes, cost savings, growth.
- 2nd category: all of the above mentioned in the 1st category (in addition to other opportunities) and, in addition, increasing the quality and productivity of employees, improving the quality of services for customers – perceived by 44.88% of businesses.
- 3rd category: all of the above mentioned in the 2nd category plus the creation of a new entrepreneurial business model — perceived by 31.68% of companies.

Companies are cognizant of the drawbacks associated with the adoption of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms, with a majority of 56.12% identifying the substantial financial expenditure as the foremost concern. A notable proportion of organizations, specifically 37.76%, perceive security threats and the associated expenses as a substantial drawback. Additionally, a smaller subset of companies, comprising 6.12%, acknowledge the existence of unspecified basic disadvantages.

In connection with competences in the field of introducing innovations and the concept of Industry 4.0, the work confirms that in 62.24% of companies these matters are the responsibility of top management, in 12.24% of companies in the competence of the IT department, and 25.52% of companies have created for these purposes a department that focuses on the introduction of innovations and the implementation of Industry 4.0.

In relation to the alterations in workforce size resulting from the integration of Industry 4.0 components and technologies, it was observed that 11.22% of enterprises experienced a rise in employee count. Additionally, 54.08% of enterprises reported no discernible changes in this regard. These calculations were derived from a sample of 413 enterprises that have either commenced or are currently engaged in the implementation of the Industry 4.0 concept. Furthermore, 34.70% of enterprises have yet to initiate the implementation process but have intentions to do so. Regarding the anticipated impact of Industry 4.0 on workforce size, it is observed that 27.55% of enterprises anticipate a decline in employee numbers, while 22.45% of enterprises foresee an increase. Additionally, 50% of enterprises do not anticipate any significant alterations in workforce development. According to the analysis of job positions among 413 organizations that have adopted or initiated the implementation of Industry 4.0, there is no significant evidence of any substantial alterations in the employment levels of individual workers. All firms surveyed reported no changes in the number of administrative personnel with either general or professional education, as well as no changes in the number of workers with professional education but no special educational requirements. A total of 12.09% of firms saw a decline in the quantity of technical workers possessing a general education, while the remaining 87.91% of enterprises reported no alterations in the number of such personnel. A total of 28.81% of firms reported an upward trend in the quantity of technical workers possessing professional education, while the remaining 71.19% of enterprises did not observe any discernible fluctuations in the number of such personnel.

Based on an analysis of the evolving job landscape within specific job roles, it has been observed that the advent of Industry 4.0 has not led to any discernible alterations in the employment status of administrative personnel possessing a broad educational background, individuals lacking specific educational prerequisites, and those with specialized vocational training. According to the findings, 32.86% of firms expressed the need to reassign some job positions held by administrative workers with professional education to alternative roles, while the remaining 67.14% of enterprises reported no discernible alterations in the employment status of these personnel. A total of 41.19% of firms indicated the need to reallocate technical personnel with a general education background to alternative employment roles, while 51.81% of enterprises had not yet undertaken any measures in regard to these individuals. A total of 39.44% of firms reported the need to reallocate technical personnel with professional degrees to alternative positions, while the remaining 60.56% of enterprises reported no discernible alterations in the job structure for these workers. In relation to the anticipated alterations in the composition and quantity of employment roles within specific job positions, the study affirms the following (Table 3).

Regarding the scarcity of workers possessing specific qualifications or expertise in particular scientific domains, the researchers have substantiated that within, the realm of natural sciences, approximately 17.24% of enterprises report a deficit of workers and anticipate its persistence in the future. Conversely, 30.05% of enterprises do not currently experience a shortage of workers and do not foresee encountering one in the foreseeable future. Lastly, 52.71% of enterprises do not currently face a shortage of workers but anticipate encountering one in the future. In the realm of technical sciences, encompassing informatics and computer technology, it has been observed that 13.28% of enterprises have reported a current shortage of qualified workers and anticipate a similar shortage in the future. On the other hand, 32.43% of enterprises have not experienced a shortage thus far and do not foresee one in the future. Additionally, 54.29% of enterprises have not encountered a shortage of workers with appropriate qualifications in these scientific domains, but they do anticipate a shortage in the future. Within the realm of social sciences and related disciplines, a significant majority of enterprises (72.57%), do not now see any scarcity and do not anticipate encountering one in the foreseeable future. Conversely, the remaining 27.43% of companies operating in these sectors acknowledge the absence of a shortfall at present, but hold the expectation that such a shortage may manifest itself in the future. In the realm of services, a majority of firms (59.48%), do not now report a shortfall and do not anticipate encountering one in the foreseeable future. Conversely, a minority of enterprises, accounting for 40.52%, do not presently experience a shortage, but anticipate facing one in the future.

