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PRODUCT QUALITY MANAGEMENT IN INDUSTRY 4.0 BASED ON DIGITAL INSTITUTIONS

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A B S T R A C T

The article aims to determine the possibilities of product quality management in industry 4.0 based on digital institutions. Based on international experience for 2022, the authors applied the regression analysis method to compile an econometric model that proves that ensuring digital competitiveness requires state and public management of product quality in industry 4.0 with the help of digital institutions. It has also been proved that digital competitiveness in local and global markets is determined by different institutions. The theoretical significance of the authors' conclusions is that they have formed a new institutional understanding of product quality in industry 4.0. The contribution of the article to the literature consists in the development of the scientific provisions of the TQM concept through the formation of a new, broad understanding of the quality of Industry 4.0 products in the unity of the completeness of the manufacturer's technical capabilities and the perceived value and usefulness of this product, as well as through a reconsideration of the approach to measuring and managing the quality of products industry 4.0 in order to strengthen their digital competitiveness in accordance with the new understanding of quality. The practical significance of the article is related to the fact that the monitoring has revealed a favorable institutional environment for quality management of products in industry 4.0 in Russia. The institutional perspective of improving the product quality of industry 4.0 in Russia has also been opened up. The managerial significance is expressed in the fact that the developed institutional approach to product quality management in industry 4.0 will improve the efficiency of this management and ensure a more complete capacity utilization of medium- and high-tech industries, as well as an increase in the export of their products. The proposed approach can be applied in any country of the world, as it has been developed taking into account a broad analysis of international experience.

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1. INTRODUCTION

In connection with the transition to industry 4.0, product quality has become of increased importance. This is due to the fact that digital products with different levels of quality (with the exception of obvious defects) can meet the target needs, although, certainly, to varying degrees. Therefore, the competitiveness of pre-digital products was mainly determined by the "price-quality" ratio. At the same time, low-quality products with a low price in certain market segments (in segments of consumers with low incomes) could be even more competitive than products of higher quality, but sold at a higher price and therefore unprofitable for purchase or not available at all.

The fundamental difference between digital competition and pre-digital one is that it takes place to a much greater extent in the field of quality than in the field of price (Sharma, 2023). The product quality in industry 4.0 is mainly determined, firstly, by compliance with quality standards, deviation from which is immediately considered a defect and makes products of industry 4.0 unsuitable for use and, accordingly, not meeting its target need (Yangailo et al., 2023). Secondly, the innovativeness of products in industry 4.0, due to which they acquire new properties and become unique, and therefore they are especially in demand on the market (Subramanian et al., 2023).
Thus, the peculiarity of industry 4.0 is that its products, as a rule, have higher digital competitiveness with a combination of high quality and high price (Yapa and Fernando, 2023).

At the same time, products of industry 4.0 with a more optimal price-quality ratio due to a lower price, but with lower quality, will have less digital competitiveness and may even be pushed out of the market (Yüksel and Ersöz, 2023). This feature dictates the need to apply a specific (different from management in the conditions of pre-digital competition) approach to the quality management of products in industry 4.0 in order to ensure its digital competitiveness.

The problem is that the existing approach to product quality management in industry 4.0 does not fully correspond to the noted features of digital competition. The applied approach focuses on internal organizational processes and on the interests of internal stakeholders – primarily owners of enterprises in industry 4.0. Guided by these interests, quality management assumes the optimization of business operations and innovation management in an effort to maximize economic efficiency - to minimize costs, guarantee the return on venture investments and increase profits.

The disadvantage of the implemented approach is insufficient consideration of the interests of external stakeholders – society (including consumers) and the state. The limitation of the information taken into account by internal sources causes intuitive decision-making in the quality management of products in industry 4.0. This determines the high susceptibility of this management to the influence of the "human factor" and, accordingly, high quality risks. This drawback of the established approach reduces the digital competitiveness of enterprises in industry 4.0 and the effectiveness of the practice of quality management of their products.

The above determines the relevance of the development of an alternative approach that ensures systematic consideration of the interests of stakeholders in the quality management of products of industry 4.0, the rationality of managerial decision-making and the disclosure of the potential of digital competitiveness. A view of the interests of stakeholders such as society and the state from the standpoint of social institutions makes it possible to generalize and comprehensively consider them. In the context of industry 4.0, digital institutions play a key role, the essence of which has been studied in sufficient detail and disclosed in the available literature. However, it is not clear from the available publications what role digital institutions play in ensuring the quality of products in industry 4.0, which is a gap in the literature.

This article is focused on filling the identified gap and aims to determine the possibilities of product quality management in industry 4.0 based on digital institutions. Further, in this article, a literature review is conducted in which research questions (RQs) and hypotheses are formulated. In it, the interpretation of the price quality of industry 4.0 is reinterpreted from the standpoint of the concept of total quality management (TQM).

The alternative organizational subsystems of the enterprise of industry 4.0, in which the quality management of its products is carried out, are opposed: industrial and manufacturing engineering and management information systems. Digital institutions are systematized and the view of the existing literature on their impact on product quality in industry 4.0 is presented.

