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THE ROLE OF QUALITY MANAGEMENT IN THE DEVELOPMENT OF HIGH-TECH INDUSTRIAL ENTERPRISES IN THE CONTEXT OF INDUSTRY 4.0

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A B S T R A C T

The article aims to develop a new model for the development of industry 4.0 that reveals cause-and-effect relationships and thereby increases the predictability and manageability of this process. The authors has compiled a structural equation model (SEM) based on the empirical experience of 45 of the most developed digital economies in the world in 2022, which has formed a systematic vision of industrial engineering 4.0 in the unity of quality management and the development of high-tech industrial enterprises. Based on the SEM model and the example of Russia, it has been proved that quality management 4.0 plays a central role in the development of high-tech industrial enterprises in developed digital economies. As a result, the article has developed a cyclical model of the development of industry 4.0, explaining the logical sequence and demonstrating the path of continuous development of industry 4.0. The novelty and value of the compiled cyclical model lies in the fact that it has proved for the first time the simultaneous existence of two previously considered alternative effects of industrial and manufacturing engineering 4.0: the effect of transition from quantity to quality and the effect of transition from quality to quantity. The theoretical significance of the model lies in the fact that for the first time it has structured the sequence of this process, by dividing it into two stages: the first is the stage of the initial launch of high-tech industries and the second is the stage of the subsequent development of industry 4.0. The authors' model demonstrated that quality management 4.0 plays a key role in the development of high-tech industrial enterprises at the second stage, while at the first stage the role of quality 4.0 is insignificant. The practical significance is expressed in the fact that reliance on the cyclical model of development of industry 4.0 will improve the efficiency of management of industrial and manufacturing engineering 4.0, selecting the most effective management measures at each of the identified two stages of development of industry 4.0.

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1. INTRODUCTION

The Fourth Industrial Revolution has not just opened a new technological horizon, but has fundamentally changed the technological landscape of the modern world economic system (Oosthuizen, 2022). Initially, it was assumed that digital technologies would create new markets that would increase the degree of diversification of the most innovative economies or become new areas of their international industrial specialization (Ghislieri et al., 2018).

However, it has now become obvious that high-tech products have not just created new separate markets, but have generated digital segments of almost all industry markets. They are increasingly filling modern markets, displacing their less competitive low-tech products. In this regard, the issue of establishing its own high-tech industries has become acute and mandatory on the agenda of each country (Singaram and Mayer, 2022).
The country's status on the world stage depends on the success of solving this issue. Countries that have already been able or in the future will be able to establish their own high-tech production will acquire the status of self-sustaining digital economies that have technological sovereignty and are exporters of high-tech products. This status increasingly guarantees a high rate and stability of economic growth, resilience to economic crises and favorable opportunities to promote the country's interests on the world stage (Bettiol et al., 2021).

Countries that will not be able to establish their own high-tech production, respectively, will be assigned the status of importers of products of these industries that do not have technological sovereignty, dependent on external supplies of technologies and products of industry 4.0. This status already brings with it a low rate of economic growth, increased economic cyclicity, its heavy dependence on price volatility on world markets, as well as limited opportunities to promote its interests on the world stage (Şimşek Demirbağ and Yıldırım, 2023).

The problem is that the existing model of development of industry 4.0 assumes a linear vision of this process. The linear nature means that the model explains only the initial launch of high-tech industries and suggests that these industries will continue to develop independently due to the mechanism of digital competition. (Khalil et al., 2022). In fact, there is a "market failure" associated with the impossibility of natural development of high-tech industries due to an aggressive market environment with imperfect global digital competition. (Vrana, 2021). The linear model does not offer management measures for the development of industry 4.0, which is its serious disadvantage.

The meaning of the problem is that, despite the awareness of the need to develop domestic, in particular, import–substituting high-tech industries and the adoption of national digitalization strategies, emerging digital economies are unable to implement these strategies in practice, since the goals and priorities set in the strategies are not supported by specific management measures - these measures are unknown and therefore they need scientific study.

