Journal of Cleaner Production 363 (2022) 132322

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A new approach to identifying high-tech manufacturing SMEs with sustainable technological development: Empirical evidence

Irina S. Pylaeva[a], Mariya V. Podshivalova[a], Andrew Adewale Alola[a,b,c,*], Dmitrii V. Podshivalov[d], Alexander A. Demin[d]

[a] School of Economics and Management, South Ural State University, Chelyabinsk, 454080, Russia
[b] Department of Economics, School of Accounting and Finance, University of Vaasa, Vaasa, Finland
[c] Department of Economics and Finance, Istanbul Gelisim University, Istanbul, Turkey
[d] Institute of Open and Distance Education, South Ural State University, Chelyabinsk, 454080, Russia

ARTICLE INFO

Handling Editor: Dr. Govindan Kannan

Keywords:
Technological development
Sustainable development
Manufacturing SMEs
Electrical and Electronic equipment (EEE)
High-tech industry
High-tech SMEs.

ABSTRACT

Industry 4.0 has already become part of the world's largest manufacturers and is beginning to influencing small and medium-sized enterprises (SMEs) through the supply chain. High-tech industries, such as pharmaceuticals, electronic equipment, aircraft manufacturing, etc., will be the first to face technological transformation. To this end, it becomes relevant to assess the sustainability of the technological development of SMEs as a factor of their successful digital transformation. This paper fills a gap in the study of such development as it pertains to Russian high-tech SMEs. Based on a critical literature review, we propose a new approach to assessing the sustainable technological development of these industries. The approach is distinguished by the use of a set of five indicators highlighted during the literature review, which can be quantified based on financial statements. The choice of variables is justified by their compliance with the specifics of industrial SMEs and KMO and Bartlett tests. We empirically tested the selected indicators using a sample of 7980 enterprises in two high-tech industries: Electrical and Electronic Equipment (EEE). We concluded that the larger the business, the higher the sustainability of its technological development. At the same time, SMEs have two key advantages in the implementation of technological development – a decrease in resource costs of production, flexibility in asset management and gross profit. The proposed approach allows us to identify promising high-tech SMEs for the transition to Industry 4.0 technologies. Our research will be useful both for private enterprises when searching for technologically promising contractors and for public authorities when analyzing and selecting enterprises for pilot digital transformation.

1. Introduction

Today, enterprises around the world are facing a new industrial pattern and trying to adapt their production to Industry 4.0 technologies. Thus, technologies and sustainable technological development form the basis of companies' competitiveness. Large corporations are still the undisputed leaders in the transition to new technologies. However, looking into the near future suggests that small businesses will soon have to adapt to this process. Thus, procedural innovations (introduction of state-of-the-art technologies, updating of old equipment) are important for small industries, and the fourth industrial revolution is characterized by these innovations (Pérez et al., 2018). Raymond and St-Pierre (2010) confirm that technological innovations are a key factor in the competitiveness of industrial small and medium-sized enterprises (SMEs). They can benefit more from procedural innovations rather than product innovations since small manufacturers are often in tight supply chains and manufacture custom-built products.

Würtz and Kölmel (2012) were the first to highlight the potential opportunities and benefits of small industrial enterprises adopting Industry 4.0 technologies. According to the research carried out by Davis et al. (2012), Hirsch-Kreinsen (2016), Kowalkowski et al. (2013), Müller et al. (2018), Shin et al. (2014), Zhang et al. (2014), and Masood and Sonntag (2020), small businesses can succeed from the transition to new

* Corresponding address. Department of Economics, School of Accounting and Finance, University of Vaasa, Vaasa, 65101, Finland.
E-mail addresses: irenpylaeva74@gmail.com (I.S. Pylaeva), podshivalovamv@susu.ru (M.V. Podshivalova), aadewale@gelisim.edu.tr (A.A. Alola), podshivalovdv@susu.ru (D.V. Podshivalov), deminaa@susu.ru (A.A. Demin).

https://doi.org/10.1016/j.jclepro.2022.132322
Received 6 December 2021; Received in revised form 15 March 2022; Accepted 18 May 2022
Available online 26 May 2022

technologies. According to Raymond and St-Pierre (2010), industrial SMEs can benefit from investments in technological innovations associated with Industry 4.0. Small-scale industry is characterized by flexible production, and the proximity to the customers forces them to constantly adapt technologies for customizing products. Among industrial SMEs, companies working in high-tech industries have the primary need for sustainable technological development because technologies are the key to their success.

Sustainable technological development in the era of Industry 4.0 has been studied quite actively especially about its nexus and/or impact on the environment (Laskurain-Iturbe et al., 2021; Narula et al., 2021; Alola et al., 2021 & 2022; Hu et al., 2022). This is quite consistent with the principles of the green economy embedded in the concept of the fourth industrial revolution. Additionally, researchers have been actively studying the transition of small businesses to Industry 4.0 technologies, developing business transformation roadmaps, known as “Maturity Models”. Mittal et al. (2018) made a major contribution to the systematization of the existing knowledge and designs of smart manufacturing & Industry 4.0 maturity models for SMEs. The authors concluded that none of the existing Maturity Models are suitable for full use by SMEs. However, the literature lacks papers aimed at high-tech industries. In particular, the recently developed maturity model by Rafael et al. (2020) is for machine tool SMEs only.

Meanwhile, sustainable development of small high-tech enterprises is also a subject of research, although not in the context of Industry 4.0 technologies. For example, the works of Barrett et al. (2021) and Tzokas et al. (2015) focused on high-tech SMEs in terms of the role of customers in their technological capabilities. Bagheri (2017), Busola Oluwafemi et al. (2019), and Gu et al. (2016) empirically studied the influence of internal factors of leadership and cooperation on the success of these companies. Another group of authors focused on the influence of such factors as the flexibility of innovative management (Ju et al., 2019), the speed and quality of the operational outcome (Guo et al., 2020), prioritizing the factors affecting success (Sadeghi et al., 2012), as well as cFertain strategic factors (Lee and Kwon, 2017). Petri Ahokangas et al. (2021), Saarenketo et al. (2004), Love and Ganotakis (2013), Arslan et al. (2020) dealt with the internationalization and export of high-tech SMEs. A separate area of research covers state support for high-tech SMEs, since these companies desperately need financial support, given the high cost of new technologies (Erol et al., 2016). This issue has been investigated in recent papers by Ghazinoory and Hashemi (2021) and Wonglimpiyarat (2015). Fadahunsi (2012) studied the growth patterns of high-tech SMEs, and Nunes et al. (2012) investigated the relationship between the growth rate and R&D for non-high-tech vs. high-tech SMEs.

Moreover, a related area of research is readiness indicators, which are used to assess the digital level of manufacturing SMEs prior to implementing Industry 4.0. Brozzi et al. (2021) and Nick et al. (2021) developed qualitative indicators of SMEs’ readiness for the Industry 4.0 transition and assessed them through survey. Saad et al. (2021) used peer review and benchmarking for the same purpose. Amaral and Peças (2021) assessed the barriers to adopting Industry 4.0 by small enterprises by examining two case studies. However, we did not find scientific studies dealing with the quantitative assessment of the sustainability of technological development of SMEs, including high-tech ones. Additionally, in spite of the prevalence of empirical reviews of small industrial businesses in the West and Asia, there are no such studies on Russian companies, a major emerging economy.

This study aims to empirically evaluate the sustainability of the technological development of high-tech SMEs. This study, on the one hand, contribute to the lack of empirical knowledge on the sustainability of the technological development of such enterprises. On the other hand, the study fills the methodological gap on how to quantify development in relation to SMEs. Such enrichment of the body of knowledge in this area will make it possible to improve the policy of stimulating high-tech small enterprises and thereby increase the competitiveness and sustainability of national economies.

For the other sections of the study, a review of literature that proposed the methods for assessing technological development is conducted. We identified 34 methods (in Section 2.1) and proposed our own abductive approach based on the indicators suitable for quantitative assessment of high-tech SMEs. Second, we revealed a methodology for creating a database containing information on 7980 high-tech enterprises (in Sections 2.2). Section 2.3 describe the methods for a generalized and ad hoc sample analysis, as well as a procedure for testing the validity of the proposed indicators while an introductory structural analysis of the sample of enterprises is performed in Section 3.1. In Section 3.2, the results of assessing the sustainability of technological development of SME’s for two high-tech industries is presented. Moreover, Section 4 discusses the main contributions and implication of this paper while Section 5 present conclusions, policy, and future work.

2. Material and methods

The research method consisted of four main steps (Fig. 1): 1) a literature review to derive the quantitative indicators available to assess the sustainability of technological development of high-tech SMEs; 2) creating a database of enterprises in the EEE sector of the Russian industry for 2001–2020 (per the SPARK database) and processing the initial database: excluding irrelevant enterprises; 3) assessing the criteria for sustainable technological development based on the data of the enterprises in the sample in terms of their scale of activity; 4) framing conclusions on the suitability of the proposed indicators by the KMO and Bartlett tests.

2.1. Theoretical framework, identification of indicators

We reviewed the existing literature to investigate whether there are methods targeting SMEs of high-tech industries. To this end, we selected 34 relevant sources of Russian and foreign authors (RSCI and Scopus databases). The methods we found allow us to assess various aspects of technological development with different levels of detail and accuracy. The overwhelming majority of methods are based on an effective approach when the technological development of an object is assessed through the result of such development. At the same time, Western authors are primarily focused on assessing the technological development of entire countries, rather than industries or individual enterprises. Therefore, most of the methods mentioned further in the text belong to Russian researchers. Notably, 76% of the analyzed sources are less than seven years old, which corresponds to the duration of development of the new industrial pattern.