After that, the methodology of the study is described and its results, including, firstly, determining the role of digital institutions in product quality management in industry 4.0. Secondly, monitoring the favorable institutional environment for product quality management in industry 4.0 in Russia. Thirdly, the substantiation of the institutional prospects for improving product quality in industry 4.0 in Russia. Fourthly, the development of an institutional approach to product quality management in industry 4.0. In the discussion, taking into account the new scientific results obtained in this article, the authors' answers to RQs are formulated in comparison with the existing literature.

2. LITERATURE REVIEW

2.1. Rethinking of the interpretation of product quality in industry 4.0 from the standpoint of the concept of total quality management (TQM)

The central category and object of study in this article is product quality of industry 4.0, which determines the importance of defining its concept and essence. The definition of product quality in industry 4.0 should not only identify its boundaries, but also open up opportunities for its quantitative measurement based on official statistics. A comparative analysis of the existing and proposed new interpretation of product quality in industry 4.0 is carried out in Table 1.

As shown in Table 1, the existing interpretation considers product quality of industry 4.0 from the standpoint of the concept of disruptive innovation, authored by Clayton M. Christensen (2022). This is a narrow interpretation of quality, limited by the interests of the enterprise itself in industry 4.0 (internal stakeholders) (Popkova, 2020a). The criterion for measuring product quality in industry 4.0 is the innovativeness of products and the degree of disclosure of the potential of advanced technologies in industry 4.0 in the production of products (Escobar et al., 2023; Popkova, 2020b).

Table 1. Comparative analysis of the existing and proposed new interpretation of product quality in industry 4.0

Components of product quality in industry 4.0	**Interpretation of product quality in industry 4.0**	
	The existing interpretation: from the standpoint of the concept of disruptive innovations	**The new interpretation: from the perspective of the TQM concept**
The author of the concept	Clayton M. Christensen	Armand W. Feigenbaum
The scale of product quality interpretation in industry 4.0	a narrow interpretation of quality, limited by the interests of the enterprise of industry 4.0	a broad interpretation of quality that comprehensively takes into account the interests of all stakeholders
Criteria for measuring product quality in industry 4.0	the innovativeness of products and the degree of disclosure of the potential of advanced technologies of industry 4.0 in the production of products	the degree of satisfaction of stakeholders' interests in the production, sale and consumption of products
The way to improve product quality in industry 4.0	creation and implementation of destructive innovations	bringing products in line with the interests of all stakeholders
The meaning of improving product quality in industry 4.0	removing competitors from the market and/or creating new markets in which the company will initially be a monopolist	strengthening the digital competitiveness of products in target local and global markets

Source: developed by the authors.

The way to improve product quality in industry 4.0 is to create and implement disruptive innovations (Alrabadi et al., 2023). The meaning of improving product quality in industry 4.0 is to push competitors out of the market and/or create new markets in which the company will initially be a monopolist (Antony et al., 2023). A critical view of the existing interpretation of product quality in industry 4.0 has revealed its disadvantage associated with the emergence of an "institutional trap": innovation for innovation's sake.

The economic meaning of this "institutional trap" is that quality improvement does not lead to an increase in the digital competitiveness of products of industry 4.0 due to the fact that its innovative properties are not in demand on the market - they are not interesting to consumers or even negatively evaluated by the general public and the state. As an example, mass protests and even cases of damage to the telecommunications infrastructure of the 5G Internet in the countries of the European Union by representatives of civil society who fear that this infrastructure is dangerous - it can damage human health and the environment.

As another example, we can cite mass discontent with the function of personal identification of users through face recognition in smartphones due to frequent errors caused by the imperfection of machine vision of artificial intelligence. The above well-reasoned criticism of the existing interpretation has led to the proposal of a new authors' interpretation of product quality in industry 4.0. The authors' interpretation is based on the concept of integrated (total) quality management (TQM) (Canbay and Akman, 2023; Cramer et al., 2023; Liu et al., 2023), the author of which is Armand V. Feigenbaum (1999).

This is a broad interpretation of quality that comprehensively takes into account the interests of all stakeholders – both internal and external. The authors' interpretation assumes the use of the degree of satisfaction of stakeholders' interests in the production, sale and consumption of products as a new criterion for measuring product quality in industry 4.0. The way to improve product quality in industry 4.0 is to bring products in line with the interests of all stakeholders. The meaning of improving product quality in industry 4.0 is associated with strengthening the digital competitiveness of products in target local and global markets.

Thus, based on the scientific provisions of the TQM concept, a new, broad understanding of product quality of industry 4.0 has been formed in the unity of the completeness of the use of the manufacturer's technical capabilities and the perceived value and usefulness of this product. The advantage of the authors' vision is the systematic accounting of internal and external stakeholders of enterprises of industry 4.0 in it, which makes it preferable for the scientific interpretation of product quality of industry 4.0. In accordance with the new definition, it is advisable to reconsider the approach to quality measurement and management of products in industry 4.0 in the interests of strengthening its digital competitiveness.

2.2. Product quality management in industry 4.0: industrial and manufacturing engineering vs management information systems

The general issues of product quality management in industry 4.0 have been studied in sufficient detail and reflected in numerous published literature, in particular, in the work of Saihi et al. (2023). However, the content analysis of the existing literature has shown that some issues of product quality management in industry 4.0 have been studied superficially. Thus, the published works do not explain the implications of this management for the digital competitiveness of enterprises in industry 4.0.

