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Determinants of Industry 4.0 Readiness in the Manufacturing of the V4 Economies

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Abstract

The article presents the results of research aimed at identifying the determinants of Industry 4.0 (I4.0) readiness in manufacturing and assessing the relevant progress made by the Visegrad Group (V4; i.e. the Czech Republic, Hungary, Poland and Slovakia) countries between 2011 and 2021.
The investigation relies on the authors' proposal for twelve variables that constitute the basis for a study using principal component analysis (PCA). Based on the calculation of factor loadings, the study produces a composite indicator of I4.0 readiness. It is followed by an assessment of the V4 economies against the backdrop of the other EU Member States.
The V4 economies showed relatively low levels of I4.0 readiness and made no significant progress. The top performer was the Czech Republic, ranked 12th, on average, between 2011 and 2021. It was closely followed by Hungary (14th) and Slovakia (17th). Poland was ranked the lowest (20th).
The main contribution is the proposal of a set of determinants of I4.0 readiness in manufacturing. Measuring the progress of I4.0 readiness in the V4 economies and identifying barriers to I4.0 implementation in manufacturing may have application value for public policies

Keywords: Industry 4.0, Industry 4.0 readiness, Industry 4.0 transformation, manufacturing, Visegrad Group

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Introduction

Technology changes over time, revolutionising production systems and thus shaping economic systems, social structures and public policies. Although the three main industrial revolutions, which began in the second half of the 18th century, had distinguishing features, the focus was always on the introduction of breakthrough technologies. By integrating material and digital resources, the ongoing Fourth Industrial Revolution has redefined production and working methods. In the context of organising manufacturing, it is characterised by breakthrough Industry 4.0 (I4.0) technologies, such as artificial intelligence (AI), the Internet of Things (IoT), additive manufacturing, robotics and cloud computing. The implementation of those solutions offers a wide range of benefits, including increased production efficiency, reduced costs, improved product quality and adaptation to ever-changing market needs. However, it involves strict cooperation between IT and production, as well as organisational flexibility in adapting to the fast pace of change in the business environment. Over the past decade, in response to the challenges of global competition, the majority of European Union (EU) governments have recognised I4.0 as a priority, adopting strategic action plans to transform existing divisions of industry, enhancing productivity and upgrading personnel skills with regard to advanced technologies. Despite this consensus, however, I4.0 readiness in manufacturing is a relatively new concept, and measuring it and selecting determinants remain a challenge.

The Visegrad Group, or V4, refers to a cultural and political alliance of four Central European countries: the Czech Republic, Hungary, Poland, and Slovakia. These nations have a significant manufacturing sector, contributing an average of 20% to their economies (according to UNIDO 2024). Additionally, they play a major role in global manufacturing supply chains, with an average participation rate of 65% (OECD 2024). Given this strong manufacturing base, the article explores the concept of I4.0 readiness within the V4 economies.

The research presented here identifies the determinants of I4.0 readiness in manufacturing and assesses the relevant progress made by the V4 countries between 2011 and 2021. A literature review allowed us to define such factors considering the challenges of the Fourth Industrial Revolution. The investigation was carried out using principal component analysis (PCA) based on twelve variables divided into four themes: production and export capacity, human capital, research and development infrastructure, and the use of ICT. Based on the factor loadings calculated for the first principal component, a composite indicator of I4.0 readiness was developed. It allowed us to estimate the V4 countries' I4.0 readiness in manufacturing and rank all of the EU economies.

The article begins by presenting a review of the literature on the essence and determinants of I4.0. It is followed by a description of the methodology and a discussion of the results. In the conclusion, the article confronts the key findings with the barriers to implementing I4.0 identified in the literature review.