In general, during our literature review, we did not find any methods focused on assessing the sustainability of technological development of high-tech SMEs. Therefore, we conducted a two-stage critical analysis of the relevant methods: a) we examined the tools for assessing the technological development applied to other research objects; b) we classified all the indicators used by other authors as technological development indicators. This allowed us to determine, on the one hand, a promising approach and valid assessment methods pertaining to our research object (SMEs), and on the other hand, to form a pool of indicators, which can be considered as relatively generally accepted for such an assessment.

A review of the relevant methods from the perspective of the applied tools showed that the main methods are the regression model, statistical averages, integral indicator, simple relative indicator, evaluation, benchmarking, ranking (ratings), and matrix assessment. The techniques listed herein certainly have a number of advantages. In particular, regression models make it possible for the relationships between technological development factors to be studied and the most significant ones identified. The average values method allow us to describe the process of technological development through the averaging of the characteristics of both individual companies and individual territories. The integral assessment method allows for a quantitative assessment

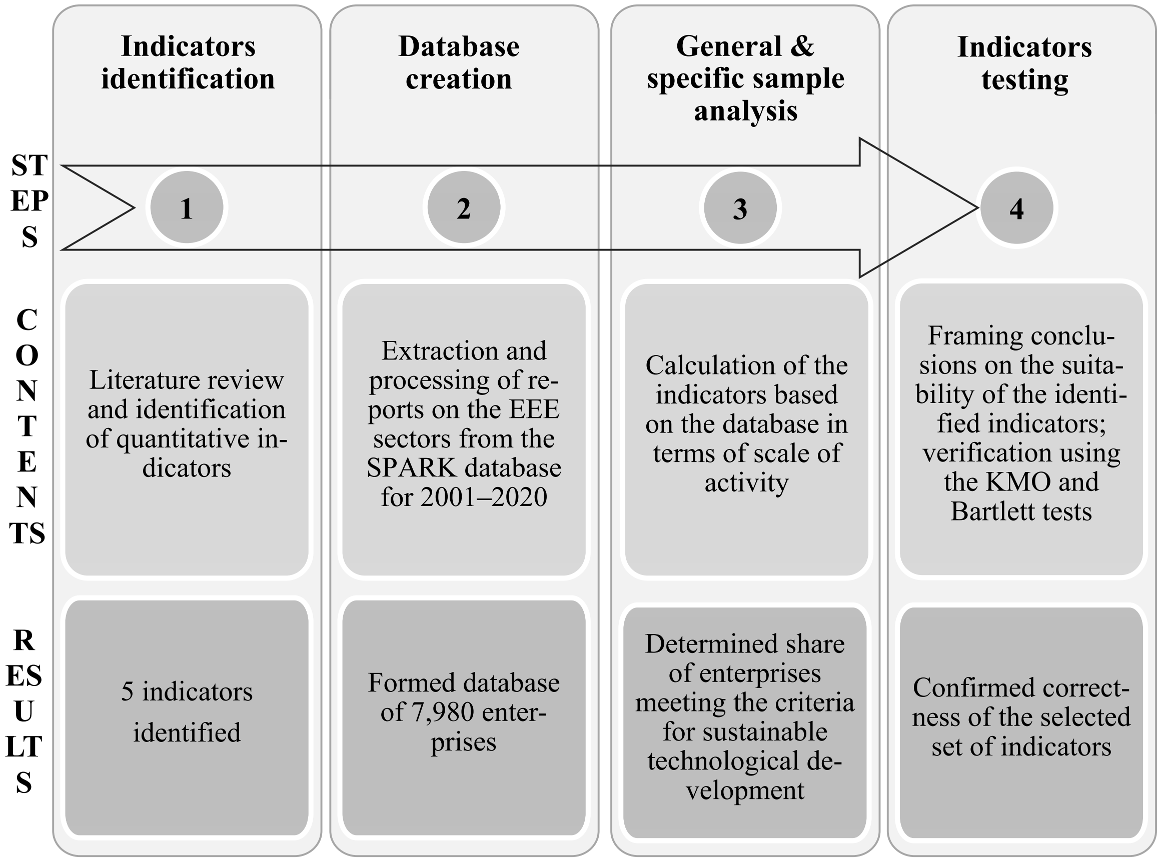

Fig. 1. The research procedures and phases.

regardless of the number of initial factors of technological development. Expert evaluation and benchmarking enable an intuitive and logical analysis of the technological development of a variety of actors to be conducted – from small firms to national economies. Closely related to these methods are the ratings which support in fact a comparative analysis of the objects of study. Despite all the listed advantages of the existing methods of assessing technological development at different levels of management, we should note that the use of fairly simple indicators is widespread. Moreover, most of the methods have no practical approbation. These conclusions convinced us that it is advisable to use the abductive approach, which is a symbiosis of the inductive and deductive approaches. Its advantage is its use of a combination of theoretical achievements and empirical research results. Next, we reviewed the relevant methods from the standpoint of modern theoretical advances—technological development indicators, and then in Section 3, we used these indicators to obtain empirical results.

We conditionally divided the indicators of technological development found in the literature into four groups: personnel, innovation, technology quality, and financial and economic performance.

The first group includes the papers of Science & Engineering Indicators (National Science Board. Science and Engineering Indicators, 2018), Pokonov (2017), Dubrovina (2015), Kortov (2004), Anisimova (2013), Strelkova and Kabanov (2012), which assess technological development through the professionalism and qualifications of employees. Other sources from this group, including Uskov and Ushakova (2018), Order of the Ministry of Economic Development of Russia (2020), United Nations (National Science Board. Science & Engineering Indicators, 2018), Yakubovsky et al. (2014), Golov (2017), Mikaeva and Mikayeva (2018) and Gulin et al. (2017), apply indicators of using labor resources in general. However, according to the studies, highly qualified personnel cannot be recognized as a valid indicator of the technological development of Russian SMEs, since such companies are characterized by a shortage of qualified personnel and turnover of employees (Baeva and Khlebovich, 2014).

The second group of indicators of technological development is connected with innovative activities. They include the expenses on innovations and the volume of innovative products (Silkina and Erygina, 2016; Rosstat, Dubrovina (2015), Anisimova (2013); Soyan, 2018), the number of industrial enterprises introducing technological innovations (Nikanorov et al., 2017; Strelkova and Kabanov, 2012; Samonova, 2020), and the level of production automation (Rachynska and Lisovska, 2011; Mikaeva and Mikayeva, 2018; Ostapenko and Kosyreva, 2017). Several authors also distinguish the fixed assets renewal rate in this group (Rosstat, Soyan, 2018; Dubrovina, 2015; Batkovsky and Styazhkin, 2016; Order of the Ministry of Economic Development of Russia, 2020). However, there is evidence that this indicator has found limited use in Russia. According to the National Research University Higher School of Economics,[1] out of the 66% of industrial enterprises replacing obsolete equipment, 43% sell it on the secondary market, which means that there are many cycles of resale of obsolete fixed assets. The use of worn-out equipment does not allow companies to implement technological innovations which can ensure the economic growth of all highly developed countries. Renewal rate cannot be used as an objective indicator of the technological development of Russian industrial enterprises.

Another indicator of the second group is the intensity of R&D expenses (Science & Engineering Indicators (National Science Board. Science & Engineering Indicators, 2018), Global Competitiveness (Global Competitiveness Report Special Edition, 2020), OECD (OECD and

[1] Investment activity of Russian industrial enterprises in 2019 –Moscow: National Research University Higher School of Economics, 2020). – 15 c. [Electronic resource] – Access mode: https://issek.hse.ru/data/2020/10/29/1359053455/Investment_activity_2019.pdf (access date: 11.08.2021).

Outlook, 2019), Mezentseva, 2015). Its use is also complicated because of the lack of access to data on R&D expenses. Moreover, this indicator is not unambiguous for assessing the technological development of SMEs. There is empirical evidence that R&D expenses can constrain the growth of industrial SMEs (Nunes et al., 2012). Canadian economists Raymond and St-Pierre (2010), using a sample of 205 industrial SMEs, proved that the impact of R&D on innovative products of industrial SMEs is mediated by new technologies. British scientists Roper and Hewitt-Dundas (2008), using a sample of 2277 Irish industries, found that industrial SMEs were characterized by less R&D and patent activities. Thus, the fixed assets renewal rate and R&D expenses cannot be recognized as valid for assessing the technological development of Russian SMEs.

The third group of indicators is related to the quality of the technologies themselves. Uskov and Ushakova (2018), Pokonov (2017), Marabaeva (2016), Shtepa (2013), Li and Schmidt (2019), Rachynska and Lisovska (2011), Golov (2017), Ostapenko and Kosyreva (2017), Dubrovina (2015), Kortov (2004), Gulin et al. (2017), Strelkova and Kabanov (2012) propose that indicators be used to assess the progressiveness of the technologies used. However, it is rather difficult quantify such indicators; therefore, they are unsuitable for the quantitative assessment of the sustainability of technological development of enterprises.