RQ$_1$: How to manage product quality in industry 4.0 to ensure digital competitiveness? Available publications of Carvalho and Lima (2022), Maganga and Taifa (2023), Shivam, Gupta (2023), Veselovsky et al. (2018a), Veselovsky et al. (2018b) propose to manage the quality of products in industry 4.0 with the help of corporate governance, the subjects of which are the enterprises of industry 4.0 themselves. Industrial and manufacturing engineering acts as the organizational subsystem of the enterprise of industry 4.0, in which the quality of its products is managed (Prashar, 2023).

The advantage of corporate governance is the breadth of capabilities of the enterprise of industry 4.0 itself to determine the quality of its products. However, its serious disadvantage is due to the fact that in this case external stakeholders are not allowed to manage the quality of products in industry 4.0, which causes high risks that the quality of these products does not meet the interests of external stakeholders. In this regard, corporate governance does not correspond to the authors' proposed interpretation of product quality in industry 4.0 from the standpoint of TQM.

The idea that digital institutions determine the level (market concentration), the scale (openness of the economy) and the nature (conditions for achieving competitive advantages) of digital competition, noted in the works of Popkova et al. (2021), Popkova (2019), Sergi et al. (2019), Sergi and Popkova (2022), better corresponds to this concept. At the same time, the requirements of the state and public opinion are conveyed to enterprises through management information systems (Tang et al., 2023). In this case, the product quality of industry 4.0 is measured:

- In local markets through the scale of production in industry 4.0 (Ahmed et al., 2022; Ko et al., 2022; Yanamandra et al., 2023);
- In global markets through the scale of export of products of industry 4.0 (Bochko et al., 2022; Popkova, 2022; Wang et al., 2023).

Based on the above literature, ***the hypothesis H$_1$*** is put forward in this article: state and public product quality management in industry 4.0 with the help of digital institutions is required to ensure digital competitiveness.

2.3. Digital institutions and their impact on product quality in industry 4.0: a view from the perspective of the existing literature

The systematization of scientific knowledge contained in the existing literature has made it possible to identify the following main digital institutions that can potentially contribute to improving the product quality of industry 4.0:

- The institution of the information society, on the basis of which information is exchanged about the experience of purchasing and consuming Industry 4.0 products and public opinion is formed about its quality. Internet affordability acts as an indicator of the level of development of this institution (Bauer, 2022; Kimura, 2022);
- The institution of electronic commerce, on the basis of which products are sold in industry 4.0, as well as gathering of consumer feedback on their quality and wishes for quality improvement. Internet quality acts as an indicator of the level of development of this institution (Shiu et al., 2023; Wulfert, 2023);
- The institution of demand for digital innovation, on the basis of which potential consumers develop new skills and technologies, and their interest in innovative products of industry 4.0 is formed. The level of development and availability of electronic infrastructure acts as an evaluation indicator of this institute (Fink et al., 2020; Haghshenas and Østerlie, 2020);
- The institution of electronic security, on the basis of which public confidence in digital technologies is formed, as well as in products of industry 4.0 (Fenzl et al., 2023; Iranmanesh, 2023);
- Thy institution of electronic government, on the basis of which digital tax administration and control over the activities of enterprises of industry 4.0, including quality control, is carried out (Hochstetter et al., 2023; Niankara, 2022).

Despite a clear understanding of the list of digital institutions, their impact on product quality in industry 4.0 has not been sufficiently studied and is not disclosed in the existing literature, which is a gap in it and raises the following research question. **RQ_2**: Which institutions determine the quality of Industry 4.0 products (its digital competitiveness) to the greatest extent? In their works, authors such as Ionescu et al. (2022), Lianos (2022), Ponzoa et al. (2023) point out that the digital institutions listed above equally determine the digital competitiveness of the products of enterprises of industry 4.0 in both local and global markets. Ghouse et al. (2022), Meyer et al. (2023), Zhuo et al. (2023), by contrast, note that there are significant differences in the institutional provision of the market environment at different levels of economic management, in particular, at the meso-level (region), at the macro-level (country) and at the global level (world economy).

On the basis of the above literature, ***the hypothesis H_2*** is put forward in this article: digital competitiveness in local and global markets is determined by different institutions. In order to find answers to the posed RQs and test the hypotheses put forward, this article performs econometric modeling of the impact of singled out digital institutions on the quality of products in industry 4.0, measured from the standpoint of its digital competitiveness in local (production scale) and global (export scale) markets.

3. MATERIALS AND METHODOLOGY

3.1. Sampling and control variables

The sample of this study contains all 112 countries of the world included in the "Ranking Countries By Digital Quality of Life in 2022" Visual Capitalist (2023), according to which this sample covers 92% of the world's population. Statistical data on indicators characterizing the level of development of the main digital institutions identified in the literature review are taken from this ranking. The following set of control variables is obtained:

- internet affordability (it will be denoted as ia), which characterizes the level of development of the institution of the information society;
- internet quality (it will be denoted as iq), characterizing the level of development of the institution of electronic commerce;
- electronic infrastructure (it will be denoted as ei), characterizing the level of development of the institution of demand for digital innovations;
- electronic security (it will be denoted as es), characterizing the level of development of the same name institution;
- electronic government (it will be denoted as eg), characterizing the level of development of the same name institution.