In the available literature, much attention is paid to the enumeration of the numerous advantages of industry 4.0, which are convincingly justified, but the process of development of industry 4.0 has not been sufficiently studied and explained. Because of this, industry 4.0 remains an unattainable ideal for many emerging digital economies. The uncertainty of the causal relationships of the development of industry 4.0 is a gap in the literature.

The need to fill the identified gap in the literature is explained by the fact that the uncertainty of cause-and-effect relationships hampers planning and management of the development of industry 4.0, making this process unpredictable and spontaneous. This creates very high organizational and managerial barriers to entry for new players in the global high-tech markets, and also causes chronically and critically high dependence of emerging digital economies on imports of high-tech industry.

The described problem restricts international digital competition and causes the monopolization of global high-tech markets by multinational corporations from developed digital economies. These destructive processes reduce the global availability of high-tech products, prevent the involvement of emerging digital economies in the Fourth Industrial Revolution and slow down scientific and technological progress. This determines the relevance of clarifying the cause-and-effect relationships of the development of industry 4.0.
In an effort to solve this problem, this article aims to develop a new model for the development of industry 4.0, revealing cause-and-effect relationships and thereby increasing the predictability and manageability of this process.

The goal is solved in the article with the help of a set of three following tasks. The first task is to form a systematic vision of industry 4.0 in the unity of quality management and the development of high-tech industrial enterprises.

The second task is to determine the prospects for the development of high-tech industrial enterprises in Russia in the context of industry 4.0 through the improvement of quality management. The third task is to develop a cyclical model for the development of industry 4.0. The originality of the article lies in the rethinking of quantitative and qualitative indicators of industrial engineering 4.0, due to which the authors proved for the first time the complementarity of these measures, rather than their alternativeness.

2. LITERATURE REVIEW

2.1. Industrial and manufacturing engineering 4.0: provisions of the scientific concept

The theoretical basis of the research carried out in this article is the concept of industrial and manufacturing engineering 4.0, the scientific provisions of which are expounded in the works ofAbu-Rumman et al. (2023), Nimawat and Das Gidwani (2022), Popkova et al. (2021), Popkova and Sergi (2022), Popkova (2023). The economic meaning of this concept is that management measures in industrial and manufacturing engineering determine the development of industry 4.0. While the range of these measures is known, the consequences of their application are little studied and remain largely uncertain.

This is a gap in the literature and raises the following research question. RQ_1: Which management measures of industrial and manufacturing engineering 4.0 are most effective? The existing literature does not answer this question and is limited to the enumeration of management measures of industrial and manufacturing engineering 4.0, the systematization of which, based on the official international statistics of digital competitiveness IMD (2023), makes it possible to distinguish:

- measures of knowledge management (the indicator “knowledge”) aimed at the development of human potential, in particular, building digital competencies, through education, especially higher education, the disclosure of talents in the activities of high-tech industrial enterprises and conducting R&D in the field of digitalization with the key role of universities and research organizations (Gharieb, 2021; Miao et al., 2020; Rawashdeh et al., 2021; Surjanti et al., 2019);
- measures of institutional management (the indicator “technology”) aimed at creating and maintaining a favorable regulatory environment for the formation and development of industry 4.0, financial support for high-tech industrial enterprises, the formation and modernization of ICT infrastructure (Meyer et al., 2023; Papathomas and Konteos, 2023; Prud’homme et al., 2021; Zhang and Chen, 2023);
- measures of technology management (the indicator “future readiness”) aimed at the formation and development of the consumer information society, the introduction of digital technologies and government support for industry 4.0, including the development of e-government and cybersecurity (Greco et al., 2019; Hrabovskyi et al., 2022; Jilledi et al., 2021; Rainatto et al., 2021).

To find the answer to RQ_1, this article performs econometric modeling of the dependence of the results of industrial and manufacturing engineering 4.0 on the implementation of the selected management measures.