According to empirical research, a notable proportion of organizations, specifically 38.29%, hold a favorable evaluation of the level of preparedness exhibited by high school and university graduates in meeting the demands of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms. This implies that, in the perspective of these companies, the graduates demonstrate an adequate level of readiness for the aforementioned industrial context. Based on the findings of 34.28% of enterprises, a significant proportion of employers perceive high school and university graduates as inadequately equipped to meet the demands of the labor market in relation to the requirements of Industry 4.0. Consequently, these employers hold a negative assessment of the preparedness of graduates. Approximately 27.43% of firms shown an inability to effectively articulate their thoughts on this matter.

The confirmation of this fact is further supported by the Digital Abilities Index of the population (DESI index), which assesses digital abilities in relation to the fourth-generation sector as well. The digital skills of the people in the Slovak Republic have been steadily increasing each year. However, in comparison to other countries in the European Union (EU), the Slovak Republic lags behind (Figure 9). This suggests that the educational processes in the country have been reluctant to adapt to the ongoing digital revolution.

In order to address the educational and developmental requirements of the workforce in relation to Industry 4.0, a significant majority of companies (75.44%) reported their dependence on the education system. However, these companies also acknowledged the importance of providing regular training to their employees in specific areas and to a certain extent, either internally or externally. This is primarily done as a precautionary measure to mitigate potential issues arising from any inadequacies in the educational process. Approximately 24.56% of firms opt not to depend on the educational system, instead choosing to independently provide regular training to their workers in the required areas and extent, either internally or externally.

Addressing research inquiries

Several research questions were formed in accordance with the specified objective of the study, and these inquiries may be addressed by analyzing the findings obtained from the conducted investigation.

RQ1: *What is the degree of implementation or planned implementation of Industry 4.0 features among major industrial production businesses in the Slovak Republic?*

- The findings of the study indicate that a majority of the surveyed big manufacturing businesses in the Slovak Republic, namely 65.29%, have either implemented or initiated the implementation of various aspects and technologies associated with the Industry 4.0 concept. Approximately 34.71% of organizations have yet to incorporate the aforementioned notion into their operations; nevertheless, they are currently engaged in the planning phase or contemplating its adoption.
- Enterprises that have initiated or are in the process of implementing the components and technologies associated with Industry 4.0 primarily prioritize the domains of production, technological preparation of production, and information technology. Several firms have begun to use the aforementioned notion in several domains, including development and construction, industrial engineering, maintenance and predictive maintenance, suppliers, and administration.
- Organizations presently incorporating the components and technologies associated with the Industry 4.0 paradigm, or intending to do so in the future, aim to broaden the scope of implementation, particularly in domains such as finance and accounting, human resources, logistics and warehousing, customer services, and other unspecified sectors.
- Enterprises that are presently not incorporating components and technologies of the aforementioned concept, but are contemplating or actively strategizing its implementation, express a desire to concentrate on various domains such as production, technological preparedness of production, development and construction, information technology, maintenance and predictive maintenance, logistics and warehousing, suppliers, finance and accounting, and administration. To a much lesser degree, organizations intend to include the notion inside the domain of sales and marketing.

- The findings of the study also indicate that organizations perceive the utilization of the Internet of Things in manufacturing as a means to enhance the effectiveness and efficiency of both external processes within the supply-customer chain and internal processes. This is identified as the most prominent avenue for leveraging Industry 4.0 elements and technologies.
- Business enterprises perceive the primary drawbacks of implementing Industry 4.0 features and technologies as the substantial financial expenses involved, with secondary concerns revolving around the related security risks and costs incurred in safeguarding the system.
- Moreover, the study revealed that in a significant majority of companies (74.48%), the responsibility for implementing Industry 4.0 elements and technologies lies with top management or the IT Department. Additionally, only approximately one-third of the surveyed companies have established a dedicated department with the explicit objective of introducing innovations and implementing Industry 4.0 initiatives.

RQ2: *What is the observed impact on employment and jobs within major industrial production firms in the Slovak Republic, and what are the anticipated outcomes resulting from the deployment of the various components associated with the Industry 4.0 concept?*

- The findings of the study indicate that organizations that have already adopted or initiated the integration of the components and technologies associated with the Industry 4.0 paradigm did not observe substantial alterations in the overall workforce growth that could be attributed to the impact of Industry 4.0. A minor fraction of firms (11.22%) indicates an observed expansion in their workforce size, attributing this growth to the adoption of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms.
- However, organizations that have begun adopting or planning to use Industry 4.0 features and technology have already observed some shifts in the workforce composition within certain job roles or professions. A total of 12.09% of firms experienced a decline in the quantity of technical workers possessing a general education, while 28.81% of enterprises observed a growth in the quantity of workers with professional education.