The article also uses statistical data characterizing the quality and digital competitiveness of the products of industry 4.0 enterprises: in local markets – using the indicator "medium and high-tech manufacturing value added (% manufacturing value added)" (it will be denoted as MHT_1) (World Bank, 2023b) and in global markets – using the indicator "medium and high-tech exports (% manufactured exports)" (it will be denoted as MHT_2) (World Bank, 2023a). The time period of the study: 2022. The data are combined into a common table and are given in the appendix to this article.

3.2. Procedure and methodology of the study

The first task is to determine the role of digital institutions in product quality management in industry 4.0. The task is solved using the regression analysis method. The regression model of the dependence of the quality and digital competitiveness of the products of enterprises of industry 4.0 on a set of control variables characterizing the level of development of digital institutions is compiled. The research model is written as follows:

$$MHT=a+b_{ia}*ia+b_{iq}*iq+b_{ei}*ei+b_{ed}*es+b_{eg}*eg \quad (1)$$

The reliability of the research model (1) is tested using the multiple correlation coefficient, Fisher's F-test and Student's t-test. The hypothesis H_1 will be considered proved if the regression dependence of the product quality of industry 4.0 on digital institutions is statistically significant (the multiple correlation coefficient exceeds 0.50 and F-test is passed), and a stable dependence on at least some digital institutions is established (Student's t-test is passed).

The hypothesis H_2 is also tested based on the research model (1) and will be considered proved if a stable dependence of the quality and digital competitiveness of the products of enterprises of industry 4.0 in different markets (local and global) on different digital institutions is established (Student's t-test for MHT_1 and MHT_2 is passed with different factor variables).

The second task is to monitor the favorable institutional environment for product quality management in industry 4.0 in Russia. For this purpose, an analytical hierarchical procedure developed by Saaty, T.L. (2016) and known as the Saaty method is chosen. This method assumes the following monitoring algorithm:

1. To compare the values of control variables characterizing the level of development of digital institutions in Russia in 2022 with the maximum values in the world (with the maximum in the sample). To find the ratio of values in Russia to the maximum values in the world;
2. To calculate the significance of each indicator as the sum of its correlation coefficients with

MT_1 and MHT_2 and find the total significance (the sum of all values);
3. To determine the weighting coefficients as the ratio of the significance of each indicator to the total significance;
4. To calculate the weighted sums as the product of the ratio of values in Russia to the maximum values in the world and weight coefficients;
5. To carry out a hierarchical synthesis: to add together all the weighted sums.

The greater the hierarchical synthesis, the more favorable the institutional environment for product quality management in industry 4.0.

The third task is to substantiate the institutional perspective of improving the product quality of industry 4.0 in Russia. To solve this task, the maximum values in the world (maximum by sample) of factor variables are substituted into the research model (1) and the consequences for the resulting variables are determined. The method of trend analysis defines the growth rate of values of all studied indicators in comparison with their values in Russia in 2022.

The fourth task is to develop an institutional approach to product quality management in industry 4.0. The approach describes the impact of singled out digital institutions on the product quality of enterprises of industry 4.0. The approach also demonstrates the differences identified in the course of econometric modeling between quality management in local and global markets to systematically strengthen the digital competitiveness of enterprises in industry 4.0 and their products.

4. RESULTS

4.1. The role of digital institutions in product quality management in industry 4.0

In order to solve the first task of this study and determine the role of digital institutions in product quality management in industry 4.0, a regression analysis of sample data has been carried out in accordance with the research model (1). The results obtained are shown in Tables 2-3.

Table 2. Regression analysis of the dependence of medium and high-tech manufacturing value added on a set of control variables characterizing the level of development of digital institutions

Regression Statistics	
Multiple R	0.7605
R-Square	0.5783
Adjusted R-Square	0.5584
Standard Error	11.7874
Observations	112

ANOVA

	df	*SS*	*MS*	*F*	*Signifi-cance F*
Regression	5	20196.8043	4039.3609	29.0721	$1.8*10^{-18}$
Residual	106	14727.9635	138.9431		
Total	111	34924.7678			

	Coeffi-cients	*Standard Error*	*t-Stat*	*P-Value*	*Lower 95%*	*Upper 95%*
Constant	-23.1470	5.3186	-4.3521	3.1E-05	-33.6917	-12.6023
ia	34.3706	52.9842	0.6487	0.5179	-70.6758	139.4169
iq	161.3602	87.6124	1.8418	0.0683	-12.3399	335.0602
ei	130.1995	70.6143	1.8438	0.0680	-9.8002	270.1992
es	15.8369	30.1068	0.5260	0.6000	-43.8527	75.5265
eg	146.5126	73.6048	1.9905	0.0491	0.5839	292.4413

Source: calculated and compiled by the authors.

In Table 2, the multiple correlation coefficient has taken the value 0.7605 (close relationship). This means that the change in the value added of medium- and high-tech production among the sample countries by 76.05% is mainly due to differences in the level of development of digital institutions. The significance of F=1.8*10-18, which indicates a small error. Fischer's F-test has been passed at a significance level of 0.01, at which the critical F (at k_1=m=5, k_2=n-m-1=112-5-1=106) is 3.1949. The observed F exceeds the critical one, amounting to 29.0721.

