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HUMAN CAPITAL DEVELOPMENT IN THE CONTEXT OF THE FOURTH INDUSTRIAL REVOLUTION
РОЗВИТОК ЛЮДСЬКОГО КАПІТАЛУ В УМОВАХ ЧЕТВЕРТОЇ ПРОМИСЛОВОЇ РЕВОЛЮЦІЇ

Summary. *Introduction. The rapid development of digital technologies associated with the Fourth Industrial Revolution has significantly transformed economic systems, labor markets, and the competencies required from the workforce. The diffusion of technologies such as artificial intelligence, automation, big data analytics, and digital platforms has increased the importance of human capital as a key determinant of economic competitiveness, innovation capacity, and sustainable economic growth. In this context, the formation and effective utilization of human capital have become central priorities of modern economic policy.*

Objective. The purpose of this study is to analyze the role of human capital in ensuring technological development and economic productivity in the context of the Fourth Industrial Revolution and to develop an econometric model for

assessing the impact of human capital, digital skills, and innovation activity on labor productivity.

Materials and Methods. The methodological basis of the research is formed by human capital theory, endogenous growth theory, and the concept of the knowledge-based economy. The study applies methods of systemic analysis, comparative analysis, synthesis of scientific literature, statistical analysis, and econometric modeling. The empirical basis of the research includes internationally recognized statistical databases, including those of the World Bank, OECD, Eurostat, and the United Nations Development Programme.

Results. The study develops a conceptual framework that illustrates the relationship between education systems, digital competencies, innovation activity, and economic productivity. International indicators of human capital development, including the Human Capital Index and Human Capital Index Plus, are analyzed, revealing significant cross-country differences in the accumulation of human capital. An econometric model based on an extended Cobb–Douglas production function is proposed to estimate the influence of human capital development, digital skills, and research and development investments on labor productivity.

Prospects. Future research may focus on expanding the empirical analysis using panel data for a larger group of countries and examining the role of education policy, innovation systems, and institutional factors in supporting human capital development in the era of digital transformation.

Key words: *human capital, human capital assessment, Human Capital Index, intellectual capital, Fourth Industrial Revolution, post-industrial transformations, digitalization, artificial intelligence, new technologies.*

Анотація. *Вступ. Стрімкий розвиток цифрових технологій, пов'язаний із Четвертою промисловою революцією, суттєво трансформує економічні системи, структуру зайнятості та вимоги до професійних*

компетентностей працівників. Поширення таких технологій, як штучний інтелект, автоматизація, великі дані та цифрові платформи, підвищує роль людського капіталу як ключового чинника економічної конкурентоспроможності, інноваційного розвитку та довгострокового економічного зростання. У цих умовах формування та ефективне використання людського капіталу стає одним із центральних завдань сучасної економічної політики.

Мета. Метою дослідження є аналіз ролі людського капіталу у забезпеченні технологічного розвитку та економічної продуктивності в умовах Четвертої промислової революції, а також розроблення економетричної моделі оцінювання впливу людського капіталу, цифрових навичок та інноваційної активності на рівень продуктивності праці.

Матеріали і методи. Методологічною основою дослідження є теорія людського капіталу, теорія ендогенного економічного зростання та концепція економіки знань. У роботі використано методи системного аналізу, порівняльного аналізу, узагальнення наукових джерел, економіко-статистичні методи та економетричне моделювання. Емпірична база дослідження сформована на основі міжнародних статистичних баз даних Світового банку, OECD, Eurostat, UNDP та інших міжнародних організацій.

Результати. У дослідженні обґрунтовано концептуальну модель розвитку людського капіталу, яка демонструє взаємозв'язок між освітою, цифровими компетенціями, інноваційною активністю та економічною продуктивністю. Проаналізовано міжнародні показники розвитку людського капіталу, зокрема Human Capital Index та Human Capital Index Plus, що відображають суттєві міжкраїнові відмінності у рівні накопичення людського капіталу. Запропоновано економетричну модель, побудовану на основі розширеної виробничої функції Кобба–Дугласа, яка

дозволяє оцінити вплив людського капіталу, цифрових навичок та інвестицій у дослідження і розробки на продуктивність праці.

Перспективи. Подальші дослідження можуть бути спрямовані на розширення емпіричного аналізу шляхом використання панельних даних для ширшого кола країн, а також на дослідження ролі освітньої політики, інноваційної інфраструктури та інституційних факторів у формуванні людського капіталу в умовах цифрової трансформації економіки.

Ключові слова: *людський капітал, оцінювання людського капіталу, індекс людського капіталу, інтелектуальний капітал, четверта промислова революція, постіндустріальні трансформації, цифровізація, штучний інтелект, нові технології.*

The statement of the problem in its general form and its connection with important scientific or practical tasks. The transition to the Fourth Industrial Revolution has fundamentally transformed the nature of economic development and the structure of labor markets. Digital technologies, artificial intelligence, automation, and advanced data analytics are increasingly integrated into production systems and organizational processes. These technological transformations significantly change the requirements for workforce competencies and increase the importance of knowledge, innovation capacity, and digital skills.

Under such conditions, human capital becomes one of the most critical factors of economic competitiveness and long-term economic growth. Countries that invest effectively in education systems, professional training, and innovation infrastructure are better positioned to adopt new technologies and maintain high productivity levels. At the same time, many economies face significant challenges related to skills mismatch, insufficient investment in education and research, and limited technological readiness.