Defining the essence of Industry 4.0 in manufacturing

Despite its popularity, the definition of I4 remains unclear (Ojra 2019; Rupp et al. 2021). Often described as the integration of complex physical machinery, equipment and devices with networked sensors and software, I4.0 aims to optimise planning and control for better business performance (Hermann, Pentek, and Otto 2016). Properly implemented I4.0 solutions are expected to enable the intelligent networking of all industrial processes and products, resulting in improved quality and efficiency (Kora and Beluli 2022).

I4.0 covers the whole value chain, from design and development through production, management and logistics, to the distribution of final products. Therefore, it involves new business models and strategies (Prause 2015). The distinguishing feature of process networking and digitisation is the horizontal and vertical integration of production systems, determined by real-time data exchange and flexible production adapted to market and customer needs (Wodnicka 2021). The core technology, as revolutionary as those related to the previous revolutions, is that of cyber-physical systems (CPS). They enable the development of autonomous production processes, which, based on double representation, become intelligent, i.e., communication algorithms and decision-making components that can determine their production line configuration (Lee, Bagheri, and Kao 2015). The development of advanced production is also referred to as smart manufacturing or an adaptable system where flexible lines automatically adjust production processes to many types of products and changing conditions (Wang et al. 2016).

The term I4.0 is frequently used more broadly to capture the sum of all breakthrough innovative solutions developed and implemented in a value chain or even identified with the Fourth Industrial Revolution (Frank, Dalenogare, and Ayala 2019). However, an industrial revolution is a more complex phenomenon which cannot be defined solely based on breakthrough technologies (Klingenberg, Borges, and Antunes 2022). Innovation certainly drives subsequent industrial revolutions, becoming their tool, but the overall outcomes are deep, structural and socio-economic changes.

Industry 4.0 readiness – the methodological assumptions

The examination proposes an indicator of I4.0 readiness, developed using PCA. In various fields of study, it is one of the most frequently used multivariate statistical methods, first proposed by Karl Pearson (1901) and then formalised and popularised by Harold Hotelling (1933). The method makes it possible to transform high-dimensional data into lower dimensional data, albeit with some loss of information regarding the original variables (Ding and He 2004).

Multivariate analysis relies on the principle of compromise or trade-off, which means that a complex system of dependencies between multiple variables is presented in simplified terms and in a strongly reduced number of dimensions. However, this simplification results in an inaccurate mapping of particular original variables (Sagan 2004). An appropriate aggregation of the original variables used in PCA produces orthogonal, uncorrelated variables, referred to as principal components (Sztemberg-Lewandowska 2017). In the next step, these components are ordered by the amount of variance that each component explains (Wnorowski 2011; Abdi, Williams, and Valentin 2013).

The mathematical model in principal component analysis can be represented as the following system of linear equations:

$$X_1 = a_{11}Z_1 + a_{12}Z_2 + \ldots + a_{1p}Z_p$$

$$X_2 = a_{21}Z_1 + a_{22}Z_2 + \ldots + a_{2p}Z_p \tag{1}$$

$$\vdots$$

$$X_3 = a_{p1}Z_1 + a_{p2}Z_2 + \ldots + a_{pp}Z_p$$

where original variables X_i for $i \in \{1, \ldots, p\}$ are expressed as linear combinations of latent variables Z_j for $j \in \{1, \ldots, p\}$, called principal components. The coefficients a_{ij} for $i, j \in \{1, \ldots, p\}$ specify the weight of a given component in the description of empirical variables.

The matrix form of the PCA model is as follows:

$$X = A^*Z, \tag{2}$$

where $X = [X_1, X_2, \ldots, X_p]^T$ is the matrix of standardised variables, $Z = [Z_1, Z_2, Z_p]^T$ – the matrix of principal components, and $A = [a_{ij}]_{pp}$ is the matrix of coefficients of that principal component (Sztemberg-Lewandowska 2017).