- Although the majority of organizations did not disclose any changes pertaining to the impact of Industry 4.0 in terms of their total staff count, it is evident that specific changes have already transpired inside these companies.
- According to empirical study, several organizations have recognized the impact of Industry 4.0 and subsequently recognized the necessity to augment the workforce with a greater number of technically skilled professionals while concurrently reducing the presence of technical workers with lesser levels of qualifications. Hence, it is evident that the integration of Industry 4.0 components and technologies into organizational operations need, and will continue to necessitate, a proficient workforce in the forthcoming years.
- Previous studies have indicated that certain companies have observed alterations in job configurations, resulting in the reassignment of employees to alternative positions. These positions can be categorized into three distinct groups: administrative workers with professional education (32.86%), technical workers with general education (41.19%), and technical workers with professional education (39.44%).
- Nevertheless, the reallocation of employees to alternative positions is intricately linked to the process of retraining or reskilling personnel. Consequently, organizations must prioritize the domains of education and workforce development to a significant degree.

In this particular context, it is important to establish the educational system in the Slovak Republic in a manner that effectively mitigates the shortage of skilled workforce required for the demands of Industry 4.0 in terms of context awareness algorithms, 3D digital twin modeling technologies, and digital twin data visualization tools. This approach aims to minimize the occurrence of enterprises experiencing significant deficits in the availability of qualified personnel in the future. Furthermore, it is imperative to prioritize the retraining and upskilling of existing workers to mitigate the risk of job displacement for individuals with lower qualifications or skills that may not align with the demands of companies adopting Industry 4.0 technologies (Mondejar *et al*., 2021; Glogovețan *et al*., 2022). This approach is crucial in order to curb the rise in unemployment rates within the Slovak Republic. The advent of Industry 4.0 will need the acquisition of novel proficiencies and competencies, hence prompting a shift in the skillset required of employees (Wallace & Lăzăroiu, 2021; Franklin & Potcovaru, 2021). In recent years, there has been a notable rise in the need for individuals with educational backgrounds in natural sciences and technological disciplines. This trend is further substantiated by the findings of this research. Based on the aforementioned information, it can be inferred that the labor market will be influenced by Industry 4.0, as anticipated by the Slovak companies under consideration. This influence will primarily manifest in the reallocation of workers to novel job roles, as well as an augmented demand for individuals with educational backgrounds, particularly in technical sciences such as informatics and computer technology. Based on initial projections made by corporations, it is anticipated that there would be a decline in the demand for technical personnel and those with lower skill levels.

RQ3: *What strategies do major industrial production firms in the Slovak Republic employ to assess and assure the readiness of their personnel to meet the demands of Industry 4.0?*

- According to empirical research, a notable proportion of companies (38.29%) express a positive evaluation of the school system's effectiveness in equipping graduates with the necessary skills for Industry 4.0. Conversely, a similar percentage of companies (34.28%) hold the view that high school and university graduates lack adequate preparation for the demands associated with this emerging paradigm (State of FDI in Slovakia, 2022; PSA Slovakia, 2022).
- Nevertheless, it is imperative to acknowledge that at present, the majority of companies are only commencing the integration of Industry 4.0 elements and technologies. Consequently, it remains inconclusive whether graduates from high schools and universities possess adequate preparation to meet their requirements. Furthermore, it is worth noting that numerous organizations opt to reallocate their workforce, with the intention of eventually reassigning people to more essential roles. Consequently, the effectiveness of the education system and the preparedness of graduates can only be truly assessed over an extended period.
- In light of expert opinions and experiences from countries with a more established implementation of the Industry 4.0 concept, it is reasonable to anticipate potential challenges regarding the preparedness of graduates to meet the demands of the labor market in the future.
- All the companies surveyed unanimously concurred that the training of high school and university graduates should be conducted through a strong collaboration between the educational system and the business

sector. This collaboration necessitates a particular emphasis on dual education, a system that has already been implemented in the Slovak Republic, but requires a significantly higher adoption rate. By adopting this approach, organizations have the opportunity to internally train and educate prospective employees, therefore mitigating the potential risks associated with a shortage of skilled personnel or inadequately prepared graduates.

The diverse perspectives of experts about the implications of the Industry 4.0 concept are evident in the theoretical framework of this study. The task of effectively requalifying all existing work roles for new ones is anticipated to be quite challenging in enterprise risk-taking. Consequently, these experts suggest that a considerable number of individuals, particularly those with lesser credentials, may face job displacement. According to some scholars (PSA Slovakia, 2022; Cooper *et al*., 2021; Kliestik *et al*., 2022b; Valaskova *et al*., 2022), there is a prevailing belief that the advent of new job opportunities will result in the replacement of existing ones. Consequently, individuals are expected to undergo retraining processes, thereby mitigating the potential rise in unemployment. Furthermore, these experts assert that there will be a heightened need for individuals possessing knowledge and skills in the fields of natural and technological sciences. As a result, they contend that a significant surge in unemployment is unlikely to occur. Moreover, it is important to acknowledge that even with the integration of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms, there will persist a demand for individuals engaged in regular manual labor, since certain tasks will continue to necessitate human intervention in terms of robotic wireless sensor networks (Galbraith & Podhorska, 2021), financial performance (Grofcikova, 2020), and artificial intelligence-based business operations (Krulicky & Horak, 2021).