The last group of indicators assesses technological development through the company's financial and economic performance. This group includes the utilization rate of production capacities (Shtepa (2013), Golov, 2017; Nikanorov et al., 2017), labor productivity (Rosstat, Volkova and Efremova, 2013; Soyan, 2018), various costs (Zharov and Zuckerman, 2015; Kavardakov and Semenenko, 2020), profitability (Kavardakov and Semenenko, 2020; Prudnikova and Kolbenok, 2017; Marabaeva, 2016), cost intensity, financial leverage ratio, capital return (Yakubovsky et al., 2014), energy intensity (Berezikov, 2017), labor intensity (Ivanova, 2014), returns on assets (Rosstat, Yakubovsky et al., 2014; Ivanova, 2014; Olefirenko et al., 2014), resource intensity (Order of the Ministry of Economic Development of Russia, 2020), materials intensity (Berezikov, 2017; Yakubovsky et al., 2014; Uzyakov, 2011; Ivanova, 2014), etc.

Of the groups of indicators considered, only financial and economic ones are most suitable for the selected object of study. They are easily accessible and consider the specifics of small industrial companies (as shown above, the remaining groups of indicators are not always suitable for this). From all financial and economic indicators of sustainable technological development in our method, we selected those that are most often used in the research of the last 10 years and can be quantified (according to the purpose of the study). These indices are the most recognized by the scientific community. As a result, we obtained a pool of indicators for a qualitative assessment of the sustainability of technological development of an industrial enterprise, including high-tech SMEs (Table 1).

Next, we used each of the selected indicators to form a pool of criteria of the sustainable technological development of an industrial enterprise (Table 2). As shown in the table, the introduction of technological innovations is generally connected with the regular creation of intellectual property objects, an increase in return on assets, a decrease in the production cycle, a decrease in the resource intensity of production, and, as a result, an increase in the company's profit (when income growth outpaces expense growth). The formula for calculating each criterion (except for the first) is based on the geometric mean method. Accordingly, the criterion of technological development is considered to be met if the values are higher than 1. The more criteria are met by the enterprise, the higher is the sustainability of its technological development. As for the first criterion, the regularity of investments in intangible assets, its empirically identified threshold value is 80% (Podshivalova et al., 2021).

Legend: Rev_i is the chain growth rate of revenue; $Assets_i$ is the chain growth rate of the return on assets ratio; Res_i is the chain growth rate of the resource intensity ratio; PC_i is the chain growth rate of the production cycle duration; n is the number of periods characterized by growth rates.

Notably, the list of the selected criteria is not only based on the theoretical achievements of the academic community but also on the practice of high-tech corporations. Research carried out by Roland Berger[2] shows that the duration of the production cycle has been reduced by 24% since 1997. The Brilliant Factory concept developed by General Electric[3] is aimed at accelerating the production cycle by up to 60%, increasing production flexibility and efficiency and reducing costs through the use of sensors and industrial Internet technologies. The above arguments support the validity of the selected indicators.

2.1.1. Database creation

To justify the object of our research, we considered the classifications of high-tech industries. Russia, similar to Western countries, applies the criteria of the Oslo Manual (OECD. Eurostat, 2018) and Eurostat (considering the OECD recommendations), namely: the intensity of R&D expenses, the number of employees engaged in R&D, the share of enterprises which introduced a new product during a certain period, and the number of patents and publications (Mezentseva, 2015; OECD and Outlook, 2019). According to the Oslo Manual (OECD. Eurostat, 2018), an enterprise's level of innovativeness can be determined based on its level of innovative activities, and since technological development is part of innovation (OECD. Eurostat, 2018), the selection criterion is innovative activities of enterprises. As a result, we selected two high-tech industries: a manufacturer of computers, electronic and optical products (hereinafter referred to as the electronics industry), and a manufacture of electrical equipment. All over the world, including Russia, these industries are the most technologically important for the digital transformation of the economy. Enterprises of these industries are not only consumers of Industry 4.0 technologies but also manufacturers of its elements to be delivered to other industries (construction, IT, housing and communal services, defense industry).

The sample enterprises were screened for subsequent empirical research. The original sample included 7283 (electronic equipment industry – EEE1) and 7029 (electrical equipment industry – EEE2) enterprises operating as of January 01, 2021. The analysis covered all scales of activities: from microenterprises to business leaders. Reports were obtained from the SPARK database, the observation period was 20 years (2001–2020).

The original samples were pre-processed (Fig. 2). First, we excluded enterprises with "zero" balances, which do not demonstrate any financial activity, without an average payroll, and (or) are not attributed to any scale of activity, i.e., those which have not submitted information. Such companies are generally abandoned by their founders and submit zero balances while waiting to be closed. This group predominately consisted of microenterprises.

As a result, the sample of enterprises was reduced by almost 40% (See Fig. 2). This means that almost one in two operating enterprises (i.e., those not undergoing liquidation) in the industry can be classified as "dead souls" or short-lived companies. Then, the microenterprises of the sample were analyzed separately from small enterprises, because in Russia microenterprises are often special-purpose entities (SPEs) for large businesses, affiliated to large businesses (the founders of such companies are relatives of senior management), or act as custodians of assets or elements of holding structures (when large and medium-sized businesses are deliberately split into micro and small businesses to gain access to tax incentives) (Kiseleva and Fonotov, 2017).

[2] Mastering product complexity. [Electronic resource] – Access mode: https://www.yumpu.com/en/document/view/33174119/mastering-product-complexity-pdf-3316-kb-roland-berger.

[3] Biller S., Annunziata M. (2014) A Brilliant Factory with 20/20 Vision. [Electronic resource] – Access mode: https://www.ge.com/news/reports/a-brilliant-factory-with-2020-vision.

Table 1
Indicators of technological development of an industrial enterprise.

Indicator	Designation	Calculation formula		Author
Presence of regular investments in intangible assets on the books	Intangible assets (IA)	$\frac{\textit{Years with IA on the books}}{\textit{Age of the company}}$	(1)	Podshivalova et al. (2021), Nunes et al. (Nunes et al., 2012), OECD (OECD. Eurostat, 2018), Strelkova and Kabanov (2012)
Ratio of the growth rate of the enterprise's revenue to the growth rate of the prime cost	Rev	$\frac{\textit{Growth rate}_{\textit{revenue}}}{\textit{Growth rate}_{\textit{prime cost}}}$	(2)	Strelkova and Kabanov (2012)
Returns on assets ratio	Assets	$\frac{\textit{Revenue}}{\textit{Average annual noncurrent assets}}$	(3)	Yakubovsky et al. (2014), Rosstat, Ivanova (2014), Olefirenko O. et al. (2014)
Resource intensity ratio	Res	$\frac{\textit{Averate annual asset value}}{\textit{Revenue}}$	(4)	Ivanova (2014), Order of the Ministry of Economic Development of Russia (2020), Prosvirina and Tashchev (2014), Berezikov (2017); Yakubovsky et al. (2014), Uzyakov (2011)
Duration of the production cycle	PC	$\frac{\textit{Average annual inventory}}{\textit{Cost of\_sales}/365}$	(5)	Yakubovsky et al. (2014), Borovkov et al. (2018)

Table 2
The criteria of sustainable technological development of an industrial enterprise (authors).

Criterion	Designation	Calculation formula	
Regularity of investments in intangible assets IA	GR_IA	$IA \cdot 100\%$	(6)
Exceeding the growth rate of the enterprise's revenue over the growth rate of the prime cost	GR_Rev	$\left(\prod_{i=1}^{n} Rev_i\right)^{\frac{1}{n}}$	(7)
Growth of return on assets	GR_Assets	$\left(\prod_{i=1}^{n} Assets_i\right)^{\frac{1}{n}}$	(8)
Decrease in resource intensity	GR_Res	$\left(\prod_{i=1}^{n} Res_i\right)^{\frac{1}{n}}$	(9)
Reduction in the production cycle	GR_PC	$\left(\prod_{i=1}^{n} PC_i\right)^{\frac{1}{n}}$	(10)

the development of industries. To this end, we used the Herfindahl-Hirschman index,[4] which allows us to assess the level of industry heterogeneity (formula (11)):

$$HHI = S_1^2 + S_2^2 + \ldots + S_n^2 \quad (11)$$

where S_i is the share of the sales revenue of the i-th enterprise in the market; and n is the number of enterprises in the industry.

To calculate the index of the sample of enterprises for the industry in general, we used the revenue shares of each individual enterprise. The index relating to scale of activity is determined from the revenue of enterprises grouped by four scales of activity (micro, small, medium, and large).

The selected indicators were assessed for their reliability and selection correctness using the Bartlett and Kaiser-Meyer-Olkin (KMO) tests

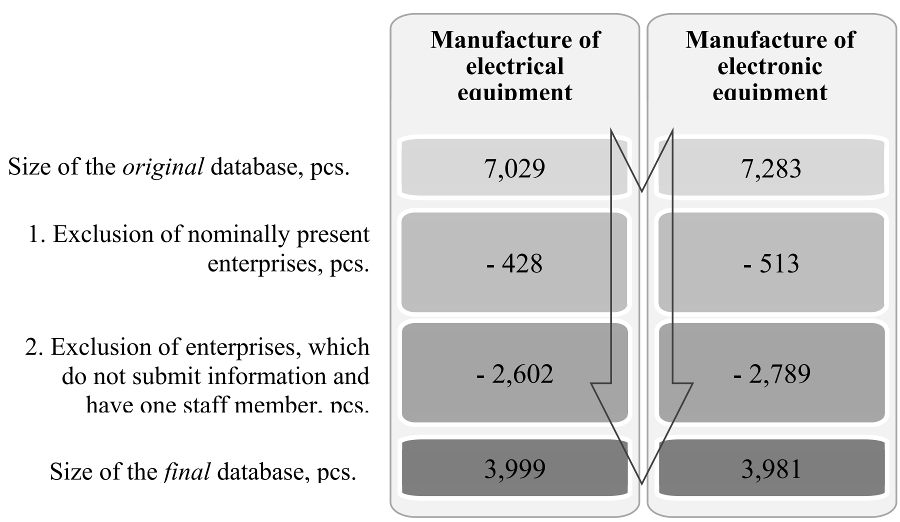

Fig. 2. Stages of screening the sample of enterprises.