To construct a composite indicator of I4.0 readiness, the values of principal components for each economy were normalised. This normalisation aims to ensure comparability of characteristics under different denominations (Borys 1980; Kukuła 2000). Based on the literature review, zero unitarisation was chosen as the normalisation method. The mathematical notation of the zero unitarisation method is as follows:

$$U_{jnt} = \frac{\left[z_{jnt} - \min\left\{z_{jnt}\right\}\right]}{r_j}, \tag{3}$$

$$r_j = \max\left\{z_{jnt}\right\} - \min\left\{z_{jnt}\right\}, \tag{4}$$

where U_{jnt} – value of the normalised *j*-th principal component *z* for the *n*-th case in year *t*, r_j – value range for z_{jn}.

The I4.0 readiness indicator relies on variables identified through a critical review of major publications in the field (Fagerberg 1987; Drabińska 2012; Brettel et al. 2014; Haverkort and Zimmermann 2017; Haddud et al. 2017; Siuta-Tokarska 2017; Kamble, Gunasekaran, and Sharma 2018; Genest and Gamache 2020; Nhamo, Nhemachena, and Nhamo 2020; Dou et al. 2021; UN 2023). Table 1 presents a systematisation of the main explanatory variables that reflect an economy's I4.0 readiness. The assessment of the V4 economies was based on a selection of indicators describing four themes: production and export capacity, human capital, research and development infrastructure, and the use of ICT.

Table 1. Explanatory variables used to determine Industry 4.0 readiness

Theme	Indicator	Abbreviation	Data source
Production and export capacity	Medium- and high-tech manufacturing value added (% of total manufacturing value added)	MHVAsh	UNIDO
	Manufacturing value added *per capita*	MVApc	UNIDO
	Medium- and high-tech manufacturing exports (% of total manufacturing exports)	MHXsh	UNIDO
Human capital	Percentage of the population aged 25–34 with tertiary educational attainment (%)	TEAsh	Eurostat
	Employment in high- and medium-high technology manufacturing sectors (% of total employment)	EMHsh	Eurostat
	ICT specialists in employment (% of total employment)	ICTEsh	Eurostat

Theme	Indicator	Abbreviation	Data source
Research and development infrastructure	Research and development expenditure (% of GDP)	RDEsh	Eurostat
	Patent applications (per million inhabitants)	PAvol	Eurostat
	Research and development personnel (% of total labour force)	RDEvol	Eurostat
Use of ICT	Percentage of people employed in manufacturing with access to the Internet for business purposes (% of total employment)	IUMsh	Eurostat
	Percentage of manufacturing enterprises that provided training to develop/upgrade their personnel's ICT skills (% of enterprises)	SKTsh	Eurostat
	E-government activities of individuals via websites (% of the population)	GOVsh	Eurostat

Source: authors' elaboration based on data from Eurostat 2023; UNIDO 2023.

The *production and export capacity* theme comprises indicators of the production capacity of manufacturing, with a particular focus on medium- and high-tech manufacturing sectors. Therefore, the selection includes:

- medium- and high-tech manufacturing value added expressed as a percentage of total manufacturing value added,
- medium- and high-tech manufacturing exports as a percentage of total manufacturing exports,
- a traditional measure of production capacity in the economy, i.e. manufacturing value added *per capita*.

Another theme for the analysis was *human capital*, reflected in the percentage of the population aged 25–34 with a university degree, employment in high- and medium-high technology manufacturing sectors as a percentage of total employment, and ICT specialists in employment as a percentage of total employment. Human capital is of paramount importance to the implementation of I4.0 technologies and, thus, of advanced production methods. Based on the literature review, the selection includes three indicators that describe *research and development infrastructure*: research and development expenditure (% of GDP), patent applications per million inhabitants, and research and development personnel as a percentage of the total labour force.

Intellectual property is essential to the competitiveness of economies and manufacturing, while the R&D sector significantly contributes to creating the framework conditions for the transition towards I4.0. As the last theme for analysis, the use of ICT was selected as a major driver of the Fourth Industrial Revolution. It is even recognised as the outcome of the dynamic expansion of information technology.