2.2 Alternative strategies for the development of industry 4.0: the number of high-tech industries vs quality 4.0

The existing linear model of development of industry 4.0 explains its origin, while further prospects for its development go beyond the linear model, which is its limitation and a gap in the existing literature, causing the following research question. RQ_2: How does industry 4.0 develop? The key results of industrial and manufacturing engineering 4.0, reflecting the development of industry 4.0, are the following:

- a quantitative result expressed in an increase in the number of high-tech industrial productions, an increase in their production capacity, as well as a growth in the volume of high-tech exports (Duan et al., 2023; Lin and Huang, 2023; Wang et al., 2022; Ye et al., 2023);
- a qualitative result expressed in the improvement of quality 4.0, the most important indicator of which is the strength of global brands (Blagoveshchenskii et al., 2021a; Blagoveshchenskii et al., 2021b; Mandler et al., 2021; Zhu and Ji, 2022).

The linear model assumes the implementation of alternative strategies for the development of industry 4.0. The first strategy is related to the development of industry 4.0 through the transition from quantity to quality. When implementing this strategy, industrial and manufacturing engineering 4.0 is focused on improving quantitative results – scaling high-tech industries and exporting their products (Franzosi, 2021).

It is expected that in the future this will naturally lead to an increase in quality 4.0. A prominent representative of the developed digital economies implementing the strategy under consideration is China, which pays great attention to the volume of domestic production of high-tech products and strengthening independence from its imports – technological sovereignty (Rao et al., 2022). At the same time, standardization, quality control and quality assurance 4.0 are paid secondary attention (Chen et al., 2023).

The second strategy is to develop industry 4.0 through the transition from quality to quantity. In implementing this strategy, industrial and manufacturing engineering 4.0 is focused on improving quality results – enhancing quality 4.0 to strengthen the global brands of domestic high-tech industry enterprises (Peng et al., 2023). It is expected that in the future this will naturally lead to the scaling of high-tech industries and the export of their products (Rahmanzadeh et al., 2022). (Rahmanzadeh et al., 2022).

As an example of a large developed digital economy implementing the strategy under consideration, is Russia, which pays great attention to standardization, quality control and garantee of quality 4.0 But, despite this, a limited volume of domestic production of high-tech products remains and additional management measures are required in industrial and manufacturing engineering 4.0 to strengthen independence from its import – technological sovereignty (Krebish and Berberoglu, 2020).

To find the answer to RQ_2, this article performs econometric modeling of the relationship between quantitative and qualitative results of industrial and manufacturing engineering 4.0.

3. MATERIALS AND METHODOLOGY

The order of this study assumes a consistent solution of the three tasks The first task is to form a systematic vision of industry 4.0 in the unity of quality management and the development of high-tech industrial enterprises. This task is solved using the structural equation modeling (SEM) method.The advantage of this method, which is the basis for its choice in this article, is that the SEM method enables to comprehensively take into account the multilateral relationships of indicators and thereby most fully and reliably reflect the cause-effect relationships of the studied economic processes.

To find the answer to RQ_1, the authors use the regression analysis method in order to model the dependence of the results of industrial and manufacturing engineering 4.0 – 1) Nation Brands Index 2022 (it will be denoted as Qlity4.0) (IPSOS, 2023); 2) Medium and high-tech manufacturing value added, % manufacturing value added (it will be denoted as $Qtity4.0_1$) (World Bank, 2023b) and 3) High-technology exports, % of manufactured exports (it will be denoted as $Qtity4.0_2$) (World Bank, 2023a) on the implementation of the identified management measures of industrial and manufacturing engineering 4.0 (IMD, 2023): measures of knowledge management (the indicator "knowledge", it will be denoted as KN); measures of institutional management (the indicator "technology", it will be denoted as TN); measures of technology management (indicator "future readiness", it will be denoted as FR).

To find the answer to RQ_2, the authors use the regression analysis method to simulate the relationship between quantitative (Medium and high-tech manufacturing value added, $Qtity4.0_1$ и High-technology exports, $Qtity4.0_2$) and qualitative (Nation Brands Index 2022, Qlity4.0) results of industrial and manufacturing engineering 4.0. The study is conducted on the basis of data relevant for 2022. The study sample includes 45 of the most developed digital economies in the world. The statistical base of the study is systematized and presented in an Excel spreadsheet in the appendix to this article.

