DOI: 10.17747/2618-947X-2024-1-30-45
UDC 338.45
JEL L52, L60, O14, O25

Conceptual aspects of constructing and interpreting of digital transformation indices for manufacturing enterprises

S.V. Ilkevich[1]

[1] Financial University under the Government of the Russian Federation (Moscow, Russia)

Abstract

The article focuses on the problem of designing, constructing, measuring and interpreting indices for assessing the digital transformation of manufacturing companies. We analyse the compositional features, advantages and limitations of the three indices, which are a fairly focused on comparing industrial sectors (or at least extended groups of industries) according to their level of digital transformation or digital maturity: Industrial Digitalisation Index MGI McKinsey, Smart Industry Readiness Index (SIRI) of the World Economic Forum, Digitalisation Index for Economy and Social Sectors by the Higher School of Economics. The main thesis of the article is the need to develop a unified, continuous and relevant index of digital transformation for manufacturing companies, taking into account all the positive experiences in the conceptual and methodological development of digitalisation assessment indices that research and analysis teams have managed to develop so far. At the same time, the author points out the need to avoid retrospective construction of indices based on lagging statistical data. It seems very important to take into account the need to introduce a strategic vector when measuring the level of digital transformation of manufacturing companies. It is not enough to simply aggregate indicators of digital adoption and identify certain indices or sub-indices as the main markers of digital transformation. From a statistical point of view, such an approach can be perfectly correct, reliable, and verifiable.Questions arise about the productive potential of clustered technologies in the context of evolving business models, particularly in manufacturing. As a part of constructing any indices and methods for assessing the dynamics of digital maturity, digitalisation, digital transformation, it is better to face the inevitable uncertainty about the potential of some frontier technologies in an attempt to foresee the intersections of technological factors and future niches for business models, than to try to generalise the trajectory already traversed with a more retrospective logic based only on the verified and more tested parts and layers of the technologies. With this approach, digital transformation indices for manufacturing companies take on projective and instrumental functions, as they serve, in a sense, as a roadmap. They make it possible to improve the strategic vision of companies in different sectors, as well as their stakeholders, associations and public authorities (especially those in charge of digitalisation and industrial policy), with a view to achieving later stages of digital maturity.

Keywords: manufacturing companies, manufacturing enterprises, manufacturing, industry, digital transformation, digital transformation indices, digital maturity, digital technologies.

For citation:

Ilkevich S.V. (2024). Conceptual aspects of constructing and interpreting of digital transformation indices for manufacturing enterprises. *Strategic Decisions and Risk Management,* 15(1): 30-45. DOI: 10.17747/2618-947X-2024-1-30-45. (In Russ.)

Acknowledgment

The article was prepared on the bases of the results of research carried out at the expense of budgetary funds within the framework of the state mission of Financial University.

工业企业数字化转型指数构建和解释的概念性方面

S.V. Ilkevich[1]

[1] 俄罗斯联邦政府财政金融大学 (俄罗斯，莫斯科)

简介

本文的重点是工业企业数字化转型评估指数的形成、构建、测量和动态跟踪问题。 本文分析了三个指数的组合特征、优势和局限性，这些指数在工业数字化转型或数字成熟度水平的行业比较（至少是大类行业）方面具有相当好的聚焦度，并且已经编制了至少几年时间：麦肯锡全球研究院的《工业数字化指数》、世界经济论坛的《智慧产业准备指数》、和高等经济学院的《经济和社会领域行业数字化指数》。 本文的主要论点是有必要开发一个统一的、连续的且与俄罗斯实践相关的工业企业数字化转型指数，同时借鉴国际和俄罗斯项目中研究分析团队在数字化评估指数的概念和方法开发方面积累的所有积极经验。同时，作者指出，应避免基于滞后的统计数据进行回顾性指数构建和仅关注已成熟的数字技术。非常重要的是在测量工业企业数字化转型水平的方法中纳入战略性方向。 简单地将数字技术应用指标进行粗略分组并称之为某些指数或子指数作为数字化转型的主要标志是不够的。从统计学的角度来看，这种方法可能是完全正确、可靠且可验证的。然而，这引发了一个关于在商业模式演变，特别是在工业领域背景下，分组技术的生产潜力的问题。在构建任何数字成熟度、数字化和数字化转型的指数和评估方法时，最好面对某些前沿技术潜力中不可避免的不确定性，尝试预测技术因素与未来商业模式新领域的交汇。采用这种方法，工业企业的数字化转型指数获得了前瞻性和工具性功能，因为它们在某种意义上成为了路线图。这些指数有助于提升各行业和工业部门公司及其利益相关者、协会、政府机构（尤其是负责数字化和工业政策的机构）在实现更高阶段数字成熟度方面的战略视野。

关键词： 工业公司、工业企业、工业、数字化转型、数字化转型指数、数字化成熟度、数字化技术。

引用文本：

Ilkevich S.V. (2024) 。工业企业数字化转型指数构建和解释的概念性方面。战略决策和风险管理, 15(1): 30–45。 DOI: 10.17747/2618-947X-2024-1-30-45。 (俄文)

致谢

该论文是使用财政大学政府任务拨款资助的研究结果编写的。

1. Why do we need industry and sector digital transformation indices?

In the current circumstances and parameters of the development of Russian industrial enterprises, taking into account the specifics of their innovative activities, industrial policy trends and external constraints, the problem of constructing, monitoring and interpreting the dynamics of indices for assessing the digital transformation of industrial enterprises is of particular conceptual and practical interest. This issue has become particularly important in recent years because it is increasingly linked to a whole range of other issues in the field of industrial digitalisation and the consideration of digitalisation as a tool for increasing production efficiency, among which the following six aspects can be highlighted:

- accelerating the pace of digital transformation, making it more continuous and comprehensive in later stages;
- increasing the level and stability of demand for digital technologies from many industry sectors;расширение государственных программ и проектов поддержки цифровой трансформации;
- accelerating the pace of implementation of artificial intelligence in various industries, especially in recent years;
- intensifying the transition of Russian industrial enterprises to home-grown software; developing models, methodologies and techniques to measure the impact of the level of digital transformation on increasing the productivity of industrial enterprises.

Technological development in a broad sense represents not only a conglomerate of aspects related to progress along the technological trajectory itself, but also a number of aspects of interaction with categories such as ‘industry life cycle’, ‘product life cycle’ and ‘technology life cycle’ [Taylor, Taylor, 2012]. Technological growth is defined as the accumulation of new ideas or methods developed by firms and scaled up across industries to create economic value [Priestley et al., 2020]. Industrial companies that have begun to digitise their business processes and digitally reinvent their business models are now moving to the next level of integration of their digital processes: the digital integration of plants and factories, which helps them to better use data to gain new insights and facilitate real-time decision making. Such significant progress in digitisation within a decade makes it very difficult to assess its effectiveness and to determine the optimal and timely phasing. In addition, the development of recommendations based on maturity models will in many cases have a lagging effect, both for individual industrial companies and at the level of industries, sub-industries and sectors. This is particularly relevant when

the methods and methodologies of digitisation models are themselves characterised by a high degree of retrospectivity, in the desire to ensure the greatest validity and verifiability of technological solutions, since attempts to anticipate the future technological landscape are associated with greater uncertainty as to which junctions of technologies and business processes will be the most productive and promising in terms of competitive positioning [Bota-Avram, 2023], as well as in terms of the formation of innovative business models [Acciarini et al., 2022]. Also of great importance is the combination of factors that contribute to the development of digital technologies in specific industry contexts, taking into account non-technological, organisational factors [Titov et al., 20-23].