To measure ICT implementation, the selection comprises two indicators that only concern manufacturing: the percentage of people employed in manufacturing with access to the Internet for business purposes (% of total employment) and the percentage of manufacturing enterprises that provided training to develop/upgrade their personnel's ICT skills (% of enterprises).

The third selected determinant is the e-government activities of individuals via websites as a percentage of the population. This somewhat reflects the digital literacy and skills of a country's population.

An important stage of the PCA procedure involved determining the principal components. Using RStudio, we generated 12 components that correspond to the 12 explanatory variables under analysis. Table 2 presents the following measures calculated for the principal components: the standard deviation, the proportion of variance, and the cumulative variance.

Table 2. Principal components

Principal component number	Standard deviation	Proportion of variance	Cumulative variance
1	2.51381	0.528382	0.528382
2	1.548146	0.200404	0.728787
3	0.908721	0.069047	0.797834
4	0.772069	0.049842	0.847676
5	0.695539	0.040451	0.888126
6	0.630969	0.033289	0.921415
7	0.545815	0.024912	0.946325
8	0.405527	0.013751	0.960076
9	0.383926	0.012325	0.972401
10	0.361613	0.010934	0.983335
11	0.316814	0.008393	0.991727
12	0.314548	0.008273	1

Source: authors' own calculations based on the data identified in Table 1.

Examination of the data in Table 2 reveals a clear decreasing trend in the variance. Each subsequent principal component explains a lower proportion of the total variance. The first two principal components account for 72.8% of information on the original variables, while the first principal component alone explains approx. 53% of total variance. Table 3 provides detailed numerical data regarding factor loadings. Analysing the data in Table 3 allows us to identify correlations between variables and between a variable and the relevant principal component.

Table 3. Factor loading values for the first and second principal components, 2011–2021

Theme	Indicator	First principal component	Second principal component
Production and export capacity	Medium- and high-tech manufacturing value added (% of total manufacturing value added)	0.25326	0.42209
	Manufacturing value added *per capita*	0.25865	0.04188
	Medium- and high-tech manufacturing exports (% of total manufacturing exports)	0.15822	0.48618
Human capital	Percentage of the population aged 25–34 with tertiary educational attainment (%)	0.14593	– 0.44553
	Employment in high- and medium-high technology manufacturing sectors (% of total employment)	0.03337	0.54687
	ICT specialists in employment (% of total employment)	0.34109	– 0.14443
Research and development infrastructure	Research and development expenditure (% of GDP)	0.34424	0.11306
	Patent applications (per million inhabitants)	0.35030	– 0.03736
	Research and development (R&D)	0.36107	– 0.01666
Use of ICT	Percentage of people employed in manufacturing with access to the Internet for business purposes (% of total employment)	0.36801	– 0.08671
	Percentage of manufacturing enterprises that provided training to develop/upgrade their personnel's ICT skills (% of enterprises)	0.30875	– 0.08128
	E-government activities of individuals via websites (% of the population)	0.32068	– 0.19160

Source: author's own calculations based on the data identified in Table 1.

When analysing factor loadings, attention must also be given to their signs, not just their values. Negative values indicate negative correlations, whereas a positive value reflects the significance of the variable concerned. The higher the value, the greater the weight of the variable for the principal component in question. Note that all the variables are positively correlated with the first principal component. The values obtained for the variables allowed us to determine the I4.0 readiness indicator.

The factor loadings for the first principal component indicate that countries with high values also maximise the performance of their manufacturing sectors in all the themes under examination, i.e. production and export capacity, human capital, research and development infrastructure, and the use of ICT. The most significant variables were those describing research and development infrastructure, the use of ICT, as well as ICT specialists in employment (ICTEsh) from the human capital theme. The least important variable was employment in high- and medium-high technology manufacturing sectors

(EMHsh). That dimension served to prepare the I4.0 readiness indicator, used to examine the Visegrad countries and the other EU Member States.