Student's T-test has been passed at a significance level of 0.1 (at which the critical t=1.6583) and only for three factor variables: 1) for iq (the observed t=1.8418); 2) for ei (the observed t=1.8438); 3) for eg (the observed t=1.9905). The conducted tests indicate a sufficiently high reliability of the results of regression analysis.

Table 3. Regression analysis of the dependence of medium and high-tech exports on a set of control variables characterizing the level of development of digital institutions

Regression Statistics	
Multiple R	0.7133
R-Square	0.5087
Adjusted R-Square	0.4856
Standard Error	17.0325
Observations	112

ANOVA

	df	*SS*	*MS*	*F*	*Signifi-cance F*
Regression	5	31845.4433	6369.0887	21.9543	$4.88*10^{-15}$
Residual	106	30751.2653	290.1063		
Total	111	62596.7086			

	Coeffi-cients	*Standard Error*	*t-Stat*	*P-Value*	*Lower 95%*	*Upper 95%*
Constant	-10.6584	7.6853	-1.3869	0.1684	-25.8952	4.5784
ia	32.9703	76.5608	0.4306	0.6676	-118.8190	184.7596
iq	135.6101	126.5976	1.0712	0.2865	-115.3820	386.6022
ei	87.7441	102.0359	0.8599	0.3918	-114.5519	290.0401
es	163.3388	43.5035	3.7546	0.0003	77.0888	249.5887
eg	76.6706	106.3571	0.7209	0.4726	-134.1926	287.5338

Source: calculated and compiled by the authors.

In Table 3, the multiple correlation coefficient has taken the value of 0.7133 (close relationship). This means that the change in medium and high-tech exports among the sample countries by 71.33% is mainly due to differences in the level of development of digital institutions. The significance of F=4.88* 10-15, which indicates a small error. Fischer's F-test has been passed at a significance level of 0.01, at which the critical F (at k_1=m=5, k_2=n-m-1=112-5-1=106) is 3.1949. The observed F exceeds the critical one, amounting to 21.9543.

Student's T-test has passed only for two factor variables: 1) for iq at a significance level of 0.3 (at which critical t=1.0412, it exceeds the observed t=1.0712); 2) for es at a significance level of 0.01 (at which critical t=2.6204, it exceeds the observed t=3.7546). The conducted tests indicate a sufficiently high reliability of the results of regression analysis. The results obtained in Tables 2-3 make it possible to compile an econometric model of the impact of digital institutions on product quality management in industry 4.0:

$$\begin{cases} MHT_1=-23.1470+34.3706*ia+161.3602*iq+ \\ \quad +130.1995*ei+15.8369*es+146.5126*eg, \\ MHT_2=-10.6584+32.9703*ia+135.6101*iq+ \\ \quad +87.7441*ei+163.3388*es+76.6706*eg. \end{cases} \quad (2)$$

Model (2) is a system of equations of multiple linear regression, indicating that medium and high-tech manufacturing value added rises by 34.3706% of manufacturing value added and medium and high-tech exports grow by 32.9703% of manufactured exports with an increase in internet affordability by 1 point. Medium and high-tech manufacturing value added rises by 161.3602% of manufacturing value added and medium and high-tech exports grow by 135.6101% of manufactured exports with an increase in internet quality by 1 point.

Medium and high-tech manufacturing value added rises by 130.1995% of manufacturing value added and medium and high-tech exports grow by 87.7441% of manufactured exports with an increase in electronic infrastructure by 1 point. Medium and high-tech manufacturing value added rises by 15.8369% of manufacturing value added and medium and high-tech exports grow by 163.3388% of manufactured exports with an increase in electronic security by 1 point. Medium and high-tech manufacturing value added rises by 146.5126% of manufacturing value added and medium and high-tech exports grow by 76.6706% of manufactured exports with the development of electronic government by 1 point.

Thus, all the obtained regression coefficients have taken a positive sign. The regression dependence of the product quality of industry 4.0 on digital institutions is statistically significant (in both cases, the multiple correlation coefficients exceed 0.50, F-test has been passed), and a stable dependence on certain digital institutions has also been established (in both cases, Student's t-test has been passed). This proves the hypothesis H_1.

The authors have established a stable dependence of the quality and digital competitiveness of the products of enterprises of industry 4.0 in different markets (local

and global) on different digital institutions – Student's t-test for the dependent variables has been passed with different factor variables: MHT_1 – with iq, ei and eg, and MHT_2 – with iq and es. This proves the hypothesis H_2.

4.2. Monitoring of the level of favorability of the institutional environment for product quality management in industry 4.0 in Russia

In order to solve the second task of this study and to determine the level of favorability of the institutional environment for product quality management in industry 4.0 in Russia, the monitoring of this environment was carried out in 2022 using the Saati method (Table 4).

As shown in Table 4, the weighting coefficients of digital institutions for the product quality of enterprises of industry 4.0 in Russia and their digital competitiveness are as follows. Weight of internet affordability is 0.1214; weight of internet quality is 0.2093; weight of electronic infrastructure is 0.2281; electronic security is 0.2134; weight of electronic government is 0.2278. The hierarchical synthesis was 0.6272. Consequently, the institutional environment for product quality management of industry 4.0 in Russia in 2022 is favorable by 62.72%.