A separate area of the digital transformation of industrial companies is the creation of competitive advantages by expanding their presence on digital platforms. Research shows that building uncopyable competitive advantage through partner relationships has subtle dynamics and consequences. In addition to the positive network effects of digital platforms, industrial firms face negative network effects - both direct (various types of platform failures and congestion) and cross-cutting, indirect (reduced profitability due to the redistribution of market power and bargaining power in favour of the platform), as well as component-based network effects [Trachuk, Linder, 2023]. It is therefore difficult to say whether a high degree of integration of industrial companies in a specific industry, sectoral context, is an indicator of digital maturity. Technologically, it may seem so, but from the point of view of sustainability (and even long-term innovation) of the business model, such digitalisation may lead to lower efficiency and effectiveness of the strategy and model of an industrial enterprise.

Nevertheless, approaches and methods for determining the dynamics of aggregated states of technological development (technological development indices, digitalisation indices or digital transformation indices) can become an important source of information for timely management decisions at all levels: both by the management of individual industrial enterprises and at the regional and sectoral levels, in the context of a more accurate determination of the parameters of industrial policy and digitalisation, the dissemination of best practices to increase labour productivity, as well as for macroeconomic forecasting and the stimulation of innovative structural restructuring of the economy.

Indices for assessing the digital transformation (or digitalisation) of industrial enterprises, like any other, are intended to act as a kind of marker and tool for comparing the degree and/or stages of digital maturity of industrial enterprises in the context of individual industries/sub-industries/sectors, as well as individual digital technologies and/or complexes of digital technologies (also known as end-to-end complexes of digital technologies). The availability of sufficiently accurate and representative digital transformation indices can stimulate the interaction of all stakeholders and investment activities in the development and implementation of industrial business strategies. Here we can also speak about the feasibility of a product approach (or product aspect) in understanding the stages of digital technology development, where all stakeholders in the technological development of an industrial enterprise set the goal of achieving a complete and seamless integration of end-to-end technologies, from the shop floor to enterprise management, based on a holistic architecture that supports the management of the entire product life cycle [Ferreira et al., 2021]. This paradigm is not only applicable to individual companies, but also to the digital transformation of homogeneous companies within sectors, industries and sub-industries.

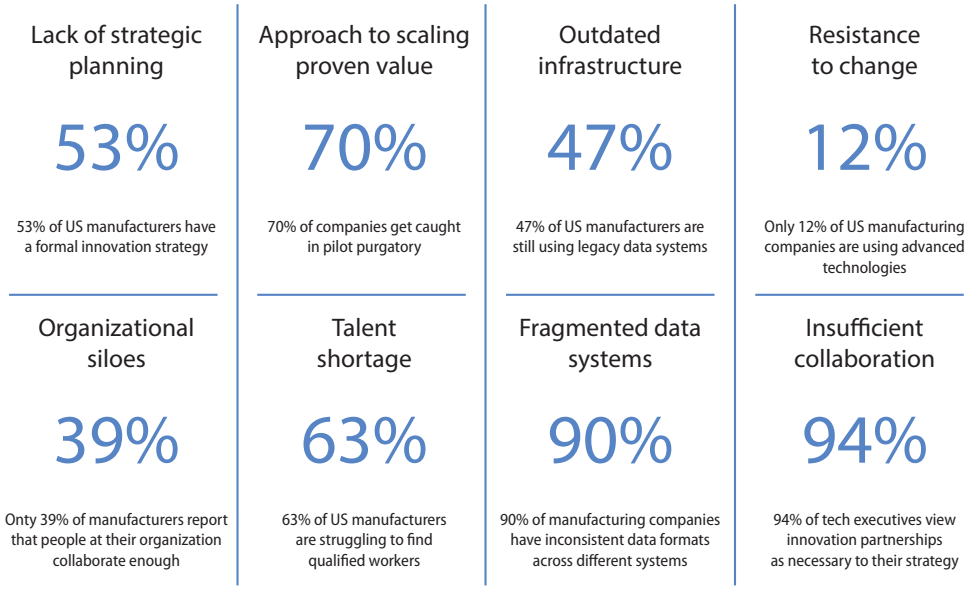
However, it seems particularly important to understand the reliability, accuracy, relevance, information content and completeness of the toolkit of indices for assessing the digital transformation of industrial enterprises, as well as to identify problems and possible directions and approaches for improving such indices. It should be emphasised that the very existence of a set of indices for assessing digital transformation, which to one degree or another (directly or indirectly) are relevant for industrial enterprises, is already a significant conceptual and methodological achievement in international and Russian practice of assessing digital maturity at the level of individual industries/sub-industries/sectors, and not only at the level of individual enterprises.

However, because of the imprecision and incompleteness of the instruments, the adaptation of many parameters to a certain standard methodology, and the simplified interpretation of indices by companies, their stakeholders, analysts and government agencies, the problem of distorted perception becomes relevant. To be convinced of this, it is enough to look at how news about the publication of certain indices, ratings and rankings is integrated into the general media field. The media, including business publications, simply reproduce them without any analysis of the basis of the components and their relevance, and even many academic publications cite the ratings as some kind of self-evident proof of the state of affairs, without bothering to note the limitations of the methods. What ends up happening is a kind of halo effect, whereby the research and professional community, relying on the overall research reputation of an institution, then uncritically passes on the assessments of an index. The point here is not so much that research groups might have chosen non-ideal ratios of parameters for scoring on certain scales, or that the methodology might have simplified interpretations or fitted some indicators into a single format.

The central issue is to find errors or inaccuracies (this is a natural part of the work of a healthy research community) and to supplement, clarify, modify and, above all, concretise the methods, also in the context of individual industries. This is also necessary for a more accurate measurement of the dynamics of indices of more finely structured industries within a large industry group (e.g. manufacturing). This will certainly require a somewhat different composition of private indicators than a more abstract comparison of all major sectors of the economy.

When we speak about the dynamics of indices for assessing the digital transformation (or digitalisation) of in-

Fig. 1. Barriers to digital transformation for 14 groups of manufacturing industries, SIRI



Sourse: [Unleashing business model.., 2023].

dustrial enterprises, we cannot fail to mention the particular importance of the problem of comparing the intertemporal values of the indices and the timely clarification and updating of the calculation base. In this context, it is important to understand that some components of digital technologies may remain relevant for a long time as essential elements for assessing digital maturity and digital transformation, while others quickly lose their informative value as a basis for comparing the stages and trajectories of digital restructuring of business processes and business models.

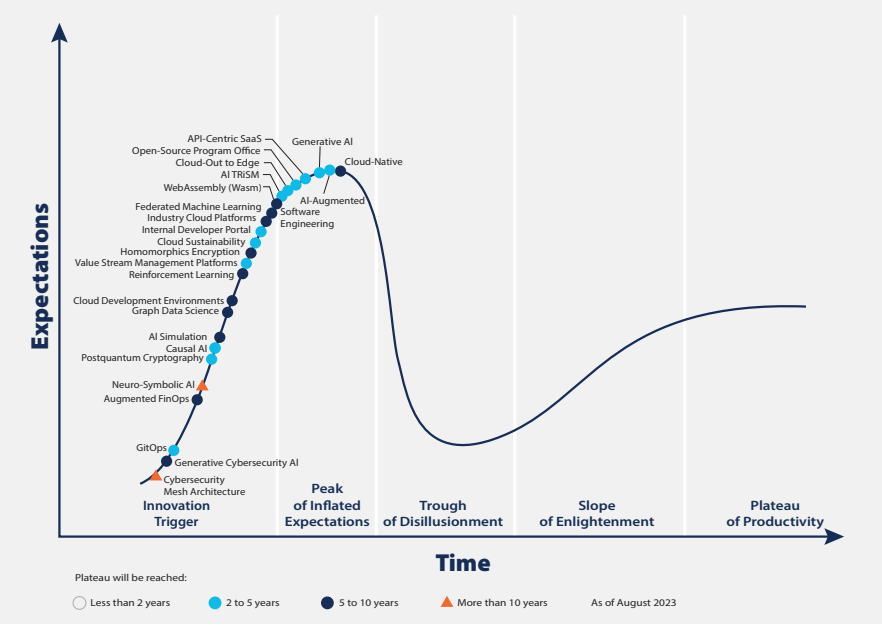
When a given digital transformation assessment index begins to include a significant proportion of rather mundane and outdated metrics and markers of digital maturity, this becomes a significant problem, both in terms of measurement and concept. Solving this problem is by no means trivial, as it involves simultaneously assessing technological novelty, practical feasibility and scalability, as well as the potential for integrating digital technologies into business processes and their overall significance in the context of transforming business models. This is a conglomerate of frontier issues on which even expert communities can be wrong. Otherwise, by definition, there would be no disruptor companies that break through industries, since dominant companies in industrial and non-industrial sectors would have seen the entire promising technological landscape in advance and directed their resources there. Numerous examples show that both the boards of the most powerful high-tech companies and leading analytical and research institutions can predict the most promising intersections of technologies and business models with very different degrees of success, leaving enough room for new companies and innovative business models.