The second task is to determine the prospects for the development of high-tech industrial enterprises in Russia in the context of industry 4.0 through the improvement of quality management. To do this, the maximum possible values of factor variables are substituted into the obtained regression equations for the results of industrial and manufacturing engineering 4.0 and the increase in all indicators compared to their values in Russia in 2022 is estimated.

The third task is to develop a cyclical model of the development of industry 4.0. The model is presented graphically and reveals the economic meaning of cause-and-effect relationships identified in the process of econometrical structural equation modeling (SEM) for industrial and manufacturing engineering 4.0. The model reflects the most preferred management measures at each selected stage of the development of industry 4.0, as well as the target (expected) results from the implementation of these measures.

4. RESULTS

4.1. The system vision of industrial and manufacturing engineering 4.0 in the unity of quality management and development of high-tech industrial enterprises

The solution of the first task of this study, aimed at forming a systemic vision of industry 4.0 in the unity of quality management and the development of high-tech industrial enterprises through structural equation modeling, a SEM model is compiled that mathematically describes the causal relationships of industrial and manufacturing engineering 4.0.

To find the answer to RQ_1, the regression analysis method is used to model the dependence of the results of industrial and manufacturing engineering 4.0 on the implementation of selected management measures. Regression analysis of the dependence of the nation brands index on the implementation of management measures in industrial and manufacturing engineering 4.0 is carried out in Table 1.

Table 1. Regression analysis of the dependence of the nation brands index on the implementation of management measures in industrial and manufacturing engineering 4.0

Regression Statistics						
Multiple R	0.6499					
R-Square	0.4223					
Adjusted R-Square	0.3800					
Standard Error	4.8272					
Observations	45					
ANOVA						
	df	SS	MS	Signi-ficance F	F critical	F observed
Regression	3	698.4086	232.8029	$4.5*10^{-5}$	9.9907	4.2986
Residual	41	955.3784	23.3019	Fischer's F-test is passed at a significance level of 0.01		
Total	44	1653.7870				
	Coeffi-cients	*Standard Error*	*t-Stat*	*P-Value*	*Lower 95%*	*Upper 95%*
Constant	43.8489	3.2846	13.3497	$1.6*10^{-16}$	37.2154	50.4823
KN	0.2127	0.0713	2.9827	0.0048	0.0687	0.3567
TN	-0.0747	0.0827	-0.9038	0.3714	-0.2417	0.0922
FR	0.1135	0.0887	1.2788	0.2082	-0.0657	0.2927

Source: calculated and compiled by the authors.

The results obtained in Table 1 make it possible to derive the following multiple linear regression equation:

$$Qlity4.0=43.8489+0.2127KN-0.0747TN+0.1135FR \quad (1)$$

Equation (1) indicates that quality 4.0 (the strength of global brands) grows by 0.2127 points with an increase in the activity of implementing measures of knowledge management by 1 point. Quality 4.0 (the strength of global brands) rises by 0.1135 points with an increase in the activity of implementing measures of technology management by 1 point. At the same time, measures of institutional management do not contribute to improving quality 4.0 (do not strengthen global brands).

According to the results from Table 1, the quality of 4.0 (the strength of global brands) is 64.99% determined by the implementation of management measures of industrial and manufacturing engineering 4.0. Fischer's F-test has been passed at a significance level of 0.01, which confirms the reliability of the model (1). Regression analysis of the dependence of medium and high-tech manufacturing value added on the implementation of management measures industrial and manufacturing engineering 4.0 is shown in Table 2.

Table 2. Regression analysis of the dependence of medium and high-tech manufacturing value added on the implementation of management measures industrial and manufacturing engineering 4.0

Regression Statistics						
Multiple R	0.5635					
R-Square	0.3175					
Adjusted R-Square	0.2676					
Standard Error	13.2811					
Observations	45					
ANOVA						
	df	SS	MS	Signi-ficance F	F critical	F observed
Regression	3	3364.4947	1121.4982	0.0012	6.3581	4.2986
Residual	41	7231.8939	176.3877	Fischer's F-test is passed at a significance level of 0.01		
Total	44	10596.3886				
	Coeffi-cients	*Standard Error*	*t-Stat*	*P-Value*	*Lower 95%*	*Upper 95%*
Constant	5.4330	9.0370	0.6012	0.5510	-12.8176	23.6836
KN	0.6016	0.1962	3.0668	0.0038	0.2054	0.9978
TN	0.0966	0.2275	0.4245	0.6734	-0.3628	0.5559
FR	-0.1711	0.2442	-0.7007	0.4875	-0.6642	0.3220

Source: calculated and compiled by the authors.