Benchmarking results for the Visegrad countries and the other EU Member States

The analysis compares the I4.0 readiness of the V4 countries with the other EU Member States (Table 4). The data reveal that the V4 economies were characterised by average levels of I4.0 readiness and made no significant progress in their performance during the 2011–2021 period. The highest indicator was noted for the Czech Republic, with an average score of 0.4854, although it showed a minor decrease of 0.007 (1.5%). Hungary was second, with an average of 0.3972. It managed to improve its score by 0.005 (1.4%). It was closely followed by Slovakia, with an average of 0.3438. However, as with the Czech Republic, its score at the end of the period was lower than that at the beginning, declining by 1.4% (0.005). Poland was ranked the lowest, with indicator values significantly below those obtained by the other V4 economies. Its average score was a mere 0.2421, despite an increase of 0.06.

No V4 country emerged as a leader in I4.0 readiness throughout the period in question. The Czech Republic ranked highest (12th on average), followed by Hungary (14th), Slovakia (17th) and Poland (20th). Hungary moved up one spot, while the Czech Republic remained stable at 12th. Poland and Slovakia dropped by one and two places, respectively. The EU's front-runners included Finland, Sweden, Denmark and Austria, while the poorest performers were Romania, Bulgaria, Cyprus and Latvia.

Table 4. Industry 4.0 readiness in the European Union Member States

Country	2011		2012		2013		2014		2015	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Austria	6	0.7250	6	0.7474	4	0.7705	4	0.7913	4	0.7947
Belgium	8	0.6710	8	0.6868	8	0.6975	8	0.6976	8	0.6844
Bulgaria	26	0.0999	26	0.1016	26	0.1274	26	0.1042	26	0.1094
Cyprus	22	0.1960	22	0.1818	25	0.1481	25	0.1616	25	0.1430
Czech Republic	**12**	**0.4841**	**12**	**0.4640**	**12**	**0.4710**	**12**	**0.4871**	**12**	**0.4785**
Germany	4	0.7805	4	0.7913	6	0.7525	7	0.7549	6	0.7458
Denmark	3	0.9431	3	0.9469	2	0.9721	3	0.9407	3	0.9270
Estonia	13	0.4156	13	0.4039	14	0.3976	15	0.3521	15	0.3863
Greece	25	0.1814	23	0.1765	22	0.2072	22	0.1996	22	0.2080

Country	2011		2012		2013		2014		2015	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Spain	14	0.3974	15	0.3912	13	0.4157	14	0.4070	13	0.4105
Finland	1	0.9943	2	0.9715	3	0.9693	1	1.0000	2	0.9438
France	11	0.6037	11	0.6046	10	0.6139	10	0.6175	9	0.6399
Croatia	21	0.2108	21	0.2024	20	0.2263	21	0.2127	20	0.2314
Hungary	**16**	**0.3543**	**14**	**0.4005**	**15**	**0.3916**	**13**	**0.4132**	**14**	**0.4046**
Ireland	5	0.7565	5	0.7836	5	0.7641	5	0.7629	7	0.7394
Italy	17	0.3526	17	0.3435	16	0.3530	17	0.3407	17	0.3506
Lithuania	23	0.1863	24	0.1756	23	0.1912	23	0.1995	23	0.2054
Luxembourg	9	0.6518	9	0.6544	9	0.6403	9	0.6561	10	0.6268
Latvia	24	0.1835	25	0.1686	24	0.1621	24	0.1735	24	0.1816
Malta	18	0.3251	18	0.3053	19	0.2719	19	0.2822	18	0.3439
Netherlands	7	0.7051	7	0.6912	7	0.7475	6	0.7552	5	0.7492
Poland	**20**	**0.2251**	**20**	**0.2290**	**21**	**0.2227**	**20**	**0.2183**	**21**	**0.2283**
Portugal	19	0.2724	19	0.2594	18	0.2751	18	0.2845	19	0.2492
Romania	27	0.0573	27	0.0983	27	0.0533	27	0.0461	27	0.0748
Sweden	2	0.9718	1	0.9909	1	0.9777	2	0.9438	1	0.9487
Slovenia	10	0.6191	10	0.6101	11	0.5943	11	0.5732	11	0.5486
Slovakia	**15**	**0.3614**	**16**	**0.3449**	**17**	**0.3118**	**16**	**0.3497**	**16**	**0.3714**