2.2. *General & specific sample analysis*

The indicators should be calculated with structural and average indicators for the sample in terms of the scale of the companies' activity. We determined the average age of enterprises, the regularity of investments in intangible assets, the ratio of the growth rate of revenue and prime cost, the ratio of return on investments and resource intensity, and the duration of the production cycle (the formulas are presented in Table 2). We calculated the shares of enterprises meeting one or multiple (more than three) technological development criteria.

We also assessed the role of enterprises of various scales of activity in (Kaiser and Rice, 1974) (Table 3). The pre-coded data were processed using the IBM SPSS software.

[4] Herfindahl - Hirschman index/A. G. Pripadcheva//Great Russian Encyclopedia: [in 35 vol]/Chief editor Yu.S. Osipov. — Moscow: Great Russian Encyclopedia, 2004–2017.

Table 3
–The results of the KMO and Bartlett tests (authors).

Indicator		EEE1	EEE2	Standard value
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.739	0.650	≥0.5
Bartlett's Test of Sphericity	Approx. Chi-Square	2845.202	1898.717	–
	df	10	10	–
	Sig.	0.000	0.000	≤0.05

The results confirmed that the selected criteria can be correctly applied in a single set.

3. Results

3.1. Structural analysis of the sample of enterprises

The structure of the samples of both industries is subject to the global regularity that microenterprises and small businesses constitute the numerical majority (93%). At the same time, small business (excluding microenterprises) are a fairly widespread form of activity (about 25% are small businesses). The enterprises in the sample are mainly characterized by a mature age, which increases proportionally with the scale of activity (Fig. 3).

Table 4 presents the results of assessing the role of enterprises of various scales of activity in the manufacturing volume for their respective industries.

The values in the table show that each industry sample is characterized by numerous enterprises, with no monopoly. The values of the indicators are within 100 (HHI <1000 means it is easy for a new company to enter the market) and the industry can be characterized as low-concentrated. However, the calculation of the indices in terms of the scale of activity showed that the market is highly concentrated (1800 < HHI <10,000), where more than half of the industry's revenue is from large enterprises. This is also evidenced by the data in Fig. 4.

Over 20 years SMEs give 50% of revenue on average in both industries, which indicates their significant role in high-tech manufacturing.

We also plotted the trend of changes in the total revenue of the industries to assess whether it corresponds to the specifics of high-tech industries (Fig. 5). The initial values were preliminarily filtered for inflation (according to the data of the Bank of Russia).

Thus, according to industry research (Bočková and Meluzín, 2016; Ehie and Olibe, 2010; Jaruzelski et al., 2015; Knott et al., 2011) and empirical data (OECD Stat.; UNESCO stat., 2019; Global Research and Development Expenditures: Fact Sheet, 2021; PWC, 2018), the growth in the competitiveness (and therefore income) of an enterprise is closely related to growth in R&D expenses and investments in intangible assets. A company's regular innovative activities in high-tech industries are a factor of its survival. Consequently, all other things being equal, high-tech industries tend to have an upward trend in total revenues. We also confirmed this hypothesis when studying another high-tech industry – pharmaceuticals (Podshivalova et al., 2021).

3.2. Results of the empirical assessment

Fig. 6 presents a visualization of the results of a quantitative assessment of the sustainability of technological development for enterprises in the sample according to the design (Fig. 1). We included the shares of small (excluding microenterprises), medium-sized, and large enterprises in terms of the established five criteria of technological development.

The values show the share of enterprises of a particular size which meet the corresponding criterion throughout the entire analyzed period. The radar charts have the same dimension; the graduation is 20%. Industry average values are marked on the axes for easy comparison. The values of small enterprises exceeding the corresponding values of medium-sized and large enterprises are marked with crosses; these include the resource intensity ratio and the ratio of the growth rate of revenue and prime cost.

The share of enterprises meeting any criterion of technological development increases as the business grows in scale. This trend is pronounced for the indicators of the regularity of investments in intangible assets, the reduction in the production cycle, and the increase in return on assets. At the same time, we revealed that the shares of enterprises with a growing return on assets ratio are approximately the same in both industries, both on average within sample and for large-scale production. For SMEs, these indicators are industry-specific. Thus, the data show that in the EEE2 sample, only one in three small businesses benefits from technological development in the form of increased efficiency of using fixed assets, and in the EEE1 sample, the result is even less – one in four. At the same time, the indicators of small companies in both samples are inferior to those of large and medium-sized companies, while in the electronic equipment industry these indicators are also inferior to microenterprises (among all the enterprises in the EEE1 sample, the share of small enterprises increasing return on assets is the lowest).

The advantage of small high-tech companies is that they are not inferior to large ones in management flexibility and in exceeding the growth rates of revenue over prime cost (which indicates a reduction in specific production costs). The results of similar empirical studies indirectly confirm the validity of our conclusions. Thus, Lefebvre et al. (2009) proved that process innovations at industrial SMEs are aimed at improving competitiveness by reducing production costs and increasing the flexibility of their productive apparatus.

Further, we assessed the sustainability of technological development of companies of different sizes for the two industries (Fig. 7). Combining the technological development criteria confirmed the validity of classifying the electronic equipment industry (EEE1) in the top tier of high-tech industries. The share of enterprises meeting three or more technological development criteria in the sample of this industry is 19.2%,[5] while the share of enterprises in the sample of electrical equipment is 13.1%. A similar distribution is observed among small companies: 22.1% and 16.1%, respectively. Based on our assumptions, we concluded that the share of enterprises with sustainable technological development is higher in the electronic equipment industry.

Notably, in both high-tech industries, the prevalence of small enterprises with sustainable technological development (three or more criteria met) is lower than that of similar medium-sized and large enterprises. This indirectly indicates that it is easier for large businesses in Russia to implement technological development than for small ones. Consequently, such enterprises need targeted government support. European researchers of SMEs in high-tech industries also note their high dependence on government financial support (Nunes et al., 2012).

4. Discussion

4.1. Justification of the result outcome

The results we obtained are interesting from two points of view – practical and theoretical. The first is to compare our results with findings from similar empirical studies. However, as shown in the literature review, there are currently no similar studies of high-tech SMEs. We have therefore drawn on the experience of developed countries and tested Russian SMEs for compliance with the specifics identified in this sector in developed economies (Table 5). In particular, Fadahunsi (2012) found that industrial SMEs which reach a higher level of technological

[5] Hereinafter, the final figure is obtained as follows: 15% + 4% + 0.2% (the sum of the shares of the enterprises meeting three or more technological development criteria).

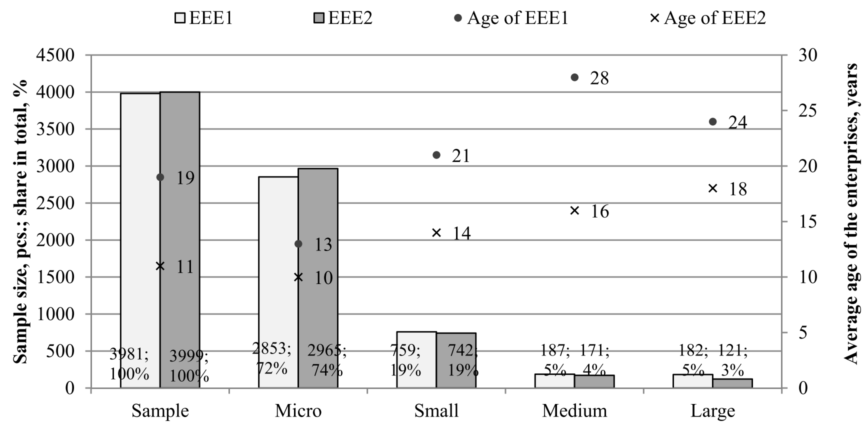

Fig. 3. Structural analysis of the sample of enterprises.

Table 4
Values of the Herfindahl-Hirschman index for the industries.

Name of industry	Value of the Herfindahl-Hirschman index (HHI)		
	For the sample in general		For the scales of activity for 2001–2020
	For 2001–2020	Only 2020	
Electronic Equipment Manufacturing (EEE1)	94	85	3462
Electrical Equipment Manufacturing (EEE2)	111	112	3433

development show more growth than analogous companies which failed to do so. Nunes et al. (2012) studied the relations between the characteristics of the development of Portuguese enterprises in high-tech and low-tech industries. According to their estimates, high-tech industrial SMEs were larger and older than low-tech companies on average.

All of the above indicators for industrial SMEs with sustainable technological development (more than three criteria met) were compared with a similar indicator for enterprises with less sustainable development (three criteria met). The results turned out to be completely comparable with the study by Fadahunsi (2012) and partially comparable with the study by Nunes et al. (2012). According to our estimates, industrial SMEs with highly sustainable technological development in the electrical equipment industry are larger but younger than enterprises with low sustainable technological development. The specifics highlighted by Nunes et al. (2012) were not confirmed in the sample of the EEE1 industry.