The results obtained from Table 2 make it possible to compile the following equation of multiple linear regression:

$$Qtity4.0_1=5.4330+0.6016KN+0.0966TN-0.1711FR \quad (2)$$

Equation (2) indicates that medium and high-tech manufacturing value added rises by 0.6016% with an increase in the activity of implementing measures of knowledge management by 1 point. Medium and high-tech manufacturing value added increases by 0.0966% manufacturing value added with an increase in the activity of implementing institutional management measures by 1 point. At the same time, measures of technology management do not contribute to the increase of medium and high-tech manufacturing value added.

According to the results from Table 2, medium and high-tech manufacturing value added is 56.35% determined by the implementation of management measures of industrial and manufacturing engineering 4.0. Fischer's F-test has been passed at a significance level of 0.01, which has confirmed the reliability of the model (2). A regression analysis of the dependence of high-technology exports on the implementation of management measures of industrial and manufacturing engineering 4.0 is carried out in Table 3.

Table 3. Regression analysis of the dependence of high-technology exports on the implementation of management measures of industrial and manufacturing engineering 4.0

Regression Statistics	
Multiple R	0.5915
R-Square	0.3499
Adjusted R-Square	0.3023
Standard Error	8.8788
Observations	45

ANOVA

	df	SS	MS	Signi-ficance F	F critical	F observed
Regression	3	1739.6056	579.8685	0.0005	7.3557	4.2986
Residual	41	3232.1425	78.8327	Fischer's F-test is passed at a signficance level of 0.01		
Total	44	4971.7481				

	Coeffi-cients	*Standard Error*	*t-Stat*	*P-Value*	*Lower 95%*	*Upper 95%*
Constant	-8.3620	6.0415	-1.3841	0.1738	-20.5630	3.8391
KN	0.4363	0.1311	3.3271	0.0019	0.1715	0.7012
TN	0.1699	0.1521	1.1176	0.2703	-0.1372	0.4770
FR	-0.2497	0.1632	-1.5295	0.1338	-0.5793	0.0800

Source: calculated and compiled by the authors.

The results obtained in Table 3 allow us to compile the following equation of multiple linear regression:

$$Qtity4.0_2=-8.3620+0.4363KN+0.1699TN-0.2497FR \quad (3)$$

Equation (3) indicates that high-technology exports increases by 0.4363% of manufactured exports with an increase in the activity of implementing measures of knowledge management by 1 point. High-technology exports grow by 0.1699% of manufactured exports with an increase in the activity of implementing institutional management measures by 1 point. At the same time, technology management measures do not contribute to the increase of high-technology exports.

According to the results from Table 3, high-technology exports is 59.15% determined by the implementation of management measures of industrial and manufacturing engineering 4.0. Fischer's F-test has been passed at a significance level of 0.01, which has confirmed the reliability of the model (3). To find the answer to RQ2, the authors use regression analysis to model the relationship between quantitative and qualitative results of industrial and manufacturing engineering 4.0. The regression analysis of the dependence of the nation brands index on the quantitative results of industrial and manufacturing engineering 4.0 is presented in Table 4.

The results obtained in Table 4 make it possible to formulate the following multiple linear regression equation:

$$Qlity4.0=54.3501+0.1238Qtity4.0_1+0.0925Qtity4.0_2 \quad (4)$$

Equation (4) indicates that quality 4.0 (nation brands index) rises by 0.1288 points with an increase in medium and high-tech manufacturing value added by 1% of manufacturing value added. Quality 4.0 (nation brands index) rises by 0.0925 points with an increase in high-technology exports by 1% of manufactured exports.