Table 4. Monitoring of the level of favorability of the institutional environment for product quality management in industry 4.0 in Russia

Monitoring element	Internet affordability	Internet quality	Electronic infrastructure	Electronic security	Electronic government
The values in Russia	0.0556	0.0794	0.1512	0.0943	0.1520
The maximum values in the world	0.1917	0.1202	0.1968	0.2000	0.1947
The ratio of values in Russia to the maximum values in the world	0.0556/ /0.1917= =0.2900	0.0794/ /0.1202= =0.6606	0.1512/ /0.1968= =0.7683	0.0943/ /0.2000= =0.4715	0.1520/ /0.1947= =0.7807
The correlation with MHT_1	0.3814	0.6727	0.7224	0.6015	0.7275
The correlation with MHT_2	0.3443	0.5780	0.6408	0.6738	0.6341
Significance, proportions from 1	(0.3814+ +0.3443)/2= =0.3629	(0.6727+ +0.5780)/2= =0.6254	(0.7224+ +0.6408)/2= =0.6816	(0.6015+ +0.6738)/2= =0.6377	(0.7275+ +0.6341)/2= =0.6808
Total significance	0.3629+0.6254+0.6816+0.6377+0.680=2.9883				
Weighting coefficients	0.3629/ /2.9883= =0.1214	0.6254/ /2.9883= =0.2093	0.6816/ /2.9883= =0.2281	0.6377/ /2.9883= =0.2134	0.6808/ /2.9883= =0.2278
Weighted sum	0.2900* *0.1214= =0.0352	0.6606* *0.2093= =0.1382	0.7683* *0.2281= =0.1752	0.4715* *0.2134= =0.1006	0.7807* *0.2278= =0.1779
Hierarchical synthesis	0.0352+0.1382+0.1752+0.1006+0.1779=**0.6272**				

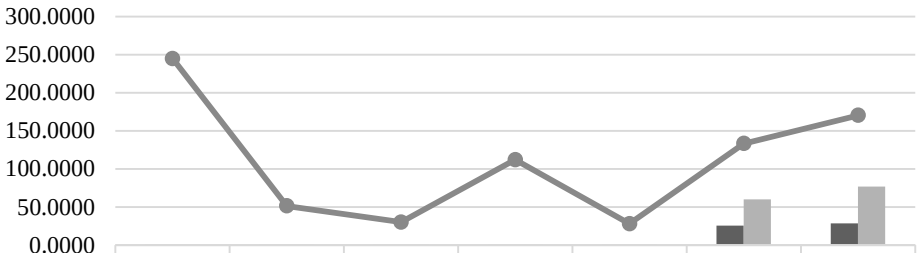
Source: calculated and compiled by the authors.

4.3. Institutional perspective of improving the product quality of industry 4.0 in Russia

In order to solve the third task of this study and substantiate the institutional perspective of improving the product quality of industry 4.0 in Russia, the maximum values in the world (maximum according to the sample from Table 4) of factor variables are substituted in model (2) and the consequences for the dependent variables are determined. The method of trend analysis has determined the growth rate of the values of all the studied indicators in comparison with their values in Russia in 2022 (Fig. 1).

As shown in Fig. 1, the product quality of enterprises in industry 4.0 will significantly grow with an increase (compared to 2022) in the level of development of digital institutions in Russia to the level of global leadership (internet affordability: +244.7842%; internet quality: +51.3854%; electronic infrastructure: +30.1587%; electronic security: +112.0891%; electronic government: +28.0921%).

Their digital competitiveness will increase. In local markets, medium and high-tech manufacturing value added will rise from 25.7891% of manufacturing value added in 2022 to 60.1540% of manufacturing value added (+133.2536%). In global markets, medium and high-tech exports will increase from 28.4249 (% manufactured exports in 2022 to 76.8259 (% manufactured exports (+170.2766%).



	Internet affordability	Internet quality	Electronic infrastructure	Electronic security	Electronic government	Medium and high-tech manufacturing value added (% manufacturing value…	Medium and high-tech exports (% manufactured exports)
The values in 2022	0.0556	0.0794	0.1512	0.0943	0.1520	25.7891	28.4249
The values in the perspective	0.1917	0.1202	0.1968	0.2000	0.1947	60.1540	76.8259
The growth of values in the future	244.7842	51.3854	30.1587	112.0891	28.0921	133.2536	170.2766

Figure 1. Institutional perspective of improving the product quality of industry 4.0 in Russia
Source: calculated and compiled by the authors.

4.4. Institutional approach to product quality management in industry 4.0

In order to solve the fourth task of this study and develop an institutional approach to product quality management in industry 4.0, the authors have made a description of the impact of selected digital institutions on the product quality of enterprises in industry 4.0. Fig. 2 clearly demonstrates the differences revealed during econometric modeling between quality management in local and global markets to systematically strengthen the digital competitiveness of enterprises in industry 4.0 and their products.