The problem of human capital development in the context of the Fourth Industrial Revolution is therefore closely connected with several important scientific and practical tasks. These include improving the quality of education systems, developing digital competencies within the workforce, supporting lifelong learning, and strengthening innovation ecosystems. Addressing these challenges is essential for ensuring sustainable economic development and improving national competitiveness in the global economy.

The scientific novelty of this research lies in the development of an integrated analytical framework combining human capital indicators, digital skills, and innovation activity in an econometric model based on the extended Cobb-Douglas production function.

An analysis of the latest research and publications in which the solution of this problem has been initiated and on which the author relies, highlighting the previously unresolved parts of the general problem to which this article is devoted. The rapid development of digital technologies associated with the Fourth Industrial Revolution (Industry 4.0) has significantly transformed economic systems, labor markets, and the competencies required from the workforce. Technologies such as artificial intelligence, robotics, big data analytics, cloud computing, and the Internet of Things increasingly influence production systems and organizational processes. As a result, human capital development has become one of the key determinants of economic competitiveness, innovation capacity, and sustainable economic growth [17].

Recent academic research emphasizes that the successful implementation of Industry 4.0 technologies depends largely on the availability of highly skilled human resources capable of adapting to technological change. In particular, Štaffenová and Kucharčíková (2024) analyze the relationship between human capital management, employee competencies, organizational values, and motivation in the context of Industry 4.0 transformation [12]. Their empirical study demonstrates that companies that systematically develop employee

competencies and motivational systems achieve higher levels of competitiveness in digitalized markets.

The transformation of workforce competencies in the context of digitalization is further examined by Idrissi Gartoumi and Koumetio Tekouabou [8]. Through a systematic literature review, the authors explore the concept of Skills 4.0 and identify the key competencies required in the digital economy. These competencies include digital literacy, analytical thinking, creativity, and collaborative problem-solving abilities. The authors emphasize that modern educational systems must adapt to technological change in order to prepare workers for new forms of employment.

Similarly, Aji, Ikhlas, and Wati (2024) investigate the development of human resource competencies in response to the challenges and opportunities created by Industry 4.0 [3]. Their research highlights the importance of lifelong learning, professional training, and organizational investment in employee development. According to the authors, continuous education and skill upgrading are essential for ensuring workforce adaptability in rapidly evolving technological environments.

The relationship between technological transformation and labor force competencies is further explored by Alhloul and Kiss [4]. Using a bibliometric analysis combined with a survey of workforce competencies, the authors identify the main skill groups required in Industry 4.0 environments. Their findings indicate that modern labor markets increasingly require a combination of technological expertise, cognitive skills, and socio-emotional competencies.

Technological transformation also influences innovation systems and collaborative networks. Córcoles, Triguero, and Cuerva (2025) analyze the role of technological cooperation in facilitating Industry 4.0 transformation among manufacturing firms [5]. Their empirical research demonstrates that collaboration between companies, research institutions, and innovation networks significantly

improves firms' technological capabilities and contributes to human capital development.

The broader impact of Industry 4.0 on human capital formation has been examined by Sima et al. (2020), who conducted a systematic review of research on the influence of digital technologies on employment and consumer behavior [11]. Their findings suggest that the Fourth Industrial Revolution increases the demand for highly skilled workers while simultaneously reducing the need for routine manual labor.

The readiness of human resources to operate in technologically advanced environments has also been studied by Vrchota et al. (2020). Their research evaluates the preparedness of employees for Industry 4.0 implementation and highlights the importance of digital competencies, educational attainment, and organizational training programs in supporting technological transformation [14].

In addition to international research, Ukrainian scholars have made significant contributions to the analysis of human capital development under conditions of digital transformation. Ukrainian researchers often focus on the institutional, socio-economic, and labor market aspects of digitalization.

For example, Kolot and Herasymenko (2020) analyze the transformation of employment structures and labor relations in the digital economy. Their research highlights the emergence of new forms of employment, including platform work and gig economy practices, which require workers to possess new digital and adaptive competencies [9].

The transformation of labor markets in the context of digitalization has also been examined by Zaloznova, Pankova, and Ostafiichuk (2020). Their study analyzes global and Ukrainian labor markets under conditions of digital transformation and identifies major challenges associated with technological change, including structural unemployment, skills mismatch, and the need for workforce retraining [16].

The broader socio-economic implications of digital transformation have been investigated by Kolot, Herasymenko, and Shevchenko (2022), who examine changes in employment structures within the digital economy. Their research demonstrates that digitalization significantly alters employment patterns and requires the modernization of labor market institutions [10].

Institutional transformations and structural modernization of the Ukrainian economy have been analyzed by Heyets (2016), who highlights the importance of innovation-driven development and knowledge-based economic growth [1]. The author argues that strengthening human capital through education, research, and innovation policy represents a key prerequisite for technological advancement and economic modernization.

Finally, Kindzerskyi (2019) examines the role of industrial policy and structural transformation in enhancing technological competitiveness. His research emphasizes that the modernization of industrial sectors requires highly qualified human capital capable of supporting innovation and technological development [2].

Overall, the reviewed literature demonstrates that human capital development is a critical factor in ensuring successful technological transformation in the era of the Fourth Industrial Revolution. Both international and Ukrainian scholars emphasize that investments in education, digital competencies, and lifelong learning are essential for ensuring economic competitiveness and sustainable development.

Research Gap. Despite the growing body of literature on human capital and technological transformation, several important research gaps remain in the existing studies.

First, many recent studies analyze the relationship between digital technologies, artificial intelligence, and labor markets, yet relatively few works provide a comprehensive analysis of how these technological transformations influence the formation, structure, and development of human capital at the

macroeconomic level. Most empirical studies focus on firm-level productivity or occupational change, leaving broader national and institutional dimensions insufficiently explored.