To illustrate the difficulties of the transition to the productive integration of technologies as a factor of innovation in the business models of industrial enterprises, we can cite a recent study by the World Economic Forum, which identified certain barriers to the implementation of innovative models in US industry (Fig. 1).

The problem of constructing and monitoring the dynamics of indices for assessing the digital transformation of industrial enterprises must be seen as a more general consideration of the technological prospects of the economy and society as a whole, in the context of managing the change of generations of technologies in order to maximise the benefits that society receives from the introduction, deployment and use of a given technological paradigm. A separate important question is how the key and determining factors in the selection and use of technologies and their complexes interact over time [Kim, 2003]. If this is not done, the digital transformation assessment indices themselves will face the ‘garbage in - garbage out’ (GIGO) problem, well known in the field of digitisation and general computer science. The GIGO principle means that incorrect input data will produce incorrect results, even if the algorithm itself is correct. When constructing digital transformation assessment indices, it is important to navigate between Scylla and Charybdis. On the one hand, it is important to promptly remove outdated technological components that are no longer representative as markers and parameters for characterising the quality of the digital transformation shift. This in itself makes it difficult to correctly compare the dynamics of the digitisation indices over longer periods (3-5 years). On the other hand, when including frontier technologies, it is important to avoid speculative reasoning and excessive ‘techno-optimism’ and excitement, as ‘digitalisation’ does not always lead to a clear increase in the productivity and efficiency of industrial enterprises.

Research shows that the relationship between technology investment, innovation outcomes and productivity growth is non-linear and shows a stable positive relationship only after

Fig. 2. Gartner hype cycle for emerging technologies



Source: https://www.gartner.com/en/articles/what-s-new-in-the-2023-gartner-hype-cycle-for-emerging-technologies.

a certain critical mass of investment is reached and the functionality of product solutions is ensured [Trachuk, Linder, 2020]. Цифровая трансформация может значительно повысить общую факторную производительность, но снизить производительность промышленных предприятий за счет увеличения уровня операционных затрат, снижения общего оборота активов и увеличения управленческих расходов [Guo et al., 2023]. From this point of view, the effectiveness of innovative activities of industrial enterprises can be negatively affected by excessive initial excitement. It is unrealistic to deny the influence of hype, manipulation and, in general, narratives on the fundamental development of companies actively implementing technologies within the framework of the emerging paradigm and financial and investment mechanisms of the effective interpreter model [Ilkevich, 2022].

To normally assess the degree of hype, the Gartner Hype Cycle model is used, which tracks the evolution of technological innovations as they go through successive stages expressed in the peak, disappointment and recovery of expectations of a technology or set of technologies [Dedehayir, Steinert, 2016]. Identifying potentially disruptive technologies allows us to predict the technological landscape and effectively allocate resources and funding for research and development [Chen, Han, 2019]. The Gartner Hype Cycle 2023 is shown in Figure 2.

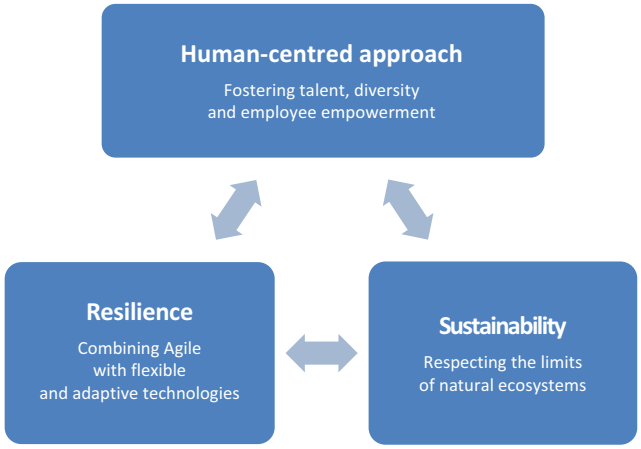
Because the hype cycle is a snapshot forecast that is taken only once a year, it provides no guidance to stakeholders on the most appropriate time to invest in and support technology initiatives [Kondo et al., 2022]. At the same time, it has been shown that some technologies can become sufficiently mature without going through a phase of significant decline in expectations [Kregel et al., 2021]. One explanation for such significant variability in the Gartner cycle in practice is the particular convergence potential of digital technologies. According to S.D. Bodrunov, highly convergent technologies include elements of digital technologies in their contours and thus stimulate digital transformation in various industries within a system with positive feedback, which by definition becomes very attractive for investors, including those with a high risk appetite [Bodrunov, 2018].

Another theoretical and methodological omission in the construction, analysis of the dynamics and interpretation of indices for assessing the digital transformation of industrial enterprises may be the neglect of the importance of the human factor and aspects of technological-human complementarity. Researchers have proposed the concept of ‘Design for the Human Factor in Industry 4.0’ (DfHFinI4.0), based on ensuring the affective-cognitive integration of the human factor in technological progress [Suarez-Fernandez de Miranda et al., 2020].

The DfHFinI4.0 concept is well aligned with the original vision of Industry 5.0 presented in 2020-2021: Industry 4.0 is technology-focused, while Industry 5.0 is value-focused [Xu et al., 2021]. Industry 5.0 is understood as recognising the potential of industry to achieve social goals beyond jobs and growth, as a sustainable source of prosperity with an understanding of the ecological limits of our planet and the well-being of workers (Figure 3).

As part of the core value emphasis of Industry 5.0, industrial workers must continue to upskill and reskill to improve career opportunities and work-life balance. In the advanced economies of the world, despite the general progressive transformation trend in industry, including an increase in entrepreneurial potential due to the formation of new niches [Nambisan et al., 2019], there has been a general deteriora-

Fig. 3. Core values of the Industry 5.0 concept



Source: [Xu et al., 2021].

tion in socio-economic well-being over the past two decades, both at the local community and national levels. Digital technologies have so far done little to address growing problems such as long-term stagnation of real wages, precarious employment, slow productivity growth of the average worker in the economy in a number of OECD countries, worsening social inequality, a significant erosion of the middle class, territorial deprivation and declining housing affordability (measured as average annual income on a typical property) even in countries with nominally very high levels of economic development. Between 2005 and 2019, for example, annual productivity growth in the United States averaged just 1.4%, despite incredible advances in digital technology that put supercomputers at the fingertips of every worker and consumer. Meanwhile, real incomes grew at a slower rate of 0.7%. Labour productivity growth has also declined in most OECD countries since 2005. Investment of all kinds has slowed despite record low interest rates and rising corporate profitability and foreign investment [Atkins et al., 20-23]. All this constitutes a major socio-economic and technological paradox: how a society that can be considered increasingly innovative turns out to be less and less productive (at least in terms of growth rates) and socially prosperous (according to a number of metrics - even in absolute terms); how the acceleration of innovation processes can be combined with a stagnation of social well-being and a slowdown of economic growth [Gordon, 2018]. There are two logical answers. Either digital technologies do not generate the measured productivity gains, or they lead directly or indirectly to some 'leakage' of wealth. Although it must be acknowledged that the stagnation of economic growth is a systemic problem to which many third factors contribute, it is probably not quite the right way to put the question to expect digital technologies to solve all the problems.