The second perspective of our discussions – theoretical – is essentially the answer to the question: how can we explain the phenomena and their differences in different economies? In our opinion, in order to justify the above differences, it would be best to turn to institutional theory. Indeed, this discrepancy in the results is partly explained by the difference in the quality of the institutional environment of developed

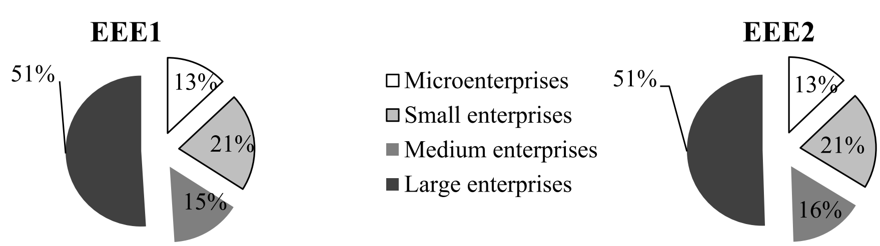

Fig. 4. Distribution of the average annual revenue shares by the scales of activity for 2001–2020 (authors).

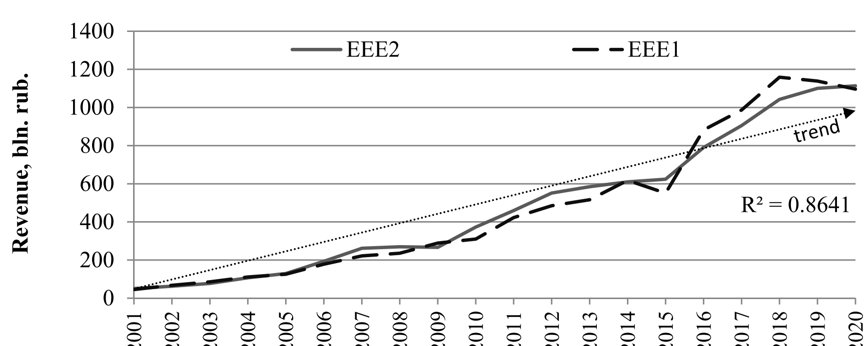

Fig. 5. Industry revenue trend for the sample.

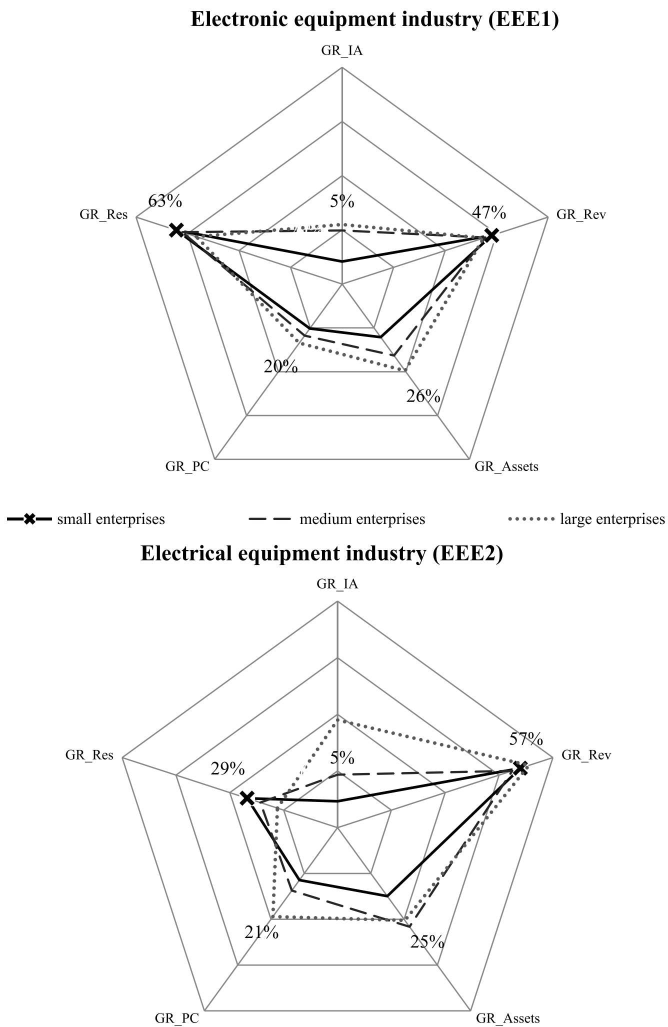

Fig. 6. Compliance of the sample of enterprises with the technological development criteria.

and developing countries. One of the recent works by Indian authors Das et al. (2020) proved that sustainable industrial SMEs are highly dependent on the technology environment, which includes "institutional capabilities" and "external capabilities". Das et al. (2020) found that institutional opportunities have become dominant over time and significantly influence the sustainability of industrial SMEs, while, on the contrary, the influence of external opportunities stands out as insignificant. Bekun et al. (2021) also report a characteristic feature of economic expansion (high-tech development especially) in developing economies – a high relationship with institutional support. According to the UN rating of technological transformation readiness[6] and the value of the World Bank's Digital Adoption Index,[7] Russia has a high level of readiness (0.75 out of 1.00 maximum), ranking 27th in the overall rating and second among developing countries (after China). Thus, the technological environment in Russia is quite friendly to new technologies of high-tech SMEs. This means that apart from the institutional factor, there are several other factors significant for the technological development of high-tech SMEs to be empirically discovered.

The theoretical explanation of our key result - The larger the business, the higher the sustainability of its technological development – can be considered the provisions of the classical theory of small business. According to this theory, small enterprises have resource limitations (Hirsch-Kreinsen, 2016; Kowalkowski et al., 2013) and a high degree of vulnerability (Davis et al., 2012), and, therefore, their technological development is subject to higher volatility. Our remaining findings are also valid, since they are consistent with other provisions of the theory of small business. In particular, high flexibility of management (Zhang et al., 2014) and adaptation to external challenges (Kowalkowski et al., 2013; Shin et al., 2014; Adamik and Sikora-Fernandez, 2021), serve as factors that allow small producers of high-tech industries to achieve sustainable rates of gross profit growth comparable to those of large companies.

4.2. Limitation of the study

Among the main limitations of the study are those related to the completeness of the sample and the limitations of the study method itself. The former includes limitations related to the inability to cover all organizational and legal formats of industrial enterprises in the industry. In particular, small enterprises operating in the form of individual entrepreneurs were not included in the sample. The second type of limitations is related to the research method used. Thus, the set of technological development indicators selected does not include indicators that are not accessible, for example, data on the costs of introducing new technologies or on the quality of the technologies themselves. These limitations provide useful guidance for future research.

4.3. Implications for sustainable development theory

Most of the contemporary studies on high-tech companies are based on the samples of enterprises in developed countries. There are very few similar studies covering developing countries, which increases their relevance. Our research fills this gap for Russian high-tech SMEs. However, these results can be useful when studying high-tech SMEs in other emerging economies with a similar institutional environment. Thus, the contribution of our research to the existing bulk of knowledge is twofold. On the one hand, we proposed an abductive approach to assessing the sustainability of technological development of high-tech SMEs. On the other hand, during the empirical testing of the method, we obtained new evidence of the specifics of such development in emerging economies.

From the point of view of theoretical contribution, the results obtained are significant for improving the theory of sustainable development and the theory of small business. In the framework of the first theory, they identify the specifics of technological development inherent in high-tech SMEs, in the framework of the second – they propose a new approach to assessing the sustainability of such development for the subjects of this sector of the economy.

5. Conclusion and policy recommendation

As a conclusion, we should note that the abductive approach combined deductive and inductive data. A critical analysis of the existing methods for assessing the technological development of industrial enterprises was used as deductive data, which allowed us to identify a set of key indicators. The inductive data resulted from the empirical testing of the indicators identified in theory. The use of our approach allowed us to assess the sustainability of the technological development of high-tech SMEs based on the methods of statistical processing of big data. Thus, we filled two significant gaps in the literature: (1) we proposed a new methodology for assessing the sustainability of technological development of industrial SMEs and (2) for the first time, we empirically

[6] Technology and Innovation Report 2021 [Electronic resource] – Access mode: https://unctad.org/system/files/official-document/tir2020_en.pdf.

[7] World Development Report 2016: Digital Dividends. [Electronic resource] – Access mode: https://www.worldbank.org/en/publication/wdr2016/Digital-Adoption-Index (access date: 15.08.2021).

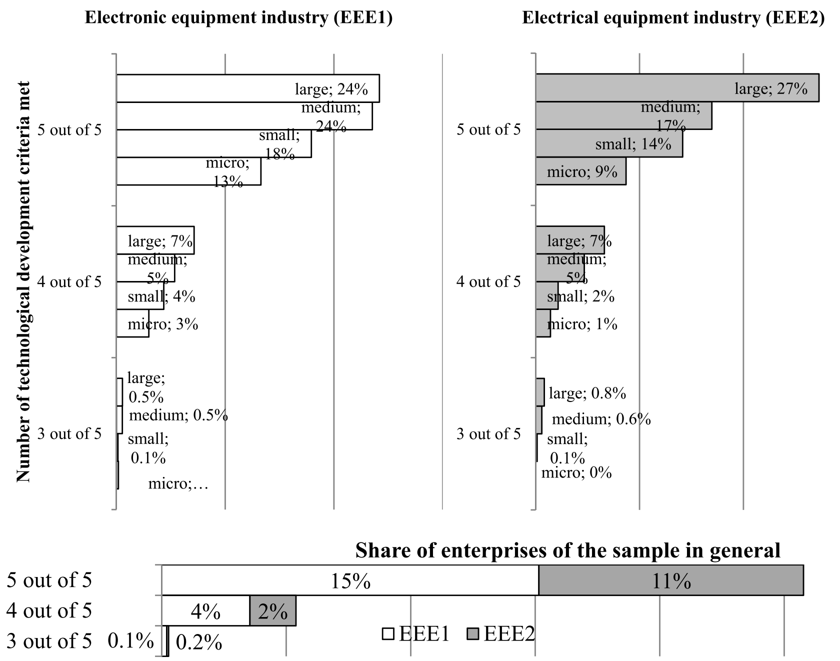

Fig. 7. The share of enterprises meeting the sustainable technological development criteria.