Second, the majority of empirical research on digital human capital has been conducted in developed economies, particularly in the European Union and North America. Consequently, there is limited empirical evidence regarding how technological transformation affects human capital development in transition and emerging economies. These economies often face additional challenges such as institutional constraints, lower levels of technological adoption, and limited investments in education and research.

Third, existing studies frequently analyze individual components of human capital, such as education or digital skills, rather than examining the multidimensional nature of human capital, which includes professional competencies, innovation capacity, adaptability, and lifelong learning abilities. As a result, the interaction between human capital development, innovation activity, and technological change remains insufficiently explored.

Fourth, while numerous studies highlight the positive effects of digital technologies on productivity and innovation, fewer works investigate the policy mechanisms required to support human capital development in the context of the Fourth Industrial Revolution, particularly in areas such as education reform, labor market policy, and innovation policy.

Therefore, further research is needed to develop an integrated analytical framework that examines the relationship between human capital development, technological progress, and innovation-driven economic growth.

Formulation of the objectives of the article (statement of the problem). The rapid development of digital technologies associated with the Fourth Industrial Revolution has significantly transformed economic systems, labor markets, and the structure of professional competencies required from the workforce. In these conditions, human capital has become one of the key

determinants of technological development, innovation capacity, and long-term economic growth.

Despite the growing number of studies devoted to the relationship between technological change and labor market transformation, the role of human capital as a systemic factor of technological adoption and productivity growth remains insufficiently explored, particularly at the macroeconomic level. Existing research often focuses on individual components of human capital, such as education or digital skills, without providing an integrated analytical framework that captures the complex interaction between human capital development, innovation activity, and technological transformation.

Moreover, many empirical studies concentrate primarily on developed economies, while relatively limited attention has been given to transition and emerging economies that face additional structural challenges in adapting to digital transformation. These challenges include limited investment in research and development, insufficient digital competencies within the workforce, and institutional barriers that constrain innovation-driven growth.

Therefore, the objective of this article is to analyze the role of human capital development in ensuring technological progress and economic productivity in the context of the Fourth Industrial Revolution. The study aims to develop a conceptual framework that explains the relationship between education systems, digital competencies, innovation activity, and economic performance.

In order to achieve this objective, the research also seeks to construct an econometric model based on the extended Cobb–Douglas production function to evaluate the impact of human capital, digital skills, and research and development investment on labor productivity. The proposed model allows for a quantitative assessment of the contribution of human capital development to economic performance and technological advancement.

Exposition of the main material of the study with full justification of the scientific results obtained

Theoretical Framework

The theoretical framework of this study is based on several complementary theoretical approaches that explain the relationship between human capital development, technological change, and economic growth.

The first theoretical foundation is the human capital theory, which emphasizes the role of education, knowledge, and professional skills as key factors of economic productivity and development. According to this approach, investments in education and skill development increase individual productivity and contribute to long-term economic growth E.R. Eide, M.H. Showalter [6].

The second theoretical perspective is endogenous growth theory, which highlights the role of knowledge, innovation, and research and development activities as central drivers of economic development. Within this framework, human capital acts as a crucial factor facilitating technological innovation and the diffusion of new technologies M. A Verba [13]. Another important theoretical approach is the concept of the knowledge-based economy, which emphasizes the growing importance of intangible assets, intellectual capital, and innovation in modern economic systems. In knowledge-based economies, human capital becomes a key resource enabling technological progress and sustainable economic growth.

Finally, the study draws upon the concept of the Fourth Industrial Revolution, which describes the ongoing technological transformation characterized by the integration of digital technologies, artificial intelligence, automation, and advanced data analytics into economic and social systems. Within this context, human capital plays a crucial role in enabling societies to adapt to technological change and to harness the potential benefits of digital transformation M.V. Freitas [7].

Together, these theoretical perspectives provide a comprehensive framework for analyzing the relationship between human capital development, technological innovation, and economic performance.

The expected scientific contribution of the study lies in developing an integrated analytical approach to examining the relationship between human capital development, technological transformation, and innovation-driven economic growth. The article aims to extend the existing literature by providing empirical evidence on how investments in education, research, and digital skills contribute to economic productivity and innovation capacity.

Furthermore, the research seeks to identify policy implications for improving human capital development strategies in the context of the Fourth Industrial Revolution.

The conceptual framework illustrates how human capital development influences technological adoption, innovation activity, and economic productivity in the context of the Fourth Industrial Revolution**.** The conceptual model assumes that human capital development acts as a central mechanism linking education systems, technological change, and economic performance. Education and training contribute to the formation of knowledge, professional competencies, and digital skills. These elements collectively form human capital, which enables workers and organizations to adopt new technologies and participate in innovation processes. Technological adoption and innovation activity, in turn, increase labor productivity and stimulate long-term economic growth. Within the context of the Fourth Industrial Revolution, the importance of human capital becomes even greater because digital technologies require a workforce capable of learning, adapting, and interacting with complex technological systems.