Table 4. Regression analysis of the dependence of the nation brands index on quantitative results of industrial and manufacturing engineering 4.0

Regression Statistics						
Multiple R	0.4135					
R-Square	0.1710					
Adjusted R-Square	0.1315					
Standard Error	5.7135					
Observations	45					
ANOVA						
	df	SS	MS	Signi-ficance F	F critical	F observed
Regression	2.0000	282.7489	141.3745	0.0195	4.3308	3.2199
Residual	42.0000	1371.0381	32.6438	Fischer's F-test is passed at a signficance level of 0.05		
Total	44.0000	1653.7870				
	Coeffi-cients	*Standard Error*	*t-Stat*	*P-Value*	*Lower 95%*	*Upper 95%*
Constant	54.3501	2.4396	22.2787	$6.9*10^{-25}$	49.4269	59.2733
$Qtity4.0_1$	0.1238	0.0628	1.9692	0.0555	-0.0031	0.2506
$Qtity4.0_2$	0.0925	0.0917	1.0081	0.3192	-0.0927	0.2776

Source: calculated and compiled by the authors.

According to the results from Table 4, quality 4.0 (the strength of global brands) is 41.35% determined by the implementation of management measures of industrial and manufacturing engineering 4.0. Fischer's F-test has been passed at a significance level of 0.05, which has confirmed the reliability of the model (4). Regression analysis of the dependence of medium and high-tech manufacturing value added on the nation brands index is carried out in Table 5.

Table 5. Regression analysis of the dependence of medium and high-tech manufacturing value added on the nation brands index

Regression Statistics						
Multiple R	0.3885					
R-Square	0.1509					
Adjusted R-Square	0.1312					
Standard Error	14.4651					
Observations	45					
ANOVA						
	df	SS	MS	Signi-ficance F	F critical	F observed
Regression	1	1599.1207	1599.1207	0.0084	7.6426	6.6924
Residual	43	8997.2679	209.2388	Fischer's F-test is passed at a signficance level of 0.01		
Total	44	10596.3886				
	Coeffi-cients	*Standard Error*	*t-Stat*	*P-Value*	*Lower 95%*	*Upper 95%*
Constant	-18.8735	21.7583	-0.8674	0.3905	-62.7533	25.0063
Qlity4.0	0.9833	0.3557	2.7645	0.0084	0.2660	1.7007

Source: calculated and compiled by the authors.

The results obtained in Table 5 make it possible to compile the following multiple linear regression equation:

$$Qtity4.0_1=-18.8735+0.9833Qlity4.0 \quad (5)$$

Equation (5) shows that medium and high-tech manufacturing value added grows by 0.9833% of manufacturing value added with an increase in quality 4.0 (nation brands index) by 1 point. According to the results from Table 4, medium and high-tech manufacturing value added is 38.85% determined by quality 4.0 (the strength of global brands). Fischer's F-test has been passed at a significance level of 0.01, which has confirmed the reliability of the model (5). A regression analysis of the dependence of high-technology exports on the nation brands index is carried out in Table 6.

The results obtained in Table 5 allow us to make the following multiple linear regression equation:

$$Qtity4.0_2=-16.7777+0.5328Qlity4.0 \quad (6)$$

Table 6. Regression analysis of the dependence of high-technology exports on the nation brands index

Regression Statistics						
Multiple R	0.3073					
R-Square	0.0944					
Adjusted R-Square	0.0734					
Standard Error	10.2325					
Observations	45					
ANOVA						
	df	SS	MS	Significance F	F critical	F observed
Regression	1	469.4722	469.4722	0.0400	4.4838	3.8625
Residual	43	4502.2759	104.7041	Fischer's F-test is passed at a signficance level of 0.05		
Total	44	4971.7481				
	Coefficients	*Standard Error*	*t-Stat*	*P-Value*	*Lower 95%*	*Upper 95%*
Constant	-16.7777	15.3917	-1.0900	0.2818	-47.8179	14.2626
Qlity4.0	0.5328	0.2516	2.1175	0.0400	0.0254	1.0402

Source: calculated and compiled by the authors.