Table 5
The specifics of small companies with highly sustainable technological development.

Industry code	Growth rate of the revenue of the industry's enterprises, unit fractions		Revenue, bln. rub.		Age, years	
	highly sustainable development	low sustainable development	highly sustainable development	low sustainable development	highly sustainable development	low sustainable development
EEE1	**1.56**	1.37	**101**	102	**18**	23
EEE2	**1.75**	1.49	**139**	115	**13**	17

studied the activities of such enterprises in Russia.

The empirical assessment of the sustainability of the technological development of high-tech SMEs allowed us to make several important conclusions.

i. Small high-tech companies are ahead of medium-sized and large businesses in reducing resource intensity; it is fair both for the electrical and electronic equipment industry.
ii. Small high-tech companies of both samples are almost on par with large and medium-sized manufacturers in excess of the growth rate of revenue over prime cost. Technological innovations (in particular, the replacement of equipment) influence the improvement of product quality, expanding the scale of business, maintaining and developing of traditional sales markets, creating new markets meeting modern standards, increased production capacity and flexibility, improved working conditions, and decreased environmental pollution.[8] These changes are matched by improvement in reduction in production costs, increase in sales, and increase in profits (Alekseeva et al., 2017). Therefore, we can recognize that industrial SMEs of high-tech industries can realize the benefits of technological innovations on an equal basis with large and medium-sized businesses, subject to proper government support.
iii. The specifics of high-tech SMEs are twofold. On the one hand, small businesses have significant advantages in organizing flexible assets and gross profit management, including within the framework of technological development.[9] In 2009, researchers in Canada came to similar conclusions after analyzing a sample of 388 enterprises (Lefebvre et al., 2009). On the other hand, small enterprises, have fewer opportunities for R&D (creation of intangible assets) and the purchase of new high-tech fixed assets, which indirectly affect the acceleration of the production cycle.
iv. The validity of our approach to assessing the sustainability of technological development of high-tech SMEs is indirectly confirmed by the compliance of our results with the Eurostat and Oslo Manual classifications (OECD. Eurostat, 2018). This means that in the absence of data on R&D expenses, the share of employees engaged in research and development, cooperation with institutes and other scientific establishments, etc., our criteria can be used as an alternative to determine the sustainability of technological development of enterprises and/or individual industries.

5.1. *Policy significance*

Technological development is generally important for industrial SMEs, but it is only feasible with government institutional support

[8] [Electronic resource] – Access mode: https://logistics.ru/learning/news/celi-i-rezultativnost-innovacionnoy-deyatelnosti (access date: 16.08.2021).

[9] Forbes. 2019. 11 Advantages Small Businesses [Electronic resource] – Access mode: https://www.forbes.com/sites/forbescoachescouncil/2019/07/22/11-advantages-small-businesses-have-over-large-corporations-and-how-to-use-them/?sh=6126bdcf2037 (access date: 16.08.2021).

(Somina, 2017). Currently, the technologies of the factories of the future are too expensive and risky for industrial SMEs, which complicates their implementation (Erol et al., 2016). Because of their weak internal capabilities, industrial SMEs are more in need of access to external knowledge than large companies with the necessary resources to master new technologies and carry out R&D (Cohen and Levinthal, 1989). Besides, there are still no clear design guidelines for how SMEs can implement Industry 4.0. We agree with the statement by Zambon et al. (2019) that the authorities determining innovative development should pursue more active policies to support industrial SMEs in investing in these technologies and increasing their market competitiveness, since technological development is a decisive advantage for national economies (Ermoshina, 2019).

The study can help in solving these problems. Pollard et al. (2021), Rizos and Bryhn (2022) electronics and electrical equipment industries significantly influence the sustainable energy source which in developing countries can be achieved in the long term through the coordination of business support mechanisms (Adedoyin et al., 2021; Agboola et al., 2021). Our approach makes it possible to strengthen such support mechanisms, as it allows for the identification of promising high-tech SMEs for the transition to Industry 4.0 technologies. In particular, our method will allow for a more reasonable allocation of limited budgetary resources. It will direct them to accelerate the technological development of those small producers who have already proven their sustainability and who have sufficient potential for the introduction of new technologies in the future.

5.2. Future study

Our further research will cover the identification of factors supporting and impeding the sustainability of technological development of high-tech SMEs. Taking into account the importance of government assistance for this sector of industry, it is also essential to propose scientifically grounded mechanisms for allocating limited budgetary funds to provide such support.

In addition, the limitations of the study indicated above may form the basis of new empirical developments to complement this study. In particular, research may be optimized by the inclusion in the sample of individual entrepreneurs, expanding the list of indicators by including in it the qualitative indicators highlighted by us when describing the research methodology.

Finally, another area of future work could be the application of the proposed approach to new research subjects – SMEs of other high-tech industries, such as the pharmaceutical industry which became strategically important for national security in the COVID-19 pandemic.

CRediT authorship contribution statement

Irina S. Pylaeva: Investigation, Data curation, Writing – original draft, Visualization. **Mariya V. Podshivalova:** Conceptualization, Methodology, Resources, Validation. **Andrew Adewale Alola:** Writing – review and editing, and corresponding. **Dmitrii V. Podshivalov:** Resources, Validation. **Alexander A. Demin:** Resources, Validation, All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132322.

References

Adamik, A., Sikora-Fernandez, D., 2021. Smart organizations as a source of competitiveness and sustainable development in the age of industry 4.0: integration of micro and macro perspective. Energies 14 (6), 1572. https://doi.org/10.3390/en14061572.

Adedoyin, F., Alola, A., Bekun, F.V., 2021. The alternative energy utilization and common regional trade outlook in EU-27: evidence from common correlated effects. Renew. Sustain. Energy Rev. 145, 1–7. https://doi.org/10.1016/j.rser.2021.111092.

Agboola, M.O., Bekun, F.V., Joshua, U., 2021. Pathway to environmental sustainability: nexus between economic growth, energy consumption, CO2 emission, oil rent and total natural resources rent in Saudi Arabia. Resour. Pol. 74, 1–8. https://doi.org/10.1016/j.resourpol.2021.102380.

Ahokangas, P., Haapanen, L., Golgeci, I., Arslan, A., Khan, Z., Kontkanen, M., 2021. Knowledge sharing dynamics in international subcontracting arrangements: the case of Finnish high-tech SMEs. J. Int. Manag. https://doi.org/10.1016/j.intman.2021.100888, 100888.

Alekseeva, I.Yu, Tretyakova, YuV., Goncharova, E.V., 2017. The role of innovative development in increasing the efficiency of the marketing activity of an enterprise. Concept Sci. Method. Electron. J. 2, 508–513.

Alola, A.A., Ozturk, I., Bekun, F.V., 2021. Is clean energy prosperity and technological innovation rapidly mitigating sustainable energy-development deficit in selected sub-Saharan Africa? A myth or reality. Energy Pol. 158, 112520.

Alola, U.V., Bekun, F.V., Alola, A.A., Ahmed, Z.U., 2022. Sustainable development amidst technological innovation and tourism activities in sub-Saharan Africa. Int. Soc. Sci. J. 72 (243), 111–127. https://doi.org/10.1111/issj.12316.

Amaral, A., Peças, P., 2021. SMEs and Industry 4.0: two case studies of digitalization for a smoother integration. Comput. Ind. 125, 103333. https://doi.org/10.1016/j.compind.2020.103333.

Anisimova, A.V., 2013. Integral Assessment of Scientific, Technical and Innovative Development of Ukraine. Effective Economy. 3 – [Electronic resource] – Access mode: (In Russian). http://www.economy.nayka.com.ua/?op=1&z=1876.

Arslan, A., Haapanen, L., Ahokangas, P., Naughton, S., 2020. Multicultural R&D team operations in high-tech SMEs: role of team task environment and individual team members' personal experiences. J. Bus. Res. https://doi.org/10.1016/j.jbusres.2020.02.003.

Baeva, O.N., Khlebovich, D.I., 2014. Staff training in small business enterprises: problems and possible solutions (entrepreneurs' view). Russ. Enterpren. 15 (12), 123–134 (In Russian).

Bagheri, A., 2017. The impact of entrepreneurial leadership on innovation work behavior and opportunity recognition in high-technology SMEs. J. High Technol. Manag. Res. 28 (2), 159–166. https://doi.org/10.1016/j.hitech.2017.10.003.

Barrett, G., Dooley, L., Bogue, J., 2021. Open innovation within high-tech SMEs: a study of the entrepreneurial founder's influence on open innovation practices. Technovation 103, 102232. https://doi.org/10.1016/j.technovation.2021.102232.

Batkovsky, A.M., Styazhkin, A.N., 2016. A toolkit for assessing the level of technological development of the defense industry enterprises. New Sci.: Strategies Dev. Vectors 9, 152–157 (In Russian).