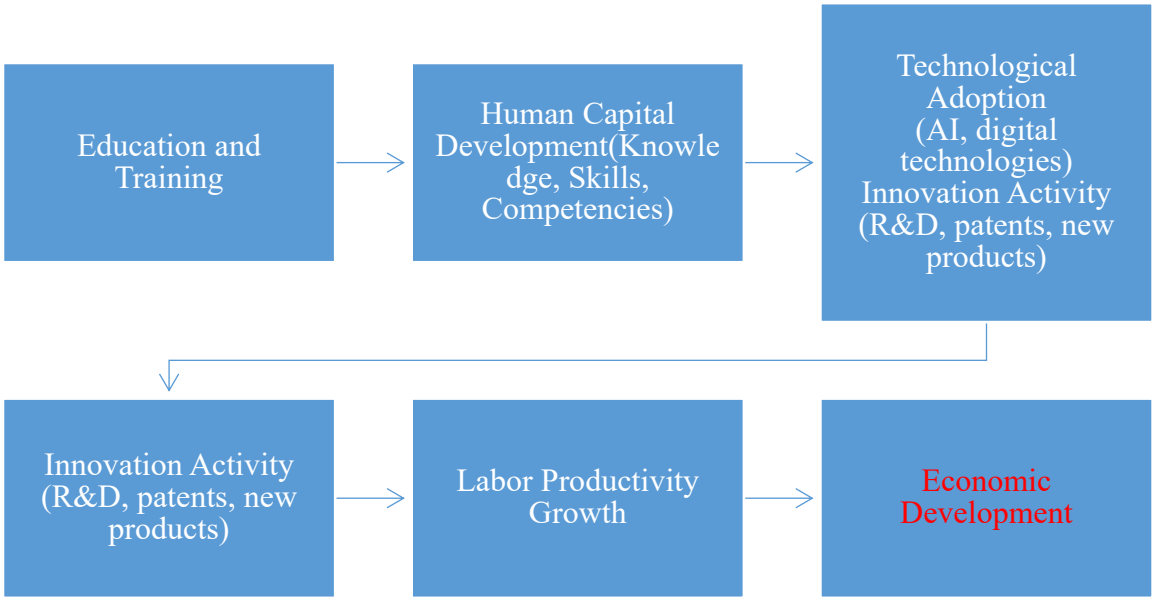


Fig. 1. Conceptual model human capital development

Source: compiled by the author based on [6; 7; 13]

The conceptual framework presented in Figure 1 illustrates the structural relationships between human capital development, technological adoption, innovation activity, and economic productivity within the context of the Fourth Industrial Revolution. The model positions human capital as a central mechanism that links education systems with technological change and economic performance.

Education and professional training constitute the foundational components of human capital formation. Through formal education, vocational training, and lifelong learning systems, individuals acquire knowledge, professional competencies, and digital skills that enable them to function effectively in technologically advanced environments. These elements collectively shape the quality of human capital available within an economy.

The conceptual model suggests that developed human capital significantly enhances the capacity of individuals and organizations to adopt new technologies. In the era of the Fourth Industrial Revolution, characterized by rapid diffusion of

artificial intelligence, digital platforms, and advanced automation, the ability of the workforce to adapt to technological change becomes a key determinant of competitiveness. Skilled labor not only facilitates the adoption of emerging technologies but also actively contributes to innovation processes.

Innovation activity represents another important channel through which human capital influences economic performance. Highly educated and skilled workers participate in research and development activities, generate new knowledge, and contribute to technological improvements. As a result, innovation leads to higher productivity, improved production processes, and the development of new products and services.

Ultimately, the interaction between human capital, technological adoption, and innovation contributes to increased labor productivity and long-term economic growth. Therefore, within the framework of the Fourth Industrial Revolution, investments in education, skills development, and knowledge generation become strategic determinants of sustainable economic development.

The next step can be to create model which will help to asses efficiency of human capital. The empirical analysis may rely on internationally recognized statistical databases, including:

- **World Bank** – human capital indicators, education, R&D expenditure
- **OECD** – skills indicators, innovation and productivity data
- **Eurostat** – digital economy indicators, labor market statistics
- **World Economic Forum** – digital skills and competitiveness indicators
- **UNDP** – human development indicators.

These databases provide comparable cross-country data that enable the analysis of structural relationships between human capital and technological development.

This is the largest global database on human capital. The World Bank created the Human Capital Project database, which includes data for over 200

countries and more than 200 indicators related to education, health, labor, and skills. (World Bank)

Main indicator

- Human Capital Index (HCI)

The Human Capital Index (HCI) measures the amount of human capital that a child born today can expect to attain by age 18, given the risks of poor health and poor education that prevail in the country where she lives. The Human Capital Index Plus (HCI+), a new global index that extends the original HCI from age 18 into adulthood, measures the human capital a child born today can expect to acquire over their working life if the current levels of health, education, and employment persist.