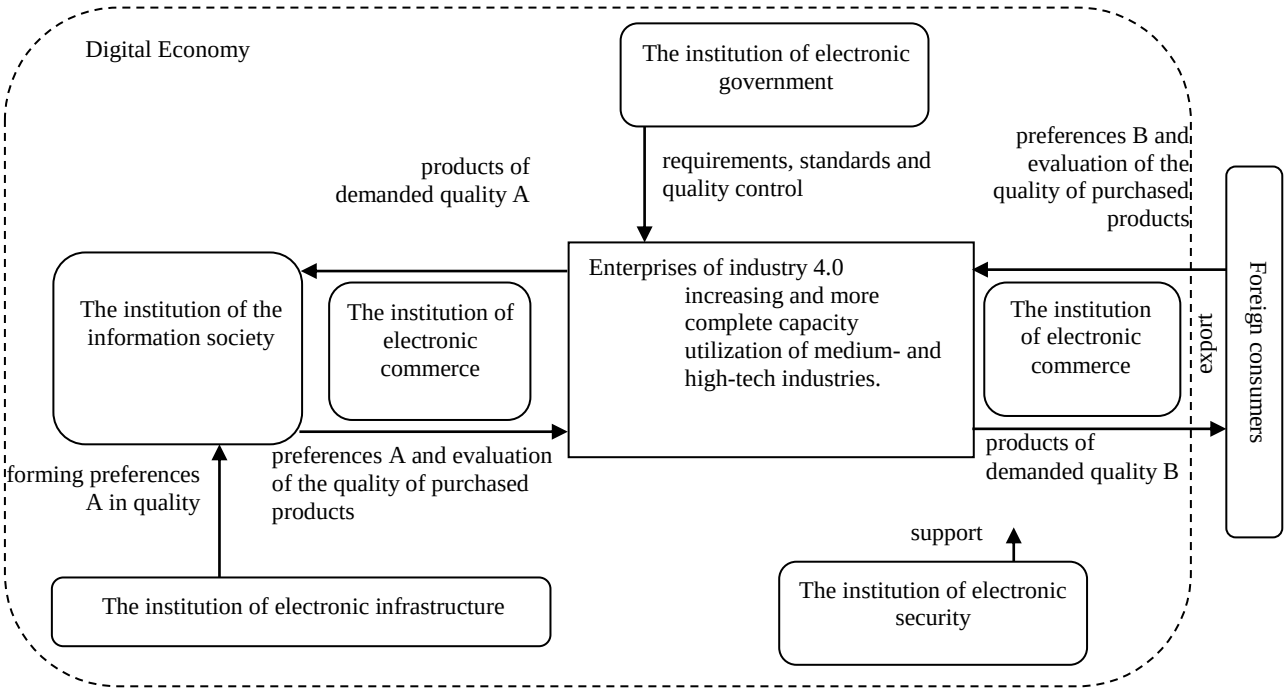


Figure 2. Institutional approach to product quality management in industry 4.0
Source: calculated and compiled by the authors.

As shown in Fig. 2, the proposed approach assumes that in the local market of the digital economy, the institute of electronic infrastructure forms preferences A in quality. The institution of the information society transmits its preferences and subjective assessment of the quality of purchased products to enterprises of industry 4.0 through the institution of electronic commerce, and in return receives products of demanded quality A. Additionally, the institution of electronic government fixes requirements A in the national quality standards and monitors their compliance.

In the global market, the enterprise of industry 4.0 learns from foreign consumers their preferences B and a subjective assessment of the quality of purchased products through the institution of electronic commerce, and also exports them products of the demanded quality B, the demand for which is supported by the institution of electronic security. The advantages of the developed approach are: increased and more complete capacity utilization of medium- and high-tech industries, as well as increased exports of their products.

5. DISCUSSION

The contribution of the article to the literature consists in the development of the scientific provisions of the TQM concept through the formation of a new – broad understanding of product quality of industry 4.0 in the unity of the completeness of the use of the manufacturer's technical capabilities and the perceived value and usefulness of this product, as well as through the reconsideration of the approach to quality measurement and quality management of products of industry 4.0 in the interests of strengthening its digital competitiveness in accordance with the new understanding qualities. In Table 5, the authors' answers to RQs are formulated in comparison with the existing literature, taking into account the new scientific results obtained in this article.

Table 5. Answers to RQs: the existing literature vs the new scientific results obtained in this article