Bekun, F.V., Gyamfi, B.A., Onifade, S.T., Agboola, M.O., 2021. Beyond the environmental Kuznets Curve in E7 economies: accounting for the combined impacts of institutional quality and renewables. J. Clean. Prod. 314, 1–10. https://doi.org/10.1016/j.jclepro.2021.127924.

Berezikov, S.A., 2017. Approaches to assessing the level of technological development of industry and the possibility of their application in the regions of the North and the Arctic. Russia. Trends Dev. Prospects 12–2, 814–817.

Bočková, N., Meluzín, T., 2016. Electronics industry: R&D investments as possible factors of firms competitiveness. Proc. Soc. Behav. Sci. 220, 51–61. https://doi.org/10.1016/j.sbspro.2016.05.468.

Borovkov, A.I., Shcherbina, A., Maruseva, V.M., Ryabov, YuA., 2018. World technological agenda and global trends in industrial development in the digital economy. Innovations 12 (242), 34–42.

Brozzi, R., Riedl, M., Matta, D., 2021. Key readiness indicators to assess the digital level of manufacturing SMEs. Proc. CIRP 96, 201–206. https://doi.org/10.1016/j.procir.2021.01.075.

Busola Oluwafemi, T., Mitchelmore, S., Nikolopoulos, K., 2019. Leading innovation: empirical evidence for ambidextrous leadership from UK high-tech SMEs. J. Bus. Res. https://doi.org/10.1016/j.jbusres.2019.10.035.

Cohen, W.M., Levinthal, D.A., 1989. Innovation and learning: the two faces of R & D. Econ. J. 99 https://doi.org/10.2307/2233763.

Das, S., Kundu, A., Bhattacharya, A., 2020. Technology adaptation and survival of SMEs: a longitudinal study of developing countries. Technol. Innovat. Manag. Rev. 10 (6), 64–72. https://doi.org/10.22215/timreview/1369.

Davis, J., Edgar, T., Porter, J., Bernaden, J., Sarli, M., 2012. Smart manufacturing, manufacturing intelligence and demand-dynamic performance. Comput. Chem. Eng. 47, 145–156.

Dubrovina, N.A., 2015. An integral assessment of scientific and technological development of mechanical engineering. Bull. Orenburg State Univ. 4 (179), 271–276 (In Russian).

Ehie, I.C., Olibe, K., 2010. The effect of R&D investment on firm value: an examination of US manufacturing and service industries. Int. J. Prod. Econ. 128 (1), 127–135. https://doi.org/10.1016/j.ijpe.2010.06.005.

Ermoshina, T.V., 2019. The cost of technological innovation as a priority factor in the development of the national innovation system. Bull. Eurasian Sci. 3, 1–9.

Erol, S., Schumacher, A., Sihn, W., 2016. Strategic guidance towards industry 4.0—a three–stage process model. Int. Conf. Compet. Manuf. 495–501.