The specific effects and impacts of the Industry 4.0 concept can only be determined over time (Rogers & Zvarikova, 2021; Tao *et al*., 2019; Pavlínek & Ženka, 2016). It can be posited that these effects will materialize once a significant number of enterprises in the Slovak Republic have fully implemented this concept and are capable of efficiently addressing challenges that may arise in relation to digitization and robotization. The phenomenon takes place. Nevertheless, the utilization of specialists' estimations and assumptions might assist the Slovak Republic (Valaskova *et al*., 2022) and its domestic enterprises in adequately preparing for potential scenarios that may emerge within this particular setting. Main research findings are shown in Table 4.

The aforementioned circumstances need a primary focus on the educational system and job support in order to mitigate the potential adverse effects of Industry 4.0, as predicted by certain experts.

First recommendation

A proposal is put out for a total overhaul of the educational system, with the aim of aligning it with the requirements of Slovak industrial businesses in relation to the skillset of the workforce, particularly in the context of Industry 4.0, by integrating image-based visual computing technologies, virtual machine algorithms, and digital twin data modeling tools. Conducting surveys or analyses to determine demands would be a suitable approach for industrial firms, and afterwards, the school education system should be altered accordingly (Lanier *et al.*, 2019; Popescu *et al.*, 2022; Vinerean *et al.*, 2022; Hamilton, 2022; Nica, 2021). It is crucial to prioritize the domains of technical sciences, informatics, and computer technology, as well as the natural sciences, alongside other scientific disciplines that hold comparable significance for the demands of Industry 4.0. One potential strategy for enhancing effectiveness is the implementation of diverse initiatives that involve collaborative participation between schools and companies. Additionally, a focus on fostering international collaboration and facilitating the exchange of experience and information might be emphasized.

Second recommendation

The objective of promoting employment through the utilization of active labor market policies. In this particular context, it is imperative for the state to prioritize its efforts towards providing support to employers. This support can take various forms, such as offering financial contributions for the purpose of retraining workers to meet the demands of new job classifications, providing contributions to facilitate employment opportunities, or even creating job positions specifically tailored for individuals who have lost their jobs due to inadequate qualifications. Additionally, it is crucial to acknowledge the significance of retraining initiatives during periods of unemployment, as they play a pivotal role in addressing these challenges.

The primary emphasis of jobseeker allowances should be directed towards addressing the requirements of Industry 4.0 (Valaskova *et al*., 2022).

This entails providing support to jobseekers in utilizing these allowances for the purpose of retraining and participating in competence courses that are relevant to the demands of digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms. Such support may be offered through initiatives such as unemployment counseling, as well as through the organization of diverse training sessions and seminars for the unemployed, facilitated by the Labor, Social Affairs, and Family Offices. These sessions would serve to inform participants about the current labor market conditions, the qualifications needed, and the potential employment opportunities available.

Conclusions

This study focuses on the topic of Industry 4.0 and its implications for the labor market in the Slovak Republic, specifically examining the effects on industrial firms inside the country. The main objective of this study was to examine the impact of implementing aspects of the Industry 4.0 concept on the labor market inside big manufacturing businesses in the Slovak Republic. This was achieved through an examination of the present status and aspirations in this sector. To gain a comprehensive understanding of the matter and contextualize it appropriately, the initial portion of the study examines the perspectives of industry experts pertaining to the phenomenon of Industry 4.0 by use of extended reality technologies, image processing computational algorithms, and cognitive mapping and navigation tools. Additionally, it conducts an analysis of the present employment landscape in the Slovak Republic, with a particular focus on the industry sector.

The examination of specialist knowledge yielded varying perspectives of the influence of Industry 4.0 on the labor market. Nevertheless, it is widely acknowledged by experts that as a result of the impact of Industry 4.0, a significant number of employment opportunities would become obsolete while concurrently giving rise to the emergence of novel professions and occupations. Hence, certain occupations will be more susceptible to danger while others would be comparatively less vulnerable. According to experts, occupations that are least susceptible to digitization in the foreseeable future are perceived as having a lower level of vulnerability. Conversely, those with limited credentials and inadequate digital skills and competencies are believed to have an elevated risk of unemployment.