Equation (6) indicates that high-technology exports grow by 0.5328% of manufactured exports with an increase in quality 4.0 (nation brands index) by 1 point. According to the results from Table 4, high-technology exports are 30.73% determined by quality 4.0 (the strength of global brands). Fischer's F-test has been passed at a significance level of 0.05, which has confirmed the reliability of the model (5). The systematization of the results obtained in Tables 1-6 make it possible to compile structural equation model (SEM) of industrial and manufacturing engineering 4.0 (Fig. 1).

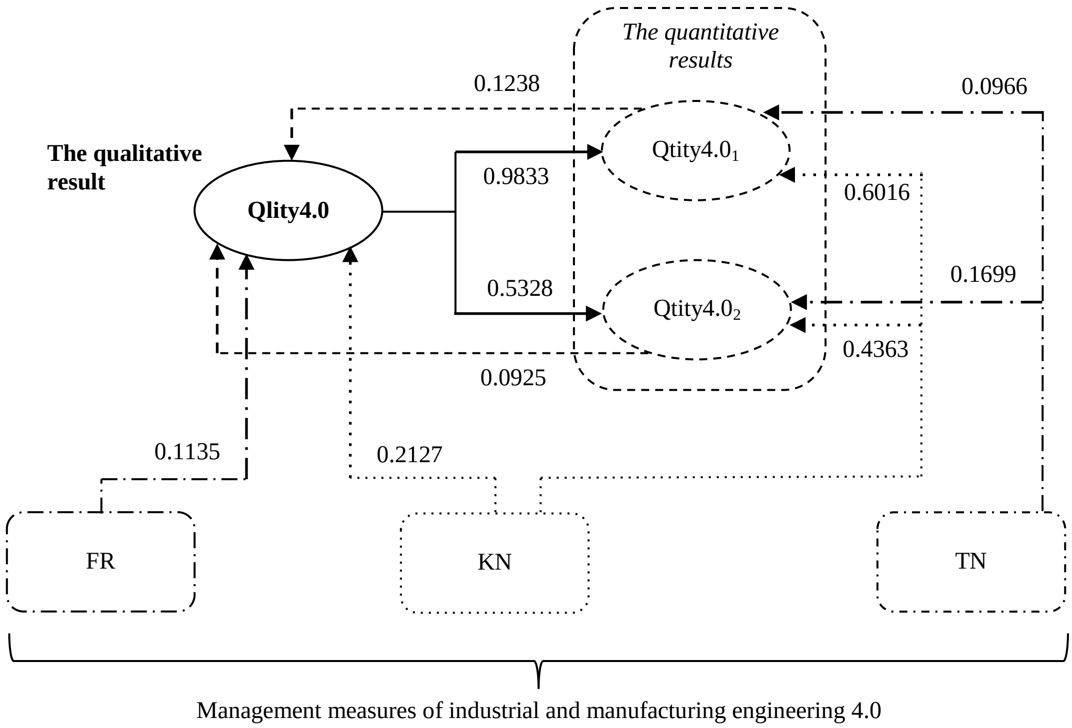

Figure 1. The structural equation model (SEM) industrial and manufacturing engineering 4.0 model
Source: calculated and compiled by the authors.

The structural equation model (SEM) in Figure 1 has demonstrated that different management measures of industrial and manufacturing engineering 4.0 are needed to achieve quantitative and qualitative results. The selected positive regression coefficients are indicated on it. The structural equation model (SEM) has also shown that the development of industry 4.0 is non-linear, since both the transition from quantity to quality, and the transition from quality to quantity are achieved in industrial and manufacturing engineering 4.0. Consequently, the development of industry 4.0 occurs cyclically.

4.2. Prospects for the development of high-tech industrial enterprises in Russia in the context of industry 4.0 through the improvement of quality management

To solve the second task of this study, aimed at determining the prospects for the development of high-tech industrial enterprises in Russia in the context of industry 4.0 through the improvement of quality management, the optimization has performed based on equations (1)-(6) (Fig. 2).

The results received in Fig. 2 show that the optimization of industrial and manufacturing engineering 4.0 makes it possible to comprehensively improve both quantitative and qualitative results. At the same time, it is worth emphasizing that optimization opportunities depend on the stage of development of industry 4.0. Since modern Russia is a developed digital economy, it is at the stage of development of industry 4.0, which has already been formed.