Of great importance for interpreting the socio-economic consequences of the digital transformation of industrial enterprises is a conglomerate of problems centred on the question of how quickly and to what extent new technologies will be able to create highly skilled jobs to adequately compensate for the rapidly outdated and disappearing professions from the economy [Grenčíková et al., 2020; Anackovski et al., 2021].

Taking into account the aspects identified, it seems appropriate to include, within the framework of indices for assessing the digital transformation of industrial companies, those metrics and parameters that are responsible for measuring or assessing the broader social context. And not only at the level of ESG factors (without diminishing the importance of this paradigm), but also at the level of the integrative paradigm of technological change within the framework of general socio-economic strategies at the level of society and individual communities. An integrative paradigm of technological development, taking into account the extended social context and the long-term orientation of all stakeholders, seems to be applicable both to the assessment of the life cycle of technologies [Ilkevich, 2023] and to the ranking (evaluation of indices) of the digital transformation of industrial enterprises.

2. Composition and dynamics of the main indices for assessing the digital transformation of industry

Measuring the level of development of the digital economy has become an important research topic over the last decade. A number of fairly well-known and relatively reputable international and all-Russian indices, rankings and ratings of the development of information and communication technologies, digital society, global digital competitiveness, digital development, as well as innovation with a large weight in the indicators of digital components have appeared [Gorbachev et al., 2019]. In terms of composite components, the clear majority of them have rather limited relevance for assessing the digital transformation of industrial companies. Some indices primarily reflect the level of development of countries' scientific research capabilities, the level of development of information and communication technologies, and cybersecurity. Other indices focus on taking into account aspects of the socio-economic integration of digitalisation, which is good in itself, but there is a disconnect from the tasks of assessing productivity, efficiency and effectiveness in the context of building an innovative and competitive business in industry and other sectors of the economy. As a result, neither index from the two designated groups focuses to any significant extent on business opportunities in terms of restructuring business processes and building new business models, let alone making comparisons of digital maturity or digital transformation specifically for these attributes in the context of individual sectors of the economy - agriculture, commerce, industry.

Even when determining the level of digitisation by country or city, many indices do not fully disclose the details of the methodology used, suggesting that, at least for certain parameters, comparisons may be oversimplified and ignore the specificities of individual countries, cities, regions or large groups of industries to fit the methodology.

The central problem in the area of the dynamics of indices for assessing the digital transformation (digitalisation) of industrial enterprises is that there are not many indices as such (i.e. annual or other frequency of measured indicators). This is despite the fact that by the end of the 2010s various methods of measuring the degree, level and maturity of digitalisation had become quite widespread, including those methods, approaches and even literally named 'indices' (but not calculated with any frequency or on any sample of enterprises) proposed by academic institutions, international organisations and leading consulting companies [Gileva, 2019].

Nevertheless, several indices still have a fairly good focus on comparing industries (at least large groups of industries) by their level of digital transformation or digital maturity, taking into account their specificities, and have been compiled for at least several years. Unfortunately, however, the publication of a number of indices has been discontinued, despite a whole series of conceptual and methodological developments of considerable value. For example, the McKinsey Global Institute has been developing and publishing the MGI McKinsey Industrial Digitalisation Index for several years. In the Russian context, the HSE Digitalisation Index of Economic and Social Sectors as an aggregated assessment of the level of digital technology penetration in large economic sectors was proposed by the HSE Institute for Statistical Studies and Economics of Knowledge in 2022, but comparisons within the framework of the completed HSE project were carried out for 2020 and 2021 and have not yet been continued.

Among other relevant indices, the World Economic Forum's Industry 4.0 Maturity Index and Smart Industry Readiness Index are also of conceptual and methodological interest.

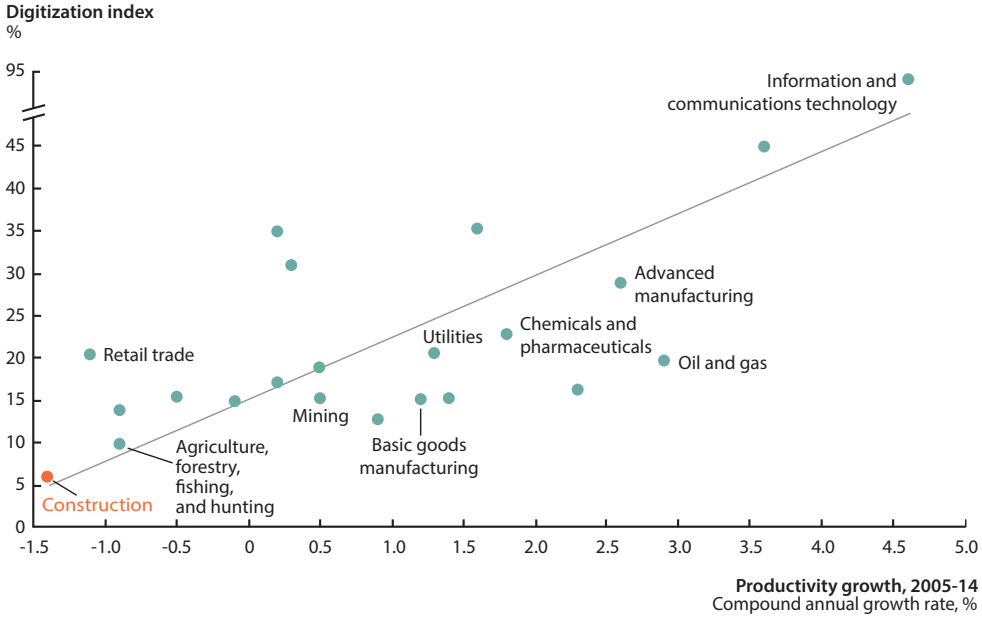
Next, we will consider the conceptual and methodological approaches of the mentioned indices, as well as what each of them brings to the multi-aspect picture of the assessment of digital transformation related to industrial enterprises, and how this entire accumulated conceptual and methodological arsenal can be used in the future if the stakeholders of the digital transformation processes of the Russian industry intend to develop the direction of indicators and indices for assessing its level.

Industrial Digitalisation Index MGI

Figure 4 shows the correlation between the Industrial Digitalisation Index (MGI) and productivity growth in different sectors of the US economy, including industries such as basic materials, chemicals and pharmaceuticals, mining, oil and gas separately, and advanced manufacturing.

Of particular interest are basic industries and advanced manufacturing. The position of these two large groups of industries in the coordinates of the relationship between digitalisation and productivity growth is quite expected. Perhaps the fact that both large groups are below the trend line can be taken as an indication that the benefits of digitisation in 2005-2015 have been used quite effectively. Unfortunately, there are no more recent comparable data for the period since 2016, as the Industrial Digitalisation Index MGI has not been published since 2015This is particularly unfortunate given that the conceptual and computational basis of the index was probably the most balanced of all available and also highly relevant for assessing the digitalisation potential of industrial sectors. It can be assumed that the further progress of the industrial sectors in increasing the level of digitalisation since 2015 has been translated into comparable rates of productivity growth, since around this time the scaling of entire complexes of end-to-end industrial tech-

Fig. 4. The relationship between the Industrial Digitalisation Index MGI and productivity growth in different sectors of the US economy