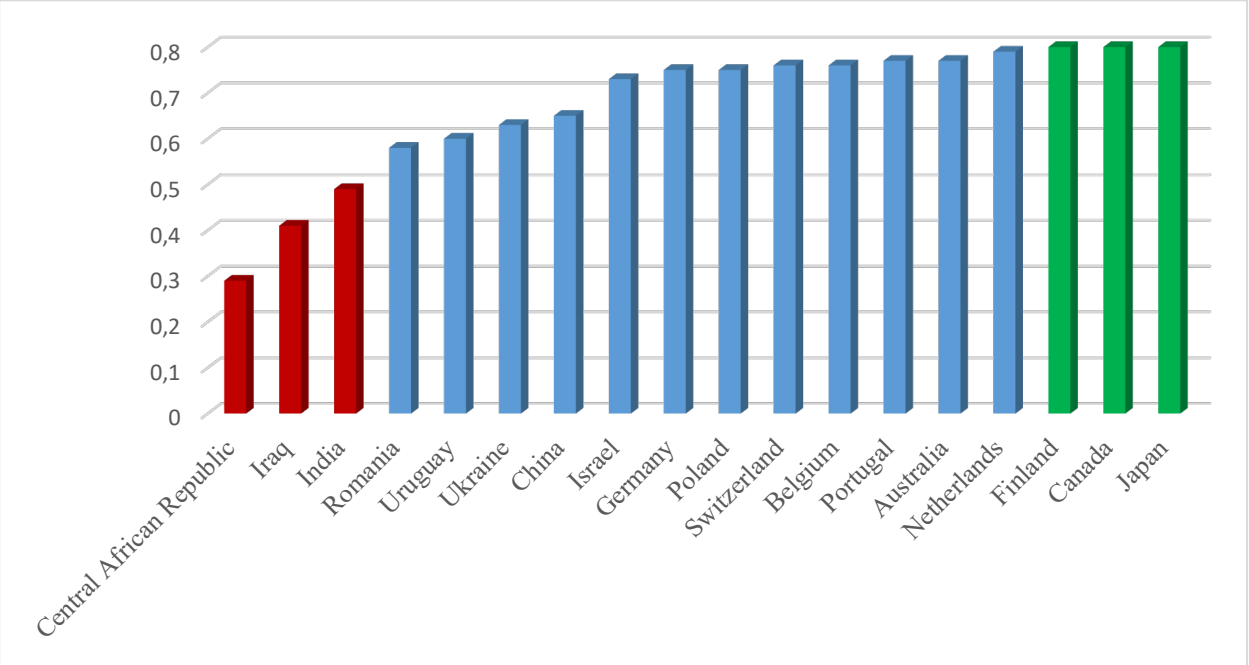


Fig. 2. Human Capital Index (HCI) (scale 0-1), 2020

Source: compiled by the author based on [15]

The diagram presented in Figure 2 illustrates the distribution of the Human Capital Index (HCI) across countries. The index ranges from 0 to 1 and measures the expected productivity of a child born today relative to a benchmark of full

health and complete education. The data demonstrate significant cross-country differences in human capital development.

Highly developed economies typically demonstrate the highest HCI values. For example, Finland, Canada, Japan reach a value of 0.80, while most of Europe country (Ukraine too) record values between 0.60-0.80. These results reflect strong education systems, high health standards, and effective human capital investment policies. In contrast, emerging and developing economies demonstrate lower HCI levels. For instance, Iraq has an index value of 0.41, while India records a value of 0.49. These differences indicate structural disparities in access to quality education, healthcare systems, and labor market opportunities.

The observed variation in HCI values highlights the uneven global distribution of human capital and suggests that differences in educational quality, health outcomes, and institutional capacity significantly influence long-term economic productivity.

Human capital is everything that makes people productive, from education and skills to health and resilience.

These qualities are valuable in their own right and essential for success in life and work. They help people learn, earn, grow, and contribute to their communities.

The World Bank's Human Capital Project (HCP) is a global effort to accelerate investments in people as the foundation for both individual success and economic growth.

The HCI+ measures this cumulative growth, showing how countries build human capital through sustained investment in education, health, and employment.

The HCI+ integrates three pillars of human development—health – 50 points, education - 188 points, and employment – 87 points —each essential to building a country's human capital.

The Human Capital Index Plus (HCI+) measures how effectively a country builds human capital, tracking the likelihood that children today will grow into healthy, educated, and productive adults.

Each pillar is weighted by its contribution toward a total potential score of 325. A score of 0 reflects conditions where human capital cannot develop: universal stunting, no schooling, and no employment prospects.

Table 1

Human Capital Index Plus (HCI+) across selected countries, 2025

Low than World economy		World economy		High than world economy	
Countries	HCI+	World	HCI+	Countries	HCI+
Afghanistan	80,25			Uruguay	206,19
Central African Republic	108,91			China	219,82
Heavily indebted poor countries (HIPC)	120,61			Ukraine	220,06
Angola	120,71		186,48	Belgium	245,53
Eastern & Southern Africa	130,21			Euro area	246,19
Iraq	137,14			Portugal	248,48
Banglades	146,71			France	251,24
				Finland	256,26
India	158,76			Germany	256,46
Egypt	161,19			Canada	256,89
Arab World	161,69			Australia	269,98
Grenada	182,59			Japan	284,34

Source: compiled by the author based on [15]

Additional insights into human capital development are provided in Table X, which presents the Human Capital Index Plus (HCI+). Unlike the traditional HCI, which focuses primarily on human capital accumulation up to the age of 18, HCI+ extends the measurement across the entire working life. The index integrates three fundamental pillars of human development: health, education, and employment.

The results demonstrate substantial global heterogeneity in the level of accumulated human capital. Countries with lower than world-average values include Afghanistan (80.25), the Central African Republic (108.91), Angola (120.71), and Bangladesh (146.71). These economies face structural challenges related to educational access, healthcare systems, and labor market development.

In contrast, countries with human capital levels exceeding the global average include Uruguay (206.19), China (219.82), Ukraine (220.06), Belgium (245.53), Portugal (248.48), France (251.24), Finland (256.26), Germany (256.46), Canada (256.89), Australia (269.98), and Japan (284.34). These results indicate strong institutional capacity to accumulate human capital through sustained investments in education, health, and employment opportunities.

The comparison across country groups clearly demonstrates that advanced economies tend to achieve significantly higher HCI+ values, reflecting more effective long-term investment strategies in human development. At the same time, many developing countries remain constrained by structural limitations that prevent the full realization of human capital potential.

The empirical indicators presented above confirm that human capital plays a critical role in shaping the economic capacity of nations. Differences in education systems, health conditions, and labor market structures lead to substantial variation in human capital accumulation and, consequently, in productivity and innovation outcomes.