Country	2016		2017		2018		2019		2020		2021	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Austria	4	0.8079	5	0.7879	4	0.7789	5	0.7503	8	0.7072	7	0.6816
Belgium	8	0.6887	8	0.7134	8	0.7253	7	0.7238	6	0.7312	6	0.7715
Bulgaria	26	0.1059	26	0.0912	26	0.1032	26	0.0914	26	0.0693	26	0.0537
Cyprus	25	0.1362	25	0.1582	25	0.1590	25	0.1830	25	0.1953	22	0.2411
Czech Republic	**12**	**0.4568**	**12**	**0.4829**	**12**	**0.5200**	**12**	**0.5089**	**12**	**0.5091**	**12**	**0.4768**
Germany	7	0.7376	7	0.7284	6	0.7343	8	0.7169	7	0.7085	9	0.6223
Denmark	2	0.9348	2	0.9133	2	0.9245	2	0.9063	3	0.9045	3	0.8692
Estonia	15	0.3936	15	0.4006	15	0.3982	13	0.4183	14	0.4049	14	0.3904
Greece	22	0.2020	23	0.1890	23	0.1944	24	0.1865	24	0.2262	25	0.2106
Spain	13	0.4179	14	0.4133	14	0.4063	15	0.3933	15	0.3980	13	0.3910
Finland	3	0.8939	3	0.8967	3	0.8984	3	0.8771	2	0.9271	2	0.9054
France	10	0.6369	10	0.6250	9	0.6438	9	0.6524	9	0.6113	10	0.5845

Country	2016		2017		2018		2019		2020		2021	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Croatia	20	0.2390	21	0.2124	21	0.2254	22	0.2169	23	0.2295	24	0.2383
Hungary	**14**	**0.3998**	**13**	**0.4186**	**13**	**0.4128**	**14**	**0.4083**	**13**	**0.4059**	**15**	**0.3594**
Ireland	5	0.7921	4	0.8039	7	0.7330	6	0.7404	5	0.7439	5	0.7740
Italy	16	0.3538	16	0.3624	16	0.3859	16	0.3727	17	0.3443	17	0.3398
Lithuania	23	0.1896	22	0.2043	22	0.2013	21	0.2445	21	0.2532	20	0.2883
Luxem-bourg	9	0.6537	9	0.6300	10	0.6101	10	0.6242	11	0.5532	8	0.6711
Latvia	24	0.1861	24	0.1829	24	0.1651	23	0.1900	22	0.2350	23	0.2406
Malta	17	0.3530	17	0.3512	18	0.3262	18	0.2808	19	0.2925	16	0.3407
Nether-lands	6	0.7647	6	0.7821	5	0.7748	4	0.7597	4	0.7874	4	0.7901
Poland	**21**	**0.2312**	**20**	**0.2365**	**19**	**0.2563**	**20**	**0.2596**	**20**	**0.2677**	**21**	**0.2882**
Portugal	19	0.2581	19	0.2553	20	0.2458	19	0.2709	18	0.2958	18	0.3189
Romania	27	0.0744	27	0.0707	27	0.0663	27	0.0434	27	0.0114	27	0.0000
Sweden	1	0.9386	1	0.9529	1	0.9382	1	0.9861	1	0.9983	1	0.9986
Slovenia	11	0.5459	11	0.5367	11	0.5474	11	0.5533	10	0.5593	11	0.5676
Slovakia	**18**	**0.3333**	**18**	**0.3254**	**17**	**0.3504**	**17**	**0.3663**	**16**	**0.3555**	**19**	**0.3117**

Source: prepared on the basis of the author's own calculations.