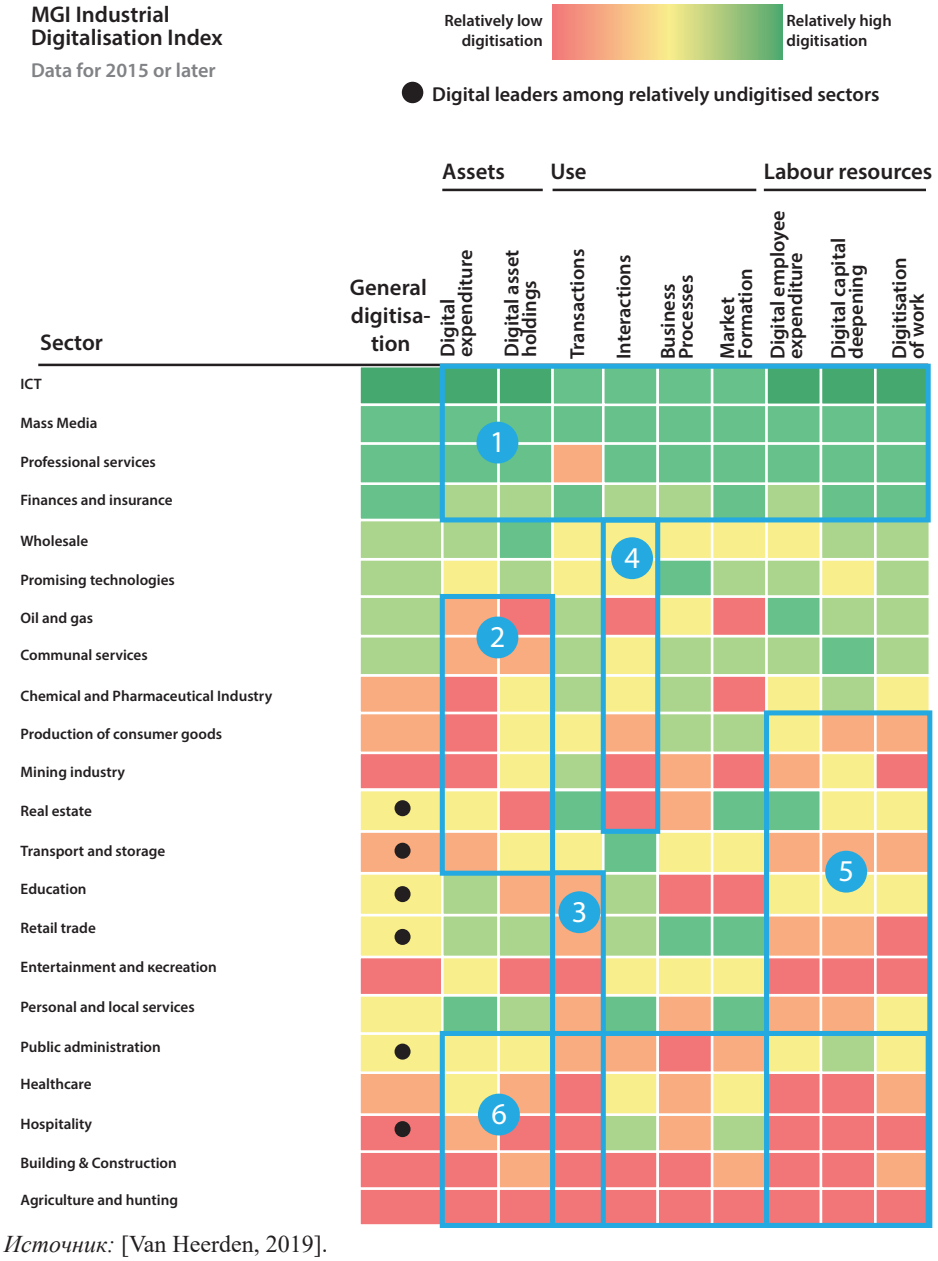
Source: [Bonini et al., 2019].

nologies was fully deployed in many industrial sectors and subsectors.

Figure 5 shows the composition of the Industrial Digitalisation Index MGI and the colour coding of the digitalisation parameters for US industries. A study by the McKinsey Global Institute (MGI) aimed to diagnose the state of digitalisation in US economic sectors and found large and growing gaps between sectors and between companies within those sectors. The metrics of the Industrial Digitalisation Index MGI were grouped into three broad categories: digital assets, digital usage and digital workforce. The latter two categories were critical.

Digital assets across the economy have grown dramatically in recent years as companies have invested not only in IT but also in digitising their physical assets. Leading industries continue to have a huge advantage in the use of digital technologies in the form of transactions, interactions with customers and suppliers, and in internal business processes. The biggest difference is in the presence of a digitally literate workforce. Over the past two decades, the leading sectors of the economy have seen an eightfold increase in their performance on various digital labour metrics, such as the share of tasks involving digital tools and the number of new digital jobs, while the rest of the economy has remained virtually idle [Van Heerden, 2019]. Is it any wonder that labour productivity in construction has stagnated over the past two decades, while it has almost doubled in manufacturing?

Fig. 5. Composition of the Industrial Digitalisation Index MGI and colour coding according to digitalisation parameters for sectors of the US economy



Источник: [Van Heerden, 2019].

Figure 6 shows a visualisation of the level of digitalisation of industries in Europe using the MGI Industrial Digitalisation Index methodology (compiled in 2016).

Figure 7 shows the methodology and metrics of the Industrial Digitalisation Index MGI.

World Economic Forum's Smart Industry Readiness Index (SIRI)

The Global Smart Industry Readiness Index (SIRI), developed as a global initiative by experts at the World Economic Forum [Global smart industry..., 2021], includes a set of frameworks and tools to help manufacturers - regardless of size or industry - start, scale and sustain their manufacturing transformation journey. As a global indicator of Industry 4.0 transformation maturity, SIRI helps to raise awareness and set goals that organisations can strive to achieve. The index also provides manufacturers with a structured basis for benchmarking against their peers, identifying their strengths and weaknesses to better prioritise development efforts and resources, and tracking their progress towards digital transformation. The SIRI Smart Industry Readiness Index is shown in Figure 8.

In addition to the compositional elements of the Smart Industry Readiness Index, experts from the World Economic Forum proposed industry archetypes of digital transformation for 14 groups of industries. The archetypes were identified using the mapping method within a plane with two axes -

digital maturity and digital variability (Figure 9).

Regarding the assessment of the dynamics of individual digital transformation archetypes, the World Economic Forum expert group provided only selective ordinal data, ranking the five most mature industries for 2019 and 2022 without specifying numerical values (Figure 10).

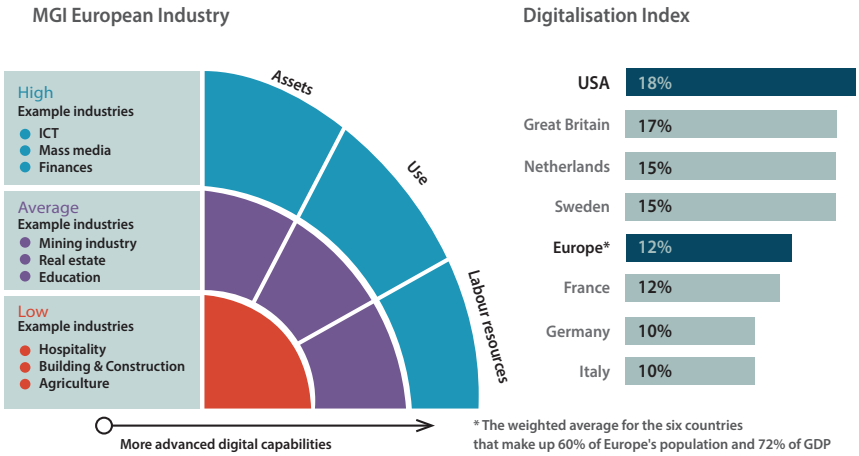
HSE index of the digitalisation of economic and social sectors

Figure 11 shows the dynamics of the integral index and sub-indices of the HSE index of the digitalisation of economic sectors and the social sphere.

Figure 12 shows the value of the HSE Digitalisation Index of Economic and Social Sectors by industry for 2021.