Eurostat, O.E.C.D., 2018. Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation. In: The Measurement of Scientific, Technological and Innovation Activities, fourth ed. OECD Publishing, Paris. Eurostat, Luxembourg, p. 258.
Fadahunsi, A., 2012. The growth of small businesses: towards a research agenda. Am. J. Econ. Bus. Adm. 4.
Ghazinoory, S., Hashemi, Z., 2021. Do tax incentives and direct funding enhance innovation input and output in high-tech firms? J. High Technol. Manag. Res. 32 (1), 100394. https://doi.org/10.1016/j.hitech.2020.100394.
Global Competitiveness Report Special Edition, 2020. How Countries Are Performing on the Road to Recovery. World Economic Forum, p. 95.
Golov, R.S., 2017. Organization of Production, Economics and Management in Industry. Dashkov and K, Moscow, p. 858 (In Russian).
Gu, Q., Jiang, W., Wang, G.G., 2016. Effects of external and internal sources on innovation performance in Chinese high-tech SMEs: a resource-based perspective. J. Eng. Technol. Manag. 40, 76–86. https://doi.org/10.1016/j.jengtecman.2016.04.003.
Gulin, K.A., Mazilov, E.A., Kuz'min, I.V., Alfer'ev, D.A., Ermolov, A.P., 2017. Scientific and technological potential of a territory and its comparative appraisal. Territ. Dev. Probl. 1 (87), 7–26 (In Russian).
Guo, F., Bo, Q., Tong, X., Zhang, X., 2020. A paradoxical view of speed and quality on operational outcome: an empirical investigation of innovation in high-tech small and medium-sized enterprises. Int. J. Prod. Econ. 229, 107780. https://doi.org/10.1016/j.ijpe.2020.107780.
Hirsch-Kreinsen, H., 2016. Digitization of industrial work: development paths and prospects. J. Lab. Mark. Res. 49 (1), 1–14.
Hu, R., Shahzad, F., Abbas, A., Liu, X., 2022. Decoupling the influence of eco-sustainability motivations in the adoption of the green industrial IoT and the impact of advanced manufacturing technologies. J. Clean. Prod. 339 https://doi.org/10.1016/j.jclepro.2022.130708.
Ivanova, M.V., 2014. The criteria for assessing the technological level of the economy in international cooperation. In: Prospects for Coordinated Socio-Economic Development of Russia and Ukraine in the European Context: Tr. II International Scientific and Practical Conference. INION RAS; Department of Scientific Cooperation and International Links. chief Yu.S. Pivovarov. - Moscow: [B. and.], pp. 349–353.
Jaruzelski, B., Schwartz, K., Staack, V., 2015. Innovation's New World Order. Strategy and Business Magazine, vol. 1 [Electronic resource] – Access mode: https://www.strategy-business.com/feature/00370?gko=9f2c4.
Ju, X., Ferreira, F.F., Wang, M., 2019. Innovation, Agile Project Management and Firm Performance in a Public Sector-Dominated Economy: Empirical Evidence from High-Tech Small and Medium-Sized Enterprises in China. Socio-Economic Planning Sciences. https://doi.org/10.1016/j.seps.2019.100779, 100779.
Kaiser, H.F., Rice, J., 1974. Little jiffy, mark IV. Educ. Psychol. Meas. 34 (1), 111–117.
Kavardakov, V.Ya, Semenenko, I.A., 2020. Theoretical and methodological foundations for assessing the levels of technological development of animal husbandry subsectors. Econ. Ecol. Territ. Entities 4 (2), 13–24. https://doi.org/10.23947/2413–1474–2020–4–2–13–24.
Kiseleva, V.V., Fonotov, A.G., 2017. Liberal theory and Russian practice in small business. Innovations 7 (225), 26–33.
Knott, A.M., Vieregger, C., Yen, J.C., 2011. IQ and the R&D market value puzzle. Manag. Sci. 54, 2054–2067.
Kortov, S.V., 2004. Analysis of the innovative development of the territory on the basis of the evolutionary approach. Innovations 6, 25–33 (In Russian).
Kowalkowski, C., Witell, L., Gustafsson, A., 2013. Any way goes: identifying value constellations for service infusion in SMEs. Ind. Market. Manag. 42 (1), 18–30.
Laskurain-Iturbe, I., Arana-Landín, G., Landeta-Manzano, B., Uriarte-Gallastegi, N., 2021. Exploring the influence of industry 4.0 technologies on the circular economy. J. Clean. Prod. 321 https://doi.org/10.1016/j.jclepro.2021.128944.
Lee, J., Kwon, H.-B., 2017. Progressive performance modeling for the strategic determinants of market value in the high-tech oriented SMEs. Int. J. Prod. Econ. 183, 91–102. https://doi.org/10.1016/j.ijpe.2016.10.014.
Lefebvre, L.-A., Lefebvre, E., Colin, D., 2009. Process innovation, productivity, and competitiveness in smaller manufacturing firms. Can. J. Adm. Sci. 8 (1), 19–28. https://doi.org/10.1111/j.1936–4490.1991.tb00659.x.
Li, Ts, Schmidt, YuD., 2019. A comparative assessment of the level of technological development of ferrous metallurgy enterprises in Russia. In: In tHe Collection: Cross-Border Markets for Goods and Services: Research Problems. Proceedings of the III International Scientific and Practical Conference. School of Economics and Management, pp. 250–252 (In Russian).
Love, J.H., Ganotakis, P., 2013. Learning by exporting: lessons from high-technology SMEs. Int. Bus. Rev. 22 (1), 1–17. https://doi.org/10.1016/j.ibusrev.2012.01.006.
Marabaeva, L.V., 2016. A methodological approach to assessing the level of technological development of an enterprise. Bull. Volzhsky Univ. 2 (2), 163–168 (In Russian).
Masood, T., Sonntag, P., 2020. Industry 4.0: adoption challenges and benefits for SMEs. Comput. Ind. 121, 1–12. https://doi.org/10.1016/j.compind.2020.103261.
Mezentseva, O.E., 2015. The development of high-tech production in Russia and worldwide. Fundam. Res. 7, 176–181 (In Russian).
Mikaeva, S.A., Mikayeva, A.S., 2018. Level and capacity assessment of technological development of enterprise. Int. J. Eng. Technol. 7 (4), 42–44. https://doi.org/10.14419/ijet.v7i4.36.22710.
Mittal, S., Khan, M.A., Romero, D., Wuest, T., 2018. A critical review of smart manufacturing & Industry 4.0 maturity models: implications for small and medium-sized enterprises (SMEs). J. Manuf. Syst. 49, 194–214. https://doi.org/10.1016/j.jmsy.2018.10.005.
Müller, J.M., Buliga, O., Voigt, K., 2018. Fortune favors the prepared: how SMEs approach business model innovations in Industry 4.0. Technol. Forecast. Soc. Change 132, 2–17.
Narula, S., Puppala, H., Kumar, A., Frederico, G.F., Dwivedy, M., Prakash, S., Talwar, V., 2021. Applicability of industry 4.0 technologies in the adoption of global reporting initiative standards for achieving sustainability. J. Clean. Prod. 305 https://doi.org/10.1016/j.jclepro.2021.127141.
National Science Board, 2018. Sci. Eng. Indicat. 1060 p. – [Electronic resource]. – Access mode:https://www.nsf.gov/statistics/seind/#tabs–1.
Nick, G., Kovács, T., Kő, A., Kádár, B., 2021. Industry 4.0 readiness in manufacturing: company Compass 2.0, a renewed framework and solution for Industry 4.0 maturity assessment. Procedia Manuf. 54, 39–44. https://doi.org/10.1016/j.promfg.2021.07.007.
Nikanorov, R.O., Merenkov, M.G., Rutelevskay, Y.D., 2017. Analysis of the level of technological development of wood-processing enterprises of Krasnoyarsk territory. Relevant Prob. Aviat. Astronaut. 3 (13), 86–88 (In Russian).
Nunes, P.M., Serrasqueiro, Z., Leitão, J., 2012. Is there a linear relationship between R&D intensity and growth? Empirical evidence of non–high–tech vs. high–tech SMEs. Res. Pol. 41 (1), 36–53. https://doi.org/10.1016/j.respol.2011.08.011.
OECD, S.M.E., Outlook, Entrepreneurship, 2019. OECD Publishing, Paris. https://doi.org/10.1787/34907e9c–en.
Olefirenko, O., Nagornyi, Y., Shevliuga, O., 2014. A methodical approach to estimation of industrial enterprises' technical and technological development. 8 (158), 464–470.
Ostapenko, A.V., Kosyreva, A.I., 2017. Basic typical indicators for assessing the level of technological development of enterprises in the rocket and space industry. Bulletin Sci. Conf. 5–3 (21), 63–66 (In Russian).
Pérez, J.D.C., Buitrón, R.E.C., Melo, J.I.G., 2018. Methodology for the retrofitting of manufacturing resources for migration of SME towards industry 4.0. Int. Conf. Appl. Inf. 337–351.
Podshivalova, M.V., Pylaeva, I.S., Almrshed, S.K., 2021. Innovative profile of the Russian pharmaceutical industry. Vopr. Ekon. 6, 139–156. https://doi.org/10.32609/0042-8736-2021-6-139-156 (In Russian).
Pokonov, A.A., 2017. Strategic Management of Technological Development of the Timber Industry in the Region, Abstract of a Thesis of the Candidate of Economical Sciences - Krasnoyarsk, p. 24 p (In Russian).
Pollard, J., Osmani, M., Cole, C., Grubnic, S., Colwill, J., 2021. A circular economy business model innovation process for the electrical and electronic equipment sector. J. Clean. Prod. 305 https://doi.org/10.1016/j.jclepro.2021.127211.
Prosvirina, I.I., Tashchev, A.K., 2014. Economics of knowledge and modern trends in the use of labor in Russia. Bulletin SUSU Econ. Manag. 8 (1), 73–79.
Prudnikova, L.V., Kolbenok, A.V., 2017. Technological level of development of the organization. Socio-economic development of organizations and regions of Belarus: efficiency and innovation. In: Materials of Reports of the International Scientific and Practical Conference. Vitebsk State Technological University, pp. 264–267.
PWC, 2018. The Global Innovation 1000 Study [Electronic resource] – Access mode: https://www.strategyand.pwc.com/gx/en/insights/innovation1000.html.
Rachynska, G.V., Lisovska, L.S., 2011. The Assessment of the Level of Technological Development of Enterprises. Bulletin of Lviv Polytechnic National University. 698: Problems of Economics and Management, pp. 277–281 (In Ukrainian).
Rafael, L.D., Jaione, G. E, Cristina, L, Ibon, S. L, 2020. An Industry 4.0 maturity model for machine tool companies. Technol. Forecast. Soc. Change 159, 120203. https://doi.org/10.1016/j.techfore.2020.120203.
Raymond, L., St-Pierre, J., 2010. R&D as a determinant of innovation in manufacturing SMEs: an attempt at empirical clarification. Technovation 30 (1), 48–56. https://doi.org/10.1016/j.technovation.2009.05.005.
Rizos, V., Bryhn, J., 2022. Implementation of circular economy approaches in the electrical and electronic equipment (EEE) sector: barriers, enablers and policy insights. J. Clean. Prod. 338 https://doi.org/10.1016/j.jclepro.2022.130617.
Roper, S., Hewitt-Dundas, N., 2008. Innovation persistence: survey and case–study evidence. Technovation 37, 149–162. https://doi.org/10.1016/j.respol.2007.10.005.
Saad, S.M., Bahadori, R., Jafarnejad, H., Putra, M.F., 2021. Smart production planning and control: technology readiness assessment. Procedia Comput. Sci. 180, 618–627. https://doi.org/10.1016/j.procs.2021.01.284.
Saarenketo, S., Puumalainen, K., Kuivalainen, O., Kyläheiko, K., 2004. Dynamic knowledge-related learning processes in internationalizing high-tech SMEs. Int. J. Prod. Econ. 89 (3), 363–378. https://doi.org/10.1016/s0925-5273(03)00185-3.
Sadeghi, A., Azar, A., Rad, R.S., 2012. Developing a fuzzy group AHP model for prioritizing the factors affecting success of high-tech SME's in Iran: a case study. Proc. Soc. Behav. Sci. 62, 957–961. https://doi.org/10.1016/j.sbspro.2012.09.163.
Samonova, ChV., 2020. The assessment of the conditions and quantitative indicators of the technological development of high-tech industries in Russia by the example of the radio-electronic industry. Online sci. J. Manag. Econ. Soc. Syst. 4 (6). URL: http://www.journal-mes.ru.
Shin, S.-J., Woo, J., Rachuri, S., 2014. Predictive analytics model for power consumption in manufacturing. Proc. CIRP 15, 153–158.
Shtepa, M.V., 2013. The assessment of the technical development of enterprises in a competitive environment. Russ. Enterpren. 14 (5), 33.
Silkina, A.V., Erygina, L.V., 2016. Assessment tools of the level of scientific-technological development of enterprises of the military-industrial complex. Bulletin Samara State Econ. Univ. 10 (144), 28–34 (In Russian).
Somina, I.V., 2017. The assessment of the current state and institutional environment for the development of the high-tech sector of the Russian economy. Soc. Humanit. Knowl. 5, 67.

Soyan, ShCh, 2018. Assessing the technological development of Tyva Republic economy. Econ. Anal.: Theor. Pract. 17 (10), 1868–1881. https://doi.org/10.24891/ea. 17. 10.1868 (In Russian).

Strelkova, L.V., Kabanov, S.S., 2012. Technological development of industry branches: assessment and prospects. Bull. Nizhny Novgorod Univ. 2 (2), 247–251 (In Russian).

Tzokas, N., Kim, Y.A., Akbar, H., Al-Dajani, H., 2015. Absorptive capacity and performance: the role of customer relationship and technological capabilities in high-tech SMEs. Ind. Market. Manag. 47, 134–142. https://doi.org/10.1016/j.indmarman.2015.02.033.

Uskov, V.S., Ushakova, YuO., 2018. Methodology for assessing the level of scientific and technological development of the industrial sector in the region in the transition to a digital economy. Relevant Prob. Mod. Econ. 9, 218–223 (In Russian).

Uzyakov, M.N., 2011. The efficiency of using primary resources as an indicator of technological development: retrospective analysis and forecast. Prob. Forecasting 2 (125), 3–18.

Volkova, I.A., Efremova, G.M., 2013. The assessment of the level of technological development of agricultural organizations. Bulletin Sib. Univ. Consum. Cooperat. 4 (7), 49–55.

Wonglimpiyarat, J., 2015. New economics of innovation: strategies to support high-tech SMEs. J. High Technol. Manag. Res. 26 (2), 186–195. https://doi.org/10.1016/j.hitech.2015.09.006.

Würtz, G., Kölmel, B., 2012. Integrated engineering A SME suitable model for business and information systems engineering (BISE) towards the smart factory. IFIP Adv. Inf. Commun. Technol. 380 (AICT), 494–502.

Yakubovsky, YuV., Karastelev, B.Ya, Brovko, P.M., 2014. Science intensive production technologies as an economic growth vector (on the example of Russian helicopter enterprises). Bull. Irkutsk State Tech. Univ. 5 (88), 215–219 (In Russian).

Zambon, I., Cecchini, M., Egidi, G., Saporito, M.G., Colantoni, A., 2019. Revolution 4.0: industry vs. Agriculture in a future development for SMEs. Processes 7 (1), 36. https://doi.org/10.3390/pr7010036.

Zhang, Y., Zhang, G., Wang, J., Sun, S., Si, S., Yang, T., 2014. Real-time information capturing and integration framework of the internet of manufacturing things. Int. J. Comput. Integrated Manuf. 28 (8), 811–822.

Zharov, V.S., Zuckerman, V.A., 2015. The system of indicators for determining the level of innovativeness of technological development of mining and industrial enterprises. Min. Inf. Anal. Bull. 1, 180–184.