Therefore, the conceptual relationships illustrated in the theoretical framework and the empirical patterns observed in the human capital indicators provide a strong justification for quantitative analysis. To formally evaluate the impact of human capital development on economic productivity and technological progress, it is necessary to construct an econometric model based on cross-country data.

Such a model allows for the statistical estimation of the relationship between human capital indicators and key economic outcomes, including labor

productivity, innovation activity, and technological adoption. Using internationally comparable datasets from organizations such as the World Bank, OECD, Eurostat, UNDP, and the World Economic Forum, it becomes possible to empirically test the hypothesized relationships presented in the conceptual framework.

Accordingly, the next stage of the research involves the specification of an econometric model designed to assess the quantitative effects of human capital development on economic performance. Such model include dependent variables, independent variables and control variables

Dependent Variables.

To evaluate the economic effects of human capital development, the study may use the following dependent variables:

1. Labor productivity (GDP per employed person).
2. Innovation activity (Number of patents or innovation index indicators).
3. Technological adoption (Digital economy or technology readiness indicators).

Independent Variables. The key explanatory variables represent different dimensions of human capital development.

Human Capital Index (Composite indicator reflecting education and health outcomes).

Education level (Average years of schooling or tertiary education rate).

Digital skills (Share of population with basic or advanced digital competencies).

R&D expenditure (Research and development spending as a percentage of GDP).

Employment in high-tech sectors (Share of workforce employed in knowledge-intensive industries).

Control Variables. To avoid omitted variable bias, the model may include several control variables: GDP per capita, investment rate, population growth, trade openness, institutional quality indicators.

The empirical analysis of the relationship between human capital development and economic productivity in the context of the Fourth Industrial Revolution requires the application of an econometric framework that captures both structural economic factors and technological dynamics. In this study, the econometric specification is based on the extended Cobb–Douglas production function, which is widely used in the literature on economic growth and productivity analysis.

The traditional Cobb–Douglas production function explains economic output as a function of capital and labor inputs. However, modern growth theories emphasize the importance of additional factors such as human capital, innovation, and technological development. In particular, the endogenous growth theory suggests that investments in education, research and development, and knowledge accumulation play a crucial role in long-term economic growth.

In the context of the Fourth Industrial Revolution, technological change is increasingly driven by digitalization, automation, artificial intelligence, and the diffusion of advanced technologies. These processes significantly transform labor markets, skill requirements, and productivity patterns. Therefore, it is necessary to extend the traditional production function by incorporating variables that capture human capital development, innovation capacity, and digital competencies.

The proposed econometric model includes the Human Capital Index as a key explanatory variable reflecting the overall level of human capital formation in a country. Human capital plays a central role in enhancing labor productivity, facilitating technological adoption, and supporting innovation processes. Countries with higher levels of education, skills, and health tend to demonstrate stronger economic performance and higher productivity levels.

In addition to human capital, the model incorporates research and development expenditure as an indicator of innovation capacity. Investments in R&D contribute to the creation of new technologies, knowledge diffusion, and the development of high-value industries. The inclusion of this variable allows the analysis to capture the role of innovation-driven growth in modern economies.

Another important component of the model is the level of digital skills within the population. Digital competencies represent a critical factor of economic development in the era of digital transformation. Workers with advanced digital skills are more capable of adapting to technological change, utilizing digital tools, and participating in knowledge-intensive activities.

Furthermore, the model includes education indicators and GDP per capita as control variables. These variables allow the analysis to account for differences in the overall economic development level and educational attainment across countries. Controlling for these factors improves the robustness and reliability of the econometric results.

Overall, the proposed econometric model provides a comprehensive framework for analyzing the impact of human capital, innovation, and digitalization on labor productivity in the context of the Fourth Industrial Revolution. The model allows for a deeper understanding of the mechanisms through which human capital contributes to economic development and technological progress.

Based on the theoretical framework and the conceptual model of human capital development, the following econometric specification can be proposed.

The baseline econometric specification can be expressed as a panel regression model:

$$\ln(\text{Productivity}_{it}) = \alpha + \beta1 \times \text{HCI}_{it} + \beta2 \times \text{RD}_{it} + \beta3 \times \text{DIG}_{it} + \beta4 \times \text{EDU}_{it} + \beta5 \times \text{GDPpc}_{_it} + \varepsilon_{it}$$

where

Productivity – GDP per worker or labor productivity (dependent variable)

i represents the country,

t represents the year.

HCI – Human Capital Index

RD – Research and Development expenditure (% of GDP)

DIG – Digital skills of the population

EDU – Education level (tertiary education attainment)

GDPpc – GDP per capita (control variable)

ε – Error term.

To illustrate the potential application of the proposed econometric model, approximate indicator values for Ukraine are used.

The following approximate values based on recent international statistics are used:

Table 2

Input data for calculation productivity in Ukraine

№	Indicator	Value	Source type
1	Human Capital Index (HCI)	0.63	international estimates
2	R&D expenditure (% of GDP)	0.33	national statistics
3	Digital skills (share of population)	0.58	regional estimates
4	α (constant)	0,15	international estimates
5	β1 (human capital)	0,35	international estimates
6	β2 (R&D)	0,20	international estimates
7	β3 (digital skills)	0,28	international estimates

Source: compiled by the author based on [6; 7; 15]

The estimated productivity index for Ukraine is approximately 7.0 in relative units. This indicates a moderate level of productivity influenced by the current levels of human capital, digital competencies, and innovation investment.