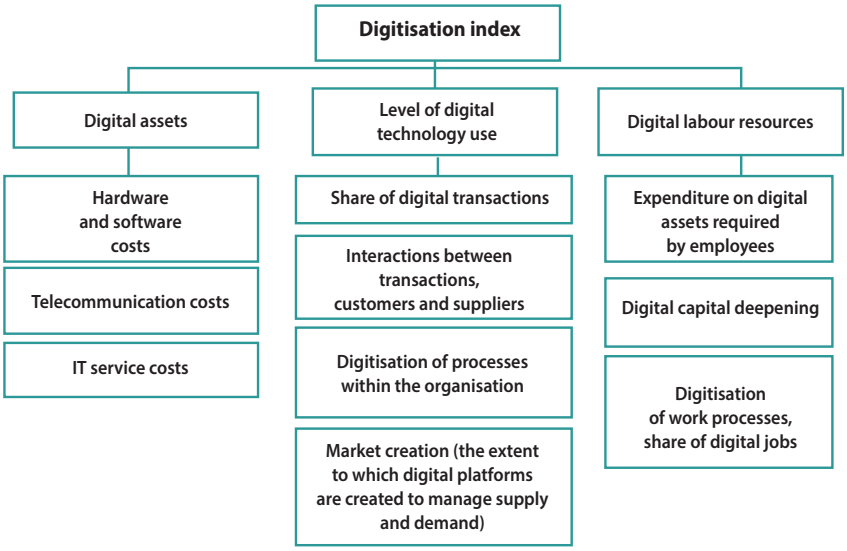
As the authors of the material prepared by the Institute for Statistical Studies and Economics of Knowledge of the National Research University Higher School of Economics note, 'the manufacturing industry is characterised by high activity in the use of specialised software for design/modeling (28.9%), systems for managing automated production and/or individual technical processes (22.2%), industrial robots/automated lines (19%) and digital twin technology (3.8%). At the same time, industrial organisations have a low level of digital skills of employees (10th place in the corresponding subindex) and costs for the implementation and use of digital technologies (they are among the bottom five industries in terms of the subindex value)' [Vasilkovsky et al., 2022].

Fig. 6. MGI European Industry Digitalisation Index



Note. The MGI Industrial Digitalisation Index includes 20 indicators to measure digital assets, digital technology usage and digital workers in each industry.
Source: [Kobzev et al., 2022].

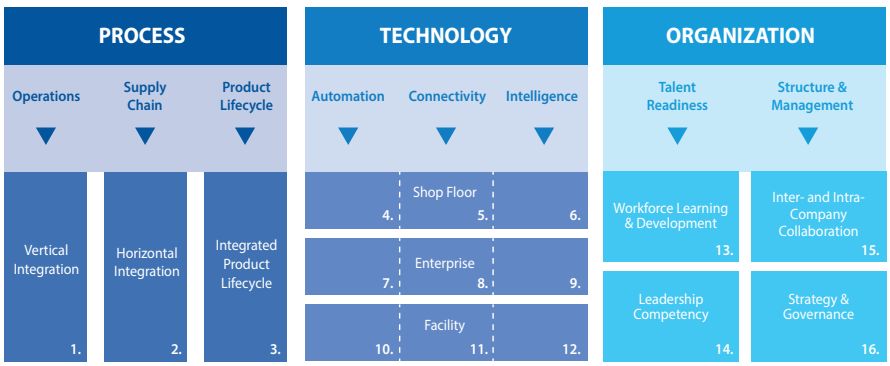
Fig. 7. Methodology and metrics of the Industrial Digitalisation Index MGI



Source: [Pechatkin, Vildanova, 2021].

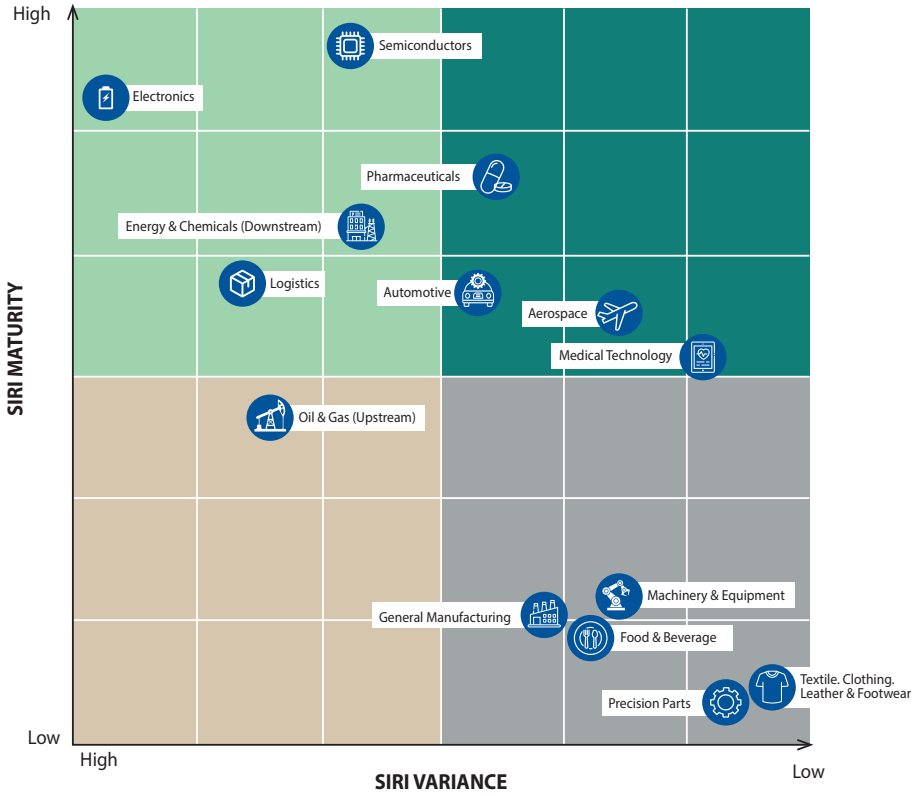
It is regrettable that the publication of the HSE Index for 2022 and 2023 has not been continued, at least for the time being. This large and productive layer of developments, maintained in a single economic and statistical logic, is extremely important for Russian researchers of the digital economy and digital transformation. Apparently, the lack of publication of the index for 2022 and 2023 is due to the fact that this very significant result, both conceptually and methodologically, in terms of the composition and dynamics of the index for 2020 and 2021, was achieved by researchers as part of the implementation of the project 'Examination of strategies for digital transformation of economic sectors and the social sphere,

Fig. 8. SIRI Smart Industry Readiness Index



Source: [The Global smart industry.., 2022].

Fig. 9. Digital transformation archetypes for 14 industry groups, SIRI



Source: [The Global smart industry.., 2022].

including taking into account the best practices of foreign countries, and the development of proposals for their revision (2022)', which was completed in 2022.

At least at the time of the development of the Index of Digitalisation of Economic Sectors and the Social Sphere, it was a comprehensive methodology for assessing digital transformation, relevant to large groups of industries and characterised by a broad coverage of specific digitalisation indicators representative of each of the five sub-indices. The specific weights of the sub-indices also appear to have been chosen in a way that is appropriate and reflects socio-technological changes. The structure of the HSE Index of Digitalisation of Economic Sectors and Social Sphere is shown in the table.