The advent of artificial intelligence and digitalization through cognitive digital twin technologies, 3D image modeling tools, and machine vision algorithms poses a potential danger to around 30% of employment opportunities. There are viewpoints suggesting that the process of digitalization would lead to a heightened polarization within society, characterized by a widening gap in socioeconomic status between individuals and the eventual erosion of the middle class from the social fabric.

Based on the findings of several investigations, it is evident that the advent of Industry 4.0 would necessitate a workforce including individuals with the requisite qualifications, as well as the cultivation of talents and abilities essential for enhancing and sustaining competitiveness. The need for individuals with a background in technological sciences, such as informatics and computer technology, as well as the natural sciences, is expected to experience a significant growth due to digital twin simulation modeling, artificial intelligence-based Internet of Manufacturing Things systems, and virtual machine and cognitive computing algorithms.

The current status of the educational system in the Slovak Republic is deemed inadequate in its readiness to adapt to the evolving work landscape brought about by Industry 4.0. Consequently, it becomes imperative to undertake substantial actions and initiatives to address this matter effectively. However, within the realm of working conditions, this notion will provide favorable transformations, particularly in relation to the reduction of physically strenuous tasks that will be automated, leading to enhanced protection of employees' well-being and safety. Manufacturing enterprises in the Slovak Republic are in the process of incorporating or have intentions to include various aspects and technologies associated with the Industry 4.0 concept across several domains of their company operations. Enterprises that have already commenced the implementation of Industry 4.0 or have initiated substantial alterations in task quantity and composition have not yet observed but anticipate forthcoming modifications.

In this particular context, it is anticipated by companies that there will be a need to introduce modifications to the composition and quantity of job positions in the foreseeable future. This pertains particularly to technical workers and laborers, as companies anticipate a rise in the employment of individuals with professional education. This observation aligns with expert opinions, which suggest that there is a potential risk for job displacement among skilled laborers and individuals with low qualifications, particularly by integrating 3D computer vision-based production, multisensory extended reality, simulation modeling, and geospatial mapping technologies, together with deep learning-based image classification algorithms and digital twin simulation tools.

To a significant degree, the organizations involved in the study anticipate the need to relocate employees to alternative job roles, a factor closely linked to worker retraining and reskilling. Regarding the workforce requirements, it is anticipated that enterprises would face a deficit of individuals possessing educational backgrounds mostly in technological fields such as informatics, computer technology, and natural sciences. In the future, it is anticipated that certain organizations will face a scarcity of employees possessing educational backgrounds in the social sciences, as well as in the sector of services. Hence, it is evident that prioritizing the educational system and ensuring the preparedness of graduates for the job market and the demands of Industry 4.0 is imperative.

In order to meet the demands of the labor market, it is imperative that the educational system undergoes a systematic and incremental transformation to ensure the provision of a qualified workforce to meet the needs of enterprises. The strong collaboration between the educational system and the corporate sector, particularly in secondary schools and universities, should be given significant importance.

Furthermore, it is imperative for the government to prioritize the provision of assistance for employment. This can be achieved by implementing proactive strategies in the labor market that are tailored to the requirements of the Industry 4.0 paradigm. Additionally, the execution of national initiatives aimed at training and enhancing the skills of the unemployed population, thereby augmenting their prospects for securing employment, should also be emphasized.

Similar to its predecessors, including Industry 4.0, the fourth industrial revolution is poised to exert a transformative impact on the labor market. Nevertheless, it is crucial to proactively anticipate and plan for these forthcoming transformations, endeavoring to forecast their magnitude and mitigate any adverse repercussions on the labor market in the Slovak Republic. Possible limitations of this investigation include the following: the research predominantly examines manufacturing enterprises situated in the Slovak

Republic, and therefore the applicability of its findings to other sectors or nations characterised by distinct socio-economic circumstances may be limited. On the other hand, the study offers valuable insights regarding the present condition and immediate expectations regarding the implementation of Industry 4.0. A longitudinal investigation may provide a more exhaustive comprehension of the enduring impacts on the labour force, however, the research in other Central European economies or V4 countries is also challenging. Nevertheless, the study also offers insights and impetus for further research, which might predominantly centre on a comparative analysis with other countries in order to identify optimal strategies and possible drawbacks in tackling the obstacles presented by Industry 4.0. This will provide policymakers with a more comprehensive outlook. It is also crucial to incorporate the viewpoints of employees, particularly those who are at risk of being laid off, in order to gain insight into their apprehensions, inclinations, and obstacles pertaining to reskilling and career changes.