Identifying barriers to Industry 4.0 implementation in manufacturing

Given the limited progress observed in the I4.0 readiness of the V4 economies, identifying barriers to implementation is crucial. The literature review reveals five key categories hindering the adoption of I4.0 solutions in manufacturing: costs, knowledge, attitude to change, the organisation and structure of production, the institutional architecture, and public policies. Table 5 presents a more detailed breakdown and description of these barriers.

Table 5. Barriers to implementing solutions of the Fourth Industrial Revolution

Barrier	Description	Authors
Costs	High capital expenditure on investments in I4.0 technologies. Uncertain return on investment	Geissbauer, Schrauf, and Koch 2014; Kiel, Arnold, and Voigt 2017; Kamble, Gunasekaran, and Sharma 2018; Halse and Jæger 2019; Horváth and Szabó 2019; Da Silva et al. 2020; Cugno, Castagnoli, and Büchi 2021

Barrier	Description	Authors
Knowledge	Lack of key skills, competence, awareness and knowledge with regard to solutions Education and training programmes adapted to I4.0 needs	Hung 2016; Kiel, Arnold, and Voigt 2017; Halse and Jæger 2019; Horváth and Szabó 2019; Karadayi-Usta 2019; Luthra and Mangla 2019; Masood and Sonnrtag 2020; Govindan and Arampatzis 2023
Attitude to change	Fear of and resistance to change on the part of personnel Management commitment and leadership	Haddud et al. 2017; Horváth and Szabó 2019; Huang, Talla Chicoma, and Huang 2019; Machado et al. 2019; Ingaldi and Ulewicz 2020; Kumar, Singh, and Dwivedi 2020; Chauhan, Singh, and Luthra 2021
Organisation and structure of production	Organisational structure of enterprises Low standardisation of production processes	Müller, Buliga, and Voigt 2018; de Sousa et al. 2018; Halse and Jæger 2019; Horváth and Szabó 2019; Bakhtari et al. 2020; Cugno, Castagnoli, and Büchi 2021; Narwane et al. 2021
Institutional architecture and public policies	Public sector support and legislation Availability of infrastructure for ICT	Schröder 2016; Kamble, Gunasekaran, and Sharma 2018; Aggarwal, Gupta, and Ojha 2019; Cugno, Castagnoli, and Büchi 2021

Source: authors' elaboration based on Kamble, Gunasekaran, and Sharma R. 2018, Raj et al. 2020, and Sayem et al. 2022.

The high costs involved in implementing I4.0 solutions present a significant challenge, although there are also considerable risks related to the high degree of complexity of such production systems. Thus, there is a need for significant capital expenditure, increasing business uncertainty and posing a major challenge to corporate liquidity.

A lack of knowledge and know-how creates another hurdle. Many companies have a poor understanding of how I4.0 impacts businesses in the global economy. Additionally, there is a shortage of personnel with the digital skills and expertise to operate these advanced technologies (Luthra and Mangla 2018). Thus, while implementing I4.0 technologies requires personnel with advanced digital competencies, the skills gap in the majority of firms hinders progress (Govindan and Arampatzis 2023).