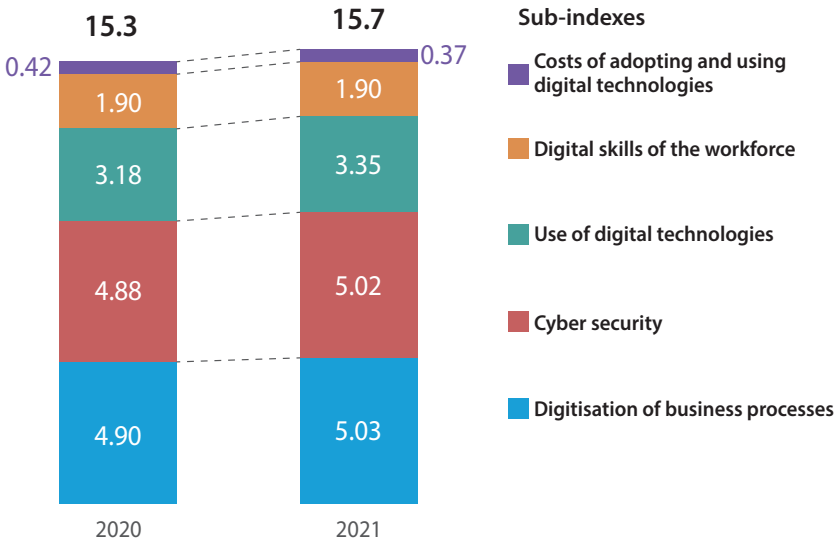
Of course, any methodology has its limitations, assumptions and simplifications. In order to realise the possibilities of a broad cross-sectoral comparison and to bring the sub-index indicators into a comparable form, the HSE methodology, as can be seen in Table 1, uses indicators calculated from the specific weight of organisations using a particular digital tool or technology when calculating the first, second and fifth sub-indices. It is clear that this indica-

Fig. 10. Five industries with the highest levels of digital maturity in 2019 and 2022, SIRI

Rankings		
Ranking	**2019**	**2022**
1	*Semiconductors*	*Semiconductors*
2	*Pharmaceuticals*	*Electronics*
3	*Electronics*	*Pharmaceuticals*
4	*Energy & Chemicals (Downstream)*	*Energy & Chemicals (Downstream)*
5	*Medical Technology*	*Logistics*

Source: [The Global smart industry.., 2022].

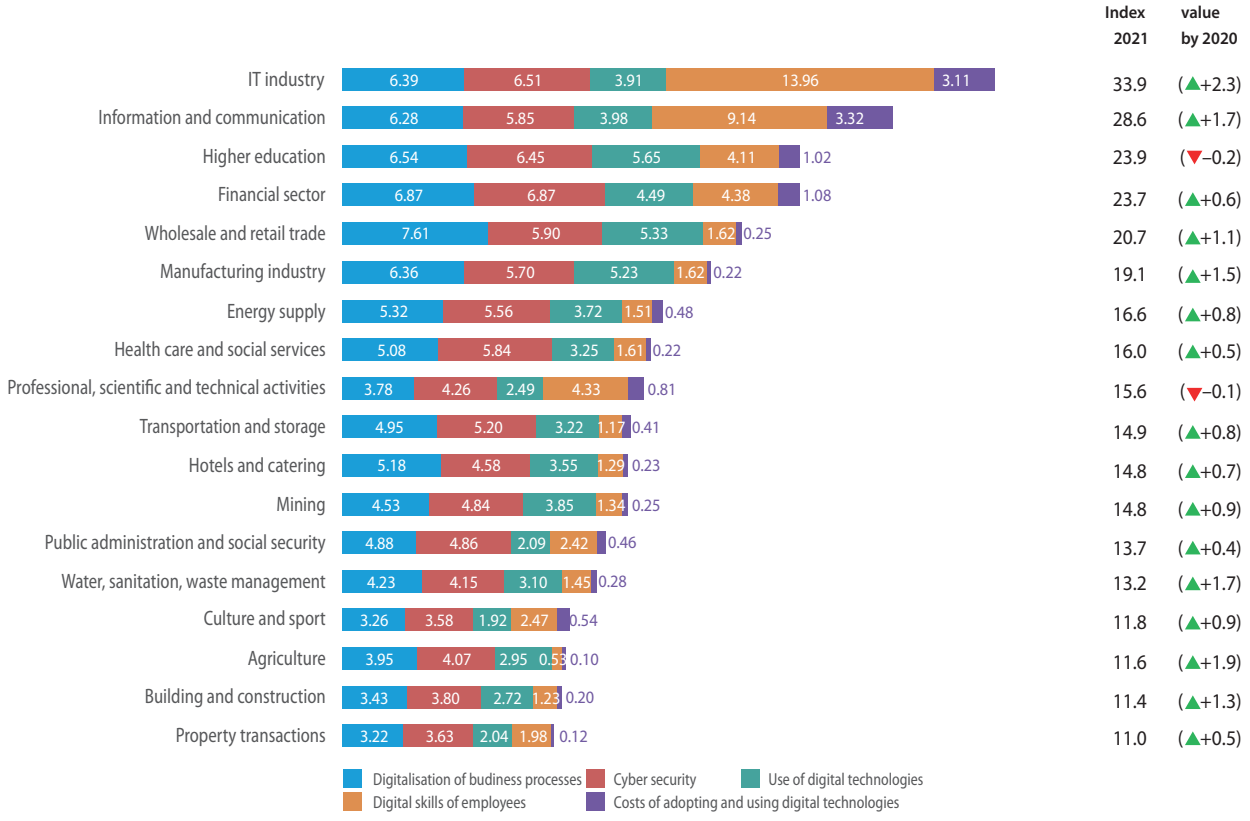
Fig. 11. Index of the digitalisation of the economicand social sphere by the Higher School of Economics



Source: [Vasilkovsky et al., 2022].

tor is very sensitive to the degree of industry consolidation. For example, if agriculture is dominated by small and medium-sized enterprises, this will lead to a decline in many indicators, even if more than half of the industry's output is provided by large enterprises that have adopted digital tools and technologies. At the same time, the use of correction factors reflecting market concentration and the dispersion of gross value added in the industry would greatly complicate and even confuse the methodology, at least when trying to compare the main large groups of industries in the economy. Another is that it is more possible and useful to do this within the framework of one or more close or homogeneous groups of industries, such as the extractive, manufacturing and advanced (high-tech) industries.

Fig. 12. Index of the digitalisation of the economy and the social sphere of the Higher School of Economics by industry for 2021



Source: [Vasilkovsky et al., 2022].

Table
The composition of the index of digitalisation of the economy and social sphere by the Higher School of Economics

Sub-index	Sub-index weight	Indicators
Use of digital technologies	0.3	Proportion of enterprises using cloud services out of total number of enterprises Proportion of organisations using Internet of Things technologies out of total number of organisations Proportion of organisations using digital twin technology out of total number of organisations Proportion of organisations using industrial robots/automated lines out of total number of organisations Percentage of organisations using dedicated design/modelling software (CAD/CAE/CAM/CAO) out of total number of organisations Percentage of organisations using PLM/PDM systems out of total number of organisations Percentage of enterprises using Geographical Information Systems (GIS) in the total number of enterprises Proportion of enterprises using special software for managing automated production and/or individual technical means and technological processes among the total number of enterprises Share of organisations using technologies for collecting, processing and analysing large amounts of data in the total number of organisations Proportion of enterprises using artificial intelligence technologies in the total number of enterprises
Digitalisation of business processes	0.2	Proportion of enterprises using ERP systems in total number of enterprises Proportion of enterprises selling via e-commerce Proportion of organisations using digital platforms out of total number of organisations Proportion of enterprises using electronic document management systems Proportion of ICT specialists in total number of employees Proportion of employees with digital skills above basic level Proportion of employees with digital skills above basic level
Digital skills of staff	0.2	Proportion of ICT specialists in the labour force Proportion of persons employed with digital skills above basic level in number of persons employed
Costs of adopting and using digital technologies	0.2	Costs of adoption and use of digital technologies as % of GVA Share of costs of advanced digital technologies in total costs of adoption and implementation of digital technologies
Cyber-security	0.1	Percentage of organisations using electronic signature tools out of total number of organisations Percentage of organisations using computer or network intrusion detection systems out of total number of organisations Percentage of organisations using strong authentication tools out of total number of organisations Percentage of organisations using software/hardware to prevent unauthorised access of malicious programs from global information networks/local area networks (firewall), of total number of organisations

Source: [Vasilkovsky et al., 2022].