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Annex

Table 1. Implementation of Industry 4.0 elements/technologies

Implementation of Industry 4.0 elements	
Businesses are considering implementation	8.18%
Enterprises are slow to deal with implementation	26.53%
Enterprises already started the implementation process	41.13%
Enterprises implement in full process	24.16%

Table 2. Categories of implementation of Industry 4.0 elements/technologies

1	17.63%
2	18.19%
3	22.64%
4	29.43%
5	12.11%

Table 3. Expected changes in the structure and number of jobs of individual job positions due to the implementation of Industry 4.0

According to the data, it is projected that 16.41% of firms anticipate a decrease in the number of administrative personnel with a general education, while the remaining 83.59% of enterprises do not foresee any alterations in their workforce.
According to the data, a significant proportion of firms (17.24%), anticipate the need to reassign certain administrative staff with professional degrees to alternative positions. Conversely, the majority of enterprises, comprising 82.76%, do not foresee any alterations in this regard.
According to the data, it is projected that 46.27% of enterprises anticipate the need to reassign certain technical workers with a general education to alternative positions. Additionally, 23.98% of enterprises foresee a reduction in their workforce, while 8.22% expect an increase in the number of workers. On the other hand, 21.53% of companies do not anticipate any changes in their workforce composition.
According to the data, a majority of firms (67.29%), anticipate the need to reassign some technical professionals to different positions. Additionally, 22.18% of enterprises foresee the requirement to hire additional workers, while 10.53% of enterprises do not anticipate any alterations in their workforce.
According to the data, a majority of firms (60.05%) anticipate the need to reassign workers without a special educational concentration to other job roles. Additionally, a significant portion of enterprises (29.42%) predict a reduction in the number of workers in this category. On the other hand, a minority of enterprises (10.53%) do not foresee any changes in this regard.
Employees with formal academic qualifications: According to the data, a majority of firms (67.24%), anticipate the need to transfer employees to different positions. Additionally, 17.12% of enterprises foresee a growth in their workforce, while 15.64% of enterprises do not anticipate any changes in their employment situation.

Table 4. Main research findings

1. The unemployment rate in Slovakia shown a slowly increasing trend from 2016 to 2022.
2. The predominant occupation among the working population in Slovakia is employment in the industrial sector.
3. With regard to the proportion of employment distribution across various sectors of the economy, it is observed that industry exhibited the largest share over the period under examination spanning from 2016 to 2022.
4. The gross added value of the manufacturing industry in Slovakia had a consistent upward trend from 2016 to 2022, resulting in an increased share of the overall gross added value (2022 – 6,195,000 mil. euro).
5. The examined period of years witnessed a rising trend in the number of industrial production firms.
6. The average monthly nominal pays of employees working in industrial production businesses shown an upward trend over the observed period.
7. Slovak manufacturing enterprises are now in the process of adopting, initiating, or strategizing the integration of various components and technologies associated with the Industry 4.0 paradigm.
8. Slovak manufacturing enterprises are currently in the process of incorporating, initiating the incorporation, or making plans to incorporate various components and technologies associated with Industry 4.0 across multiple domains of their business operations. These domains primarily encompass production, technological preparation of production, development and construction, information technology, industrial engineering, maintenance and predictive maintenance, administration, logistics and storage, finance, accounting, and other relevant spheres.
9. Slovak manufacturing enterprises perceive notable prospects for the implementation of Industry 4.0 across various domains. One such area involves leveraging the Internet of Things in production, thereby enhancing the performance and efficiency of external processes within supplier-customer relationships, as well as optimizing internal processes.
10. According to Slovak industrial enterprises, the primary drawback of Industry 4.0 lies in its significant financial implications.
11. The primary responsibility for implementing Industry 4.0 in Slovak manufacturing enterprises lies with top management and the IT department. Some Slovak manufacturing companies believe that the training provided to secondary and university graduates regarding the adoption of the Industry 4.0 concept is satisfactory, while others find it inadequate. It is generally agreed among Slovak manufacturing companies that the education system, in collaboration with the business sector, should be responsible for adequately preparing high school and university graduates to meet the requirements of the Industry 4.0 concept.