A third group of barriers is associated with attitudes to change, as evidenced by Ingaldi and Ulewicz (2020), Kumar, Singh, and Dwivedi (2020) and Chauhan, Singh, and Luthra (2021). Personnel's resistance to change and modern technological solutions poses a significant obstacle, adversely affecting transition-related business decisions, particularly in small and medium-sized enterprises. Inadequate leadership and managerial attitudes can be a hindrance, as managers should be advocates of change (Huang, Talla Chicoma, and Huang 2019; Kumar, Singh, and Dwivedi 2020). Leadership plays a key role in the era of I4.0 as business leaders decide on the implementation of solutions and should inspire their personnel (Govindan and Arampatzis 2023). The fear of failing, a low risk tolerance, or frequently both, pose key barriers to innovation. Perseverance and learning from failures characterise most technology companies. At present, the focus is still on risk minimisation, even though doing things differently or new things is risky (Savage 2022).

The lack of standardised production processes and unsuitable organisation of production can hinder automation (Halse and Jæger 2019). Lastly, some barriers concern public policies and the institutional architecture in general. Given the complexity and dynamics of I4.0, governments must support, facilitate and speed up the digital transition (Bakhtari et al. 2020). Müller, Buliga, and Voigt (2018) pointed out that appropriate policy-making plays a key role in encouraging the adoption of I4.0 solutions.

Conclusions

The article presented the determinants of I4.0 readiness in manufacturing. By analysing these determinants, the study assessed the progress made by the V4 economies. The results reveal that the V4 economies lagged behind the other EU Member States at the end of the period under examination. The countries concerned were leaders of the proposed I4.0 readiness ranking nor did they note any significant improvements. In fact, Poland and Slovakia were lower in the ranking in 2021 compared to the beginning of the period covered.

Considering the pace and scale of the ongoing Fourth Industrial Revolution, this situation may adversely affect the competitiveness of manufacturing in the V4 in the coming years. Their relatively significant (both backward and forward) participation in global value chains, and the substantial contribution of their manufacturing sectors to GDP and employment, determines the need for systemic solutions.

To address this challenge, the article identified barriers to I4.0 implementation, and their analysis clearly points to the need for economic policy instruments to stimulate structural adjustments to improve the I4.0 readiness of the V4 economies. Priority areas include research and development infrastructure, the use of ICT, and human capital. The diffusion and proper implementation of I4.0 technologies are key to the further development and growth of manufacturing in the V4 economies.

An important added value of the research is the proposal of a set of determinants of I4.0 readiness in manufacturing. The index can be a useful research tool to analyse and compare other economies in this area.

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Determinanty gotowości przetwórstwa przemysłowego gospodarek V4 do wdrożenia Przemysłu 4.0

W artykule zaprezentowano wyniki badania, którego celem była identyfikacja czynników warunkujących poziom gotowości na wdrożenie Przemysłu 4.0 w obszarze przetwórstwa przemysłowego oraz ocena postępów gospodarek Grupy Wyszehradzkiej (V4) w tym zakresie w latach 2011–2021. W opracowaniu przedstawiono autorską propozycję dwunastu zmiennych, stanowiących podstawę badania przeprowadzonego metodą analizy głównych składowych (*Principal Component Analysis* – PCA). W efekcie badania na podstawie wartości ładunków czynnikowych opracowano syntetyczny wskaźnik gotowości na wdrożenie Przemysłu 4.0. Następnie oceniono pozycję gospodarek V4 na tle pozostałych krajów UE. Gospodarki krajów V4 prezentowały w badanym okresie relatywnie niski poziom gotowości na wdrożenie Przemysłu 4.0 i nie dokonały znaczącej poprawy swoich wyników w okresie poddanym analizie. Najwyższą pozycję osiągnęły Czechy, które w latach 2011–2021 plasowały się średnio na 12. miejscu. Tuż za Czechami znalazły się Węgry – średnio na 14. pozycji i Słowacja, której przypadło średnio 17. miejsce. Na najbardziej odległej pozycji znalazła się Polska, która była na 20. miejscu spośród wszystkich gospodarek UE.

Słowa kluczowe: Przemysł 4.0, gotowość na Przemysł 4.0, transformacja Przemysłu 4.0, przetwórstwo przemysłowe, Grupa Wyszehradzka