However, relatively low R&D expenditure significantly limits potential productivity growth.

If R&D expenditure increased to approximately 1.5% of GDP, similar to several Central European economies, productivity could increase substantially.

This suggests that strengthening human capital development, innovation policy, and digital skills formation could significantly improve economic performance in Ukraine.

Conclusions from this study and prospects for further research in this direction. The conducted research confirms that human capital development represents a fundamental factor of economic productivity and technological progress in the era of the Fourth Industrial Revolution. Theoretical analysis demonstrates that education, professional competencies, digital skills, and innovation capacity form the core components of modern human capital. These elements significantly influence the ability of economies to adopt new technologies, develop innovative activities, and achieve sustainable economic growth.

The conceptual framework developed in this study illustrates the structural relationship between education systems, human capital formation, technological adoption, innovation processes, and labor productivity. The empirical indicators analyzed in the study, particularly the Human Capital Index and Human Capital Index Plus, reveal substantial cross-country differences in the level of human capital accumulation. These differences largely reflect disparities in education quality, healthcare systems, innovation investment, and labor market structures.

The econometric model proposed in the study, based on the extended Cobb–Douglas production function, demonstrates that human capital, digital skills, and research and development investments play a significant role in determining labor productivity. The model confirms that strengthening human capital development policies and increasing investments in innovation can substantially improve economic performance.

The results of the research highlight the importance of integrated public policies aimed at improving education systems, promoting digital competencies, and supporting innovation-driven development. In particular, increasing investments in research and development, expanding access to quality education,

and fostering lifelong learning systems are essential for strengthening human capital in the digital economy.

Prospects for further research include expanding the empirical analysis through the use of panel data for a larger number of countries and longer time periods. Future studies may also focus on examining the institutional and policy mechanisms that influence human capital formation, including education reform, innovation policy, and labor market regulation in the context of digital transformation.

Література

1. Геєць В. Формування економічного профілю стратегічно важливих видів промислової діяльності в Україні (ретроспективний погляд). *Економіка України.* 2023. № 66(8 (741). С. 3–27. DOI: https://doi.org/10.15407/economyukr.2023.08.003

2. Кіндрецький, Ю. Промислова політика для економічного розвитку: до проблеми її обґрунтування з позицій світового досвіду та в контексті необхідності використання у воєнний період та при повоєнному відновленні в Україні. *Economic analysis.* 2023. № 33 (3). С. 110-129. DOI: https://doi.org/10.35774/econa2023.03.110

3. Aji B.A., Ikhlas D.I., Wati I.R. Human resource competency development in facing the challenges and opportunities of the Industry 4.0 era. *Research Horizon.* 2024. Vol. 4(6). P. 301–308. DOI: https://doi.org/10.54518/rh.4.6.2024.425

4. Alhloul A., Kiss E. Industry 4.0 as a challenge for the skills and competencies of the labor force: A bibliometric review and a survey. *Sci.* 2022. Vol. 4(3). Article 34. DOI: https://doi.org/10.3390/sci4030034

5. Córcoles D., Triguero Á., Cuerva M.C. Technological collaboration and the Industry 4.0 transformation: Evidence for Spanish manufacturing firms.

Journal of the Knowledge Economy. 2025. Vol. 16. P. 17664–17698. DOI: https://doi.org/10.1007/s13132-024-02501-y

6. Eide E.R., Showalter M.H., Human Capital, Editor(s): Penelope Peterson, Eva Baker, Barry McGaw, *International Encyclopedia of Education (Third Edition), Elsevier.* 2010. P. 282-287. DOI: https://doi.org/10.1016/B978-0-08-044894-7.01213-6

7. Freitas M.V. The Fourth Industrial Revolution Policy center for the new south PP 41/25. 2025. URL: www.policycenter.ma/sites/default/files/2025-11/PP_41-25_Marcus%20Vinicius%20De%20Freitas.pdf (access date: 02.01.2026).

8. Idrissi Gartoumi K., Koumetio Tekouabou S.C. Exploring African skills 4.0 required for 4IR industry: a systematic literature review. *Data & Policy.* 2024. Vol. 6. Article e36. DOI: https://doi.org/10.1017/dap.2024.28

9. Kolot A., Herasymenko O. Digital transformation and new business models as determinants of formation of the economy of nontypical employment. *Social and Labour Relations: Theory and Practice*. 2020. Vol. 10(1). P. 33–54. DOI: https://doi.org/10.21511/slrtp.10(1).2020.06281%29.2020.06

10. Kolot A., Herasymenko O., Shevchenko A., Riabokon I. Employment in the coordinates of digital economy: current trends and foresight trajectories. *Neuro-Fuzzy Modeling Techniques in Economics.* 2022. No. 11. DOI: https://doi.org/10.33111/nfmte.2022.078

11. Sima V., Gheorghe I.G., Subić J., Nancu D. Influences of the Industry 4.0 revolution on human capital development and consumer behavior: a systematic review. *Sustainability.* 2020. Vol. 12(10). Article 4035. DOI: https://doi.org/10.3390/su12104035

12. Štaffenová N., Kucharčíková A. Human capital management – values, competencies, and motivation – concerning Industry 4.0. *Economic Research-Ekonomska Istraživanja.* 2024. Vol. 37(1). DOI: https://doi.org/10.1080/1331677X.2024.2324160

13. Verba M. A. Growth and innovation in the presence of knowledge and R&D accumulation dynamics. *Economics of Innovation and New Technologyю* 2022. 31(6). P. 485–510. DOI: https://doi.org/10.1080/10438599.2020.1828510

14. Vrchota J., Mařiková M., Řehoř P., Rolínek L., Toušek R. Human resources readiness for Industry 4.0. *Journal of Open Innovation: Technology, Market, and Complexity.* 2020. Vol. 6(1). Article 3. DOI: https://doi.org/10.3390/joitmc6010003

15. World Bank Group. Human Capital Data Porta. URL: https://humancapital.worldbank.org/en/indicator/WB_HCP_HCI (access date: 06.01.2026).