Figure 1. The share of enterprises by region of operation

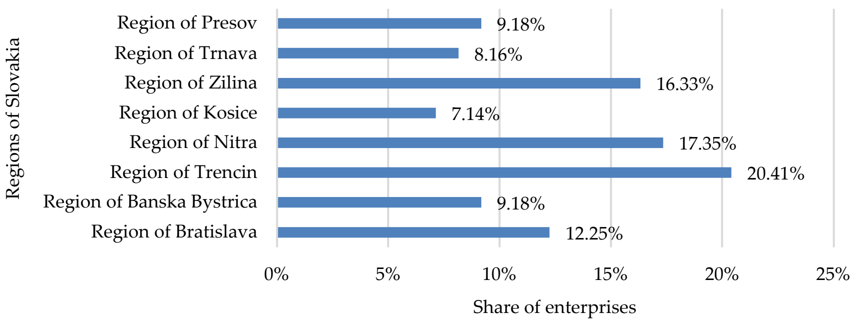


Figure 2. The share of enterprises by industry sector

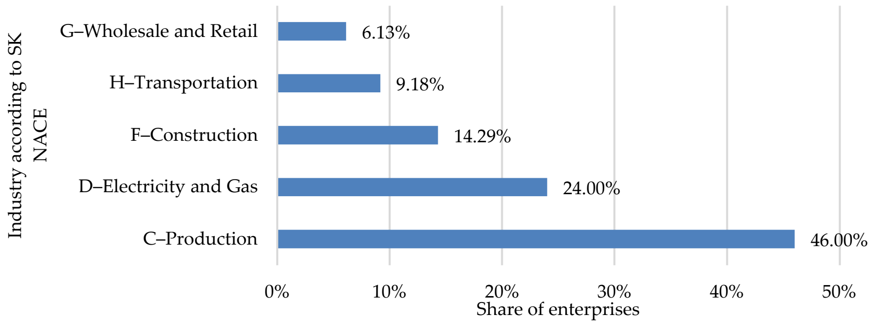


Figure 3. The share of enterprises according to the number of employees

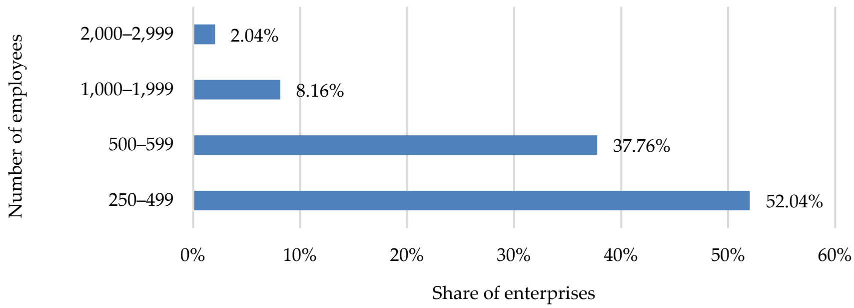
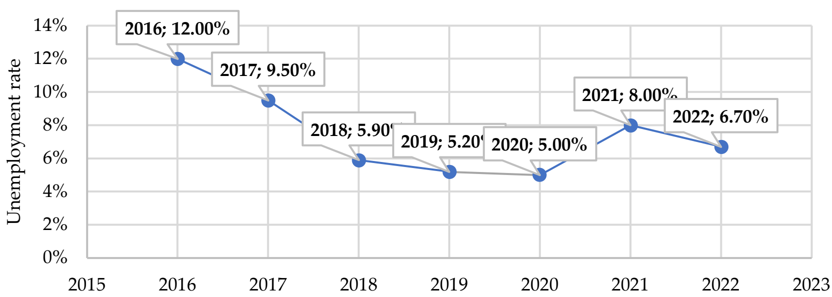
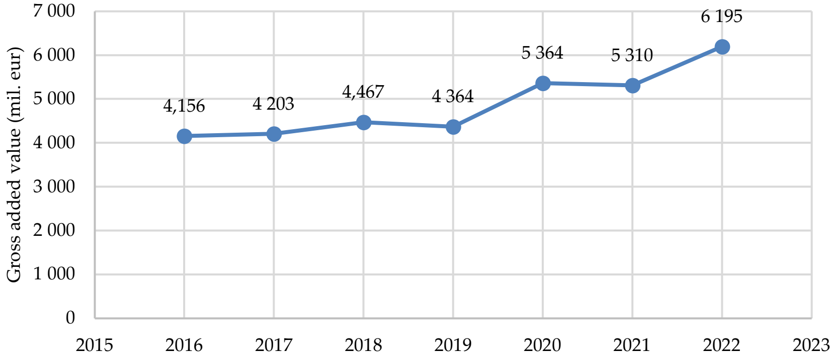


Figure 4. Development of the unemployment rate in the Slovak Republic for the period 2016–2022 (%)



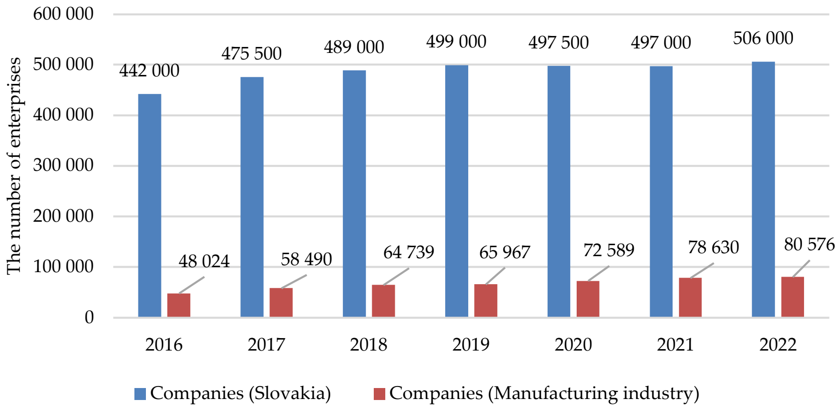
Source: Authors' compilation according to www.tradingeconomics.com (19.08.2023).