<table>
<tr><th rowspan="2">Research question</th><th colspan="2">The existing literature</th><th colspan="2">The new results of this article</th></tr>
<tr><th>The provisions of the literature</th><th>References</th><th>The meaning of the answer</th><th>The quantitative measurement</th></tr>
<tr><td rowspan="3">RQ₁: How to manage product quality in industry 4.0 to ensure digital competitiveness?</td><td rowspan="3">Corporate governance through industrial and manufacturing engineering</td><td rowspan="3">Carvalho and Lima (2022), Maganga and Taifa (2023), Shivam, Gupta (2023), Veselovsky et al. (2018a), Veselovsky et al. (2018b)</td><td colspan="2">State and public governance through management information systems with the help of digital institutions, which determines:</td></tr>
<tr><td>● Production in industry 4.0</td><td>by 76,05%;</td></tr>
<tr><td>● Export of products of industry 4.0</td><td>by 71,33%.</td></tr>
<tr><td rowspan="9">RQ₂: Which institutions determine the quality of Industry 4.0 products (its digital competitiveness) to the greatest extent?</td><td colspan="2" rowspan="4">Digital competitiveness in both local and global markets is equally determined by (Ionescu et al., 2022; Lianos, 2022; Ponzoa et al., 2023) the following institutions:</td><td colspan="2">Digital competitiveness in local markets is determined by the following digital institutions:</td></tr>
<tr><td>● The institution of electronic commerce</td><td>by 61,27%;</td></tr>
<tr><td>● The institution of demand for digital innovation</td><td>by 72,24%;</td></tr>
<tr><td>● The institution of electronic government</td><td>by 72,75%.</td></tr>
<tr><td>● The institution of the information society</td><td>(Bauer, 2022; Kimura, 2022);</td><td colspan="2" rowspan="3">Digital competitiveness in global markets is determined by the following digital institutions:</td></tr>
<tr><td>● The institution of electronic commerce</td><td>(Shiu et al., 2023; Wulfert, 2023);</td></tr>
<tr><td>● The institution of demand for digital innovation</td><td>(Fink et al., 2020; Haghshenas and Østerlie, 2020);</td></tr>
<tr><td>● The institution of electronic security</td><td>(Fenzl et al., 2023; Iranmanesh, 2023);</td><td>● The institution of electronic commerce</td><td>by 57,80%;</td></tr>
<tr><td>● The institution of electronic government</td><td>(Hochstetter et al., 2023; Niankara, 2022).</td><td>● The institution of electronic security</td><td>by 67,38%;</td></tr>
</table>

Source: developed by the authors.

As shown in Table 5, the results obtained in this paper has provided a new answer to RQ_1. In contrast to the position of such researchers as Carvalho and Lima (2022), Maganga and Taifa (2023), Shivam, Gupta (2023), Veselovsky et al. (2018a), Veselovsky et al. (2018b), the authors of the article have proved that product quality management in industry 4.0, aimed at ensuring digital competitiveness, should be carried out

not on the basis of corporate governance, but on the basis of state and public management with the help of digital institutions.

Unlike Prashar (2023), the organizational subsystem of an enterprise of industry 4.0, in which the quality of its products is managed, is management information systems, but not industrial and manufacturing engineering (in support of the view of Tang et al., 2023). Based on international experience in 2022, it has been proved that product quality management in industry 4.0, based on digital institutions, determines production in industry 4.0 by 76.05% (in support of the view of Ahmed et al., 2022; Ko et al., 2022; Yanamandra et al., 2023), and also determines exports industry 4.0 products by 71.33% (in support of the view of Bochko et al., 2022; Popkova, 2022; Wang et al., 2023).

The results obtained in this paper have also provided a new answer to RQ_2. UnlikeIonescu et al. (2022), Lianos (2022), Ponzoa et al. (2023), it has been proved that digital competitiveness in local and global markets is determined not by the same, but by different institutions (in support of the position of Ghouse et al., 2022; Meyer et al., 2023; Zhuo et al., 2023).

It has been proved that digital competitiveness in local markets is determined by the following digital institutions: the institution of electronic commerce by 61.27% (in support of the opinion oa Shiu et al., 2023; Wulfert, 2023), the institution of demand for digital innovation by 72.24% (in support of the view of Fink et al., 2020; Haghshenas and Østerlie, 2020) and the institutin of electronic government by 72.75% (in support of the position of Hochstetter et al., 2023; Niankara, 2022).

Digital competitiveness in global markets is determined by the following digital institutions: the institution of electronic commerce by 57.80% (in support of Shiu et al., 2023; Wulfert, 2023) and the institution of electronic security by 67.38% (in support of Fenzl et al., 2023; Iranmanesh, 2023).

In contrast to the position of such authors as Bauer (2022), Kimura (2022), the article has proved that the role of the institution of the information society in product quality management of enterprises of industry 4.0 is insignificant for their competitiveness in both local and global markets.

6. CONCLUSION

The main conclusion of this study is that digital institutions make it possible to improve the practice of product quality management in industry 4.0. It has been substantiated that ensuring digital competitiveness requires state and public management of product quality in industry 4.0 with the help of digital institutions (the hypothesis H_1 has been proved).

It has also been justified that digital competitiveness in local and global markets is determined by different institutions (the hypothesis H_2 has been proved). Consequently, the possibility to benefit from the "economies of scale" in the context of industry 4.0 depends on digital competitiveness achieved through ensuring high quality and its differentiation in the local and global market.

The theoretical significance of the authors' conclusions is that they have formed a new – institutional understanding of product quality in industry 4.0. The practical significance of the article is related to the fact that the monitoring has revealed a favorable institutional environment for product quality management in industry 4.0 in Russia. The institutional perspective of improving the product quality of industry 4.0 in Russia has also been revealed.

The managerial significance is expressed in the fact that the developed institutional approach to product quality management in industry 4.0 will improve the efficiency of this management and ensure a more complete capacity utilization of medium- and high-tech industries, as well as an increase in the export of their products. The proposed approach can be applied in any country of the world, as it has been developed taking into account a broad analysis of international experience.

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