16. Zaloznova Y., Pankova O., Ostafiichuk Y. Global and Ukrainian labour markets in the face of digitalization challenges and the threats of the COVID-19 pandemic. *Virtual Economics.* 2020. Vol. 3(4). P. 106–130. DOI: https://doi.org/10.34021/ve.2020.03.04(6)

17. Pylypenko H., Fedorova N., Lytvynenko N., Pylypenko Yu. Breakthrough technologies of social transformations: devising an identification methodology. *Eastern-European Journal of Enterprise Technologies*. 2025. Vol. 2, № 13 (134). P. 15-27. DOI: https://doi.org/10.15587/1729-4061.2025.326555

References

1. Heyets, V. (2023). Economic profile formation of strategically important types of industrial activity in Ukraine (retrospective view). *Economy of Ukraine, 8*, 3–27. https://doi.org/10.15407/economyukr.2023.08.003

2. Kindzerskyi, Yu. (2023). Industrial policy for economic development: To the problem of its justification from the standpoint of world experience and in the context of the need for use during the war period and post-war recovery in Ukraine. *Economic Analysis, 33*(3), 110–129. https://doi.org/10.35774/econa2023.03.110

3. Aji, B. A., Ikhlas, D. I., & Wati, I. R. (2024). Human resource competency development in facing the challenges and opportunities of the Industry 4.0 era. *Research Horizon, 4*(6), 301–308. https://doi.org/10.54518/rh.4.6.2024.425

4. Alhloul, A., & Kiss, E. (2022). Industry 4.0 as a challenge for the skills and competencies of the labor force: A bibliometric review and a survey. *Sci, 4*(3), Article 34. https://doi.org/10.3390/sci4030034

5. Córcoles, D., Triguero, Á., & Cuerva, M. C. (2025). Technological collaboration and the Industry 4.0 transformation: Evidence for Spanish manufacturing firms. *Journal of the Knowledge Economy, 16*, 17664–17698. https://doi.org/10.1007/s13132-024-02501-y

6. Eide, E. R., & Showalter, M. H. (2010). Human capital. In P. Peterson, E. Baker, & B. McGaw (Eds.), *International encyclopedia of education* (3rd ed., pp. 282–287). Elsevier. https://doi.org/10.1016/B978-0-08-044894-7.01213-6

7. Freitas, M. V. (2025). *The Fourth Industrial Revolution*. Policy Center for the New South (Policy Paper PP 41/25).

8. Idrissi Gartoumi, K., & Koumetio Tekouabou, S. C. (2024). Exploring African skills 4.0 required for 4IR industry: A systematic literature review. *Data & Policy, 6*, e36. https://doi.org/10.1017/dap.2024.28

9. Kolot, A., & Herasymenko, O. (2020). Digital transformation and new business models as determinants of formation of the economy of nontypical employment. *Social and Labour Relations: Theory and Practice, 10*(1), 33–54. https://doi.org/10.21511/slrtp.10(1).2020.06

10. Kolot, A., Herasymenko, O., Shevchenko, A., & Riabokon, I. (2022). Employment in the coordinates of digital economy: Current trends and foresight trajectories. *Neuro-Fuzzy Modeling Techniques in Economics, 11*. https://doi.org/10.33111/nfmte.2022.078

11. Sima, V., Gheorghe, I. G., Subić, J., & Nancu, D. (2020). Influences of the Industry 4.0 revolution on human capital development and consumer

behavior: A systematic review. *Sustainability, 12*(10), Article 4035. https://doi.org/10.3390/su12104035

12. Štaffenová, N., & Kucharčíková, A. (2024). Human capital management – values, competencies, and motivation – concerning Industry 4.0. *Economic Research – Ekonomska Istraživanja, 37*(1). https://doi.org/10.1080/1331677X.2024.2324160

13. Verba, M. A. (2022). Growth and innovation in the presence of knowledge and R&D accumulation dynamics. *Economics of Innovation and New Technology, 31*(6), 485–510. https://doi.org/10.1080/10438599.2020.1828510

14. Vrchota, J., Mařiková, M., Řehoř, P., Rolínek, L., & Toušek, R. (2020). Human resources readiness for Industry 4.0. *Journal of Open Innovation: Technology, Market, and Complexity, 6*(1), Article 3. https://doi.org/10.3390/joitmc6010003

15. World Bank Group. (n.d.). *Human Capital Data Portal*. https://humancapital.worldbank.org/en/indicator/WB_HCP_HCI

16. Zaloznova, Y., Pankova, O., & Ostafiichuk, Y. (2020). Global and Ukrainian labour markets in the face of digitalization challenges and the threats of the COVID-19 pandemic. *Virtual Economics, 3*(4), 106–130. https://doi.org/10.34021/ve.2020.03.04(6)

17. Pylypenko, H., Fedorova, N., Lytvynenko, N., & Pylypenko, Y. (2025). Breakthrough technologies of social transformations: Devising an identification methodology. *Eastern-European Journal of Enterprise Technologies, 2*(13(134)), 15–27. https://doi.org/10.15587/1729-4061.2025.326555