Figure 5. Development of the gross added value of the manufacturing industry in the Slovak Republic for the period 2016–2022 (mil. of €)



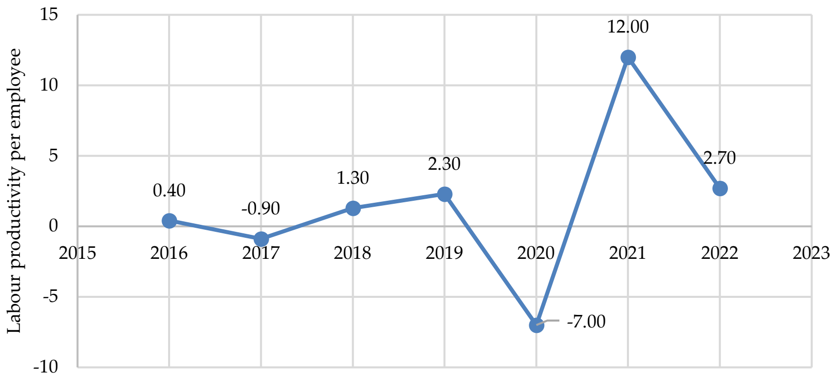
Source: Authors' compilation according to www.tradingeconomics.com (19.08.2023).

Figure 6. The number of enterprises operating in Slovakia and the share of industrial production enterprises for the period 2016–2022 (number)



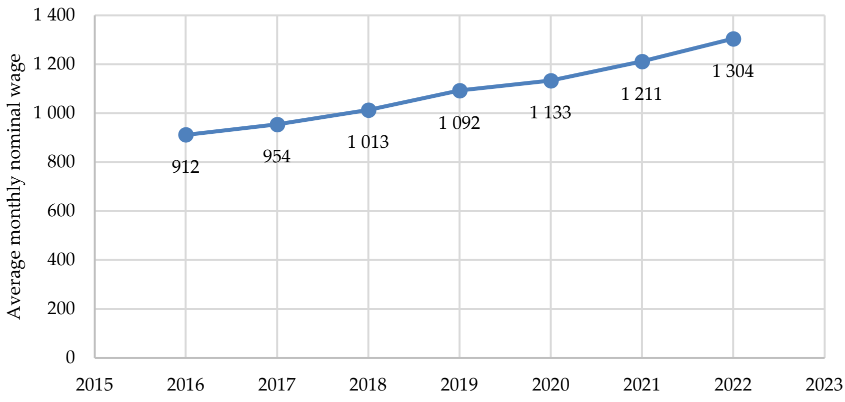
Source: Authors' compilation according to www.tradingeconomics.com (accessed on 19.08.2023).

Figure 7. Development of labor productivity per worker in industrial production enterprises with more than 20 employees for the period 2016–2022 (%)



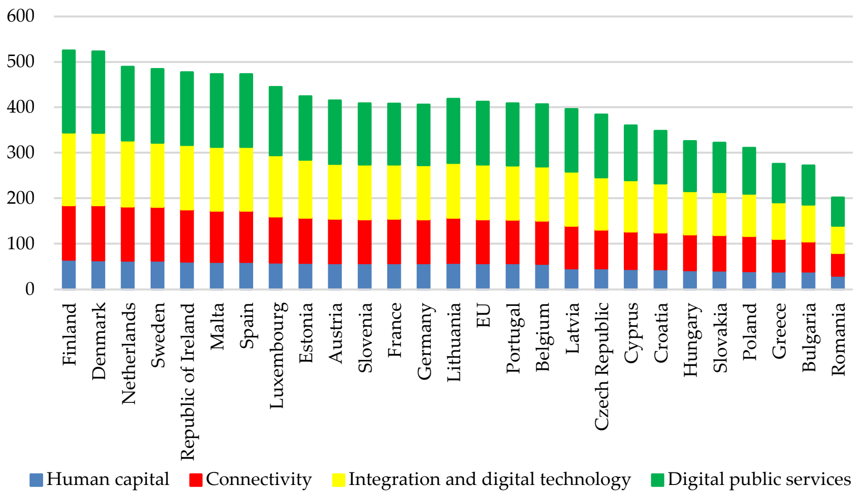
Source: Authors' compilation according to www.tradingeconomics.com (19.08.2023).

Figure 8. Development of the average monthly nominal wage of employees working in industrial production enterprises with more than 20 employees for the period 2016–2022 (€)



Source: Authors' compilation according to www.tradingeconomics.com (19.08.2023).

Figure 9. DESI index ranking 2022 (EU countries)



Source: Authors' compilation according to www.ec.europa.eu (19.08.2023).