3. Conclusions and recommendations for the development of digital transformation indices for industrial enterprises

The theoretical and conceptual aspects considered and the analysis of the dynamics of three indices for assessing the digital transformation of industrial companies allow us to speak about the general productive trajectory of the development of industrial digitalisation. However, the data available are fragmentary and intermittent, as two indices have already been discontinued (or at least paused), another has only recently been introduced, and there is no historical momentum as such to allow for methodologically correct comparisons. In addition, none of the existing and ongoing projects to develop and measure the level of digitisation of the economy by industry has provided sufficiently discrete comparisons of digitisation dynamics in the context of individual industries. The discussion was either about a single category of industrial production (or manufacturing), or about dividing the whole industry into several maximally

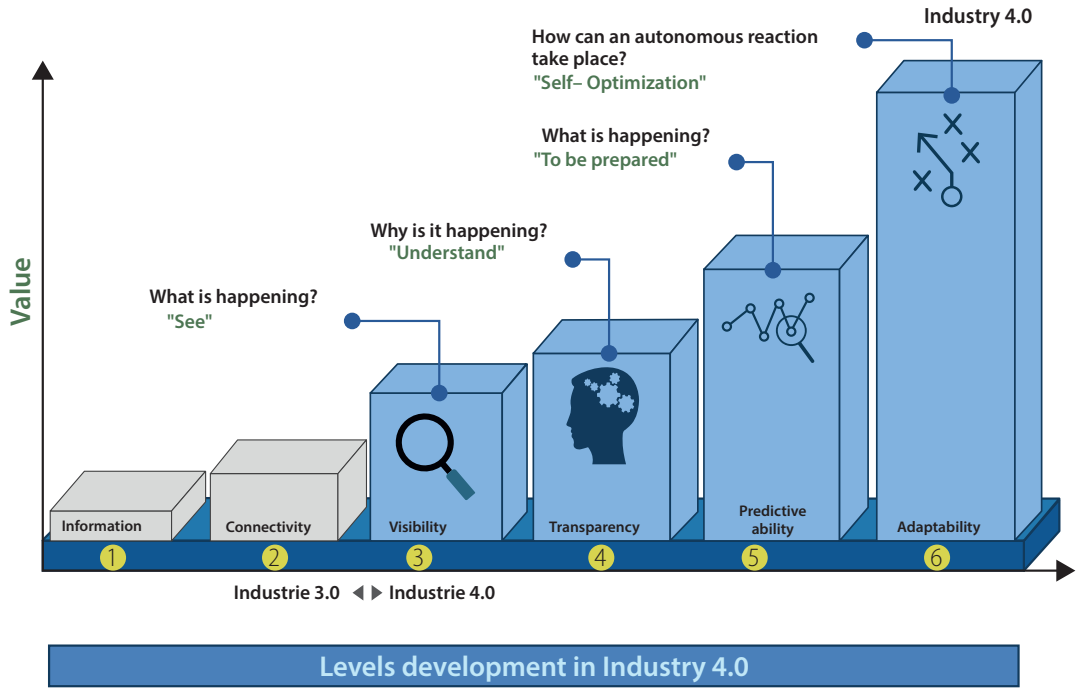
large categories: general manufacturing, advanced (high-tech) manufacturing, mining, chemicals, and oil and gas. Therefore, the main resulting thesis is the need to develop a unified and relevant to Russian practice index of digital transformation of industrial enterprises, taking into account all the positive experience in conceptual and methodological development of indices of assessment of digitalisation that research and analytical teams of international and Russian projects in this area have managed to accumulate.

It also seems very important to consider the need for a strategic vector in understanding the digital transformation of industrial companies. It is not enough to aggregate indicators and call some sub-indices the main markers of digital transformation. From a statistical point of view, such an approach can be perfectly correct, reliable, verifiable and even elegant in its own way. But the question arises about the productive potential of bundled technologies. In other words, how does it all work together to create value and what business model innovations will it lead to in the coming years? Of course, with such a more interdisciplinary formulation of the question, researchers of the dynamics of digital transformation will find themselves on shakier ground, but this is an unavoidable problem of uncertainty. The digital transformation of industrial enterprises does not simply exist as a neutral natural or social phenomenon, unconscious or poorly understood by its subjects. It is a highly subjective phenomenon, centred on the motivation of industrial companies to survive in a competitive environment and to ensure the sustainability and long-term value of their business. In the context of constructing indices and methods for assessing the dynamics of digital maturity, digitalisation and digital transformation, it is better to face the inevitable uncertainty regarding the potential of some frontier technologies. It is necessary to try anticipating the intersection of technological factors and future niches for business models, than with a more retrospective logic, try to generalise the trajectory already taken, based only on a verified and more tested part of the technologies. For the public electronic services or education sectors, the emphasis on the frontier aspects of assessing the dynamics of digital transformation and the projective function of the corresponding indices is probably not so necessary. However, for industry, especially high-tech industry, this aspect needs to be taken into account.

In order to implement the projective function of the indices, the expert community must promptly remove obsolete technological components that are no longer representative as markers, indicators and parameters for characterising the quality of the digital transformation shift in the context of individual industries or their extended groups. Otherwise, it is impossible to ensure the accuracy of the comparison of digitalisation indices in terms of dynamics over longer periods (3-5 years), even if they are compiled on the basis of a single research team or institution. This is particularly important for assessing the dynamics of the digital transformation of industrial enterprises.

As a result, with the approach described above, digital transformation indices for industrial companies acquire projective and instrumental functions, acting in a sense as a coordinate system and a roadmap. They enable companies

Fig. 13. Industry 4.0 Maturity Index



Source: [Gärtner, 2018].

from different industries, as well as their stakeholders, associations and government bodies (primarily those responsible for digitalisation and industrial policy) to improve their strategic vision for achieving later stages of digital maturity.

One of the possible approaches to interpret the strategic vector of digital transformation of industrial companies is the six levels of digital transformation within the framework of the Industry Maturity Index 4.0 model [Souhail et al., 2023] (Figure 13). As part of the digital evolution, industrial companies are moving from simply working with information flows and communications to a deeper and more comprehensive understanding of digitised business processes. At the highest levels, the potential for foresight and increased adaptability, including the ability to innovate, is revealed.

Of course, the path to Industry 4.0 will be different for each industrial company. Each industrial enterprise must make strategic decisions about the benefits it wants to achieve, its priorities, and the sequence of stages to achieve Industry 4.0. As a company's target state depends on its business strategy, each company must decide which stage represents the best balance of costs, opportunities and benefits, taking into account how these requirements may change over time in response to changes in the business environment. At the same time, in the context of industries or groups of industries in the industrial sector, it seems that we can talk about our own significant universals of digitalisation. And then it becomes possible to evaluate the dynamics of digital transformation in a more detailed industry context.

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About the author

Sergey V. Ilkevich
Candidate of economic sciences, associate professor at the Chair of Strategic and Innovative Development, leading researcher at the Institute for Management Studies and Consulting, Financial University under the Government of the Russian Federation (Moscow, Russia). ORCID: 0000-0002-8187-8290; Scopus ID: 56028209600; SPIN: 6655-7300.
Research interests: innovations and business models, international business, digital transformation of industries, sharing economy, stock market, portfolio investment, experience economy, internationalisation of education.
SVIlkevich@fa.ru

作者信息

Sergey V. Ilkevich
经济学副博士，战略与创新发展系副教授，管理研究与咨询研究所主要研究员，俄罗斯联邦政府财政金融大学（俄罗斯，莫斯科）。
ORCID: 0000-0002-8187-8290; Scopus ID: 56028209600; SPIN: 6655-7300.
科研兴趣领域：创新与商业模式、国际业务、行业数字化转型、共享经济、股票市场、投资组合、体验经济、教育国际化。
SVIlkevich@fa.ru

The article was submitted on 30.01.24; revised on 18.02.24 and accepted for publication on 20.02.24. The author read and approved the final version of the manuscript.
文章于 30.01.24 提交给编辑。文章于 18.02.24 已审稿，之后于 20.02.24 接受发表。作者已经阅读并批准了手稿的最终版本。