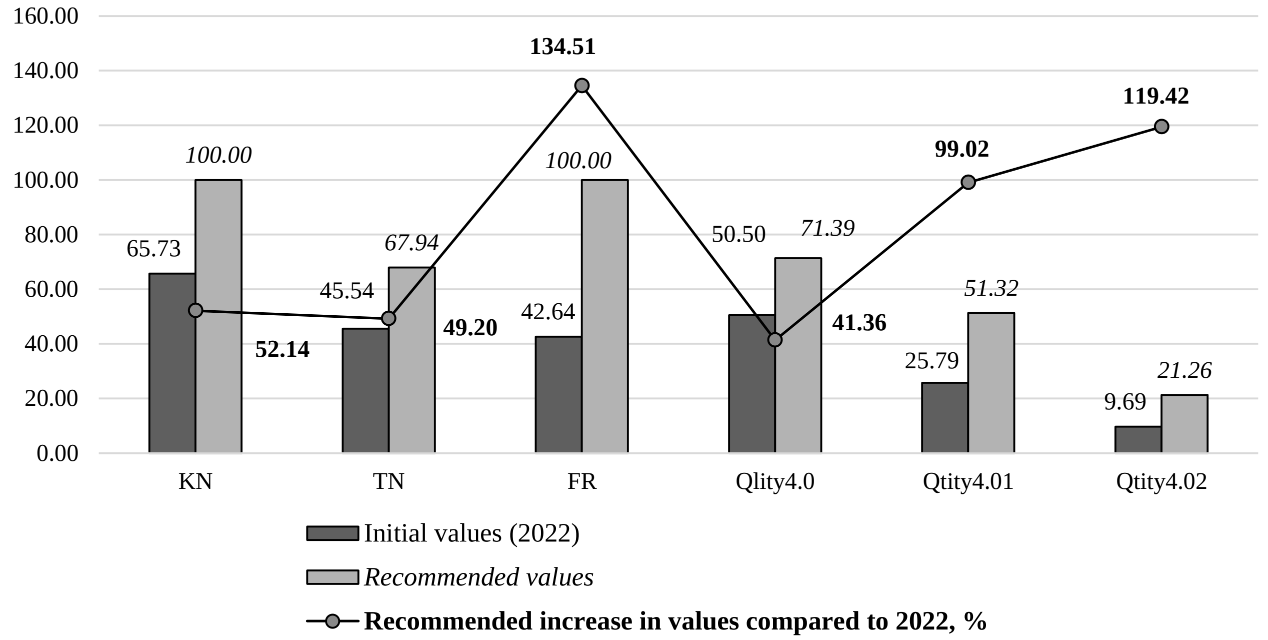

Figure 2. Prospects for the development of high-tech industrial enterprises in Russia in the context of industry 4.0 through the improvement of quality management

Source: calculated and constructed by the authors.

At this stage, the optimization of industrial and manufacturing engineering 4.0 involves increasing the activity of implementing measures of knowledge management (it is recommended +52.14% in Russia) and technology management measures (it is recommended +134.51% in Russia). Due to this, quality 4.0 (the strength of global brands of Russian companies) will increase by 41.36% (from 50.50 points in 2022 to 71.39 points). Medium and high-tech manufacturing value added will grow by 99.02% (from 25.79% of manufacturing value added in 2022 to 51.32% of manufacturing value added) High-technology exports will increase by 119.42% (from 9.69% of manufactured exports in 2022 to 21.26% of manufactured exports).

4.3. Cyclical model for the development of industry 4.0.

As part of the solution of the third task of this study, for the qualitative interpretation of the quantitative results obtained (embodied in the structural equation model (SEM)), a cyclical model of the development of industry 4.0 has been developed. The authors' model reveals the economic meaning of the established causal relationships of industrial and manufacturing engineering 4.0, and also suggests the most preferred order for the development of industry 4.0, reflecting the specifics of each stage of this process (Fig. 3).

The developed cyclical model for the development of industry 4.0 assumes that this process occurs in two stages. At the first stage, the initial launch of high-tech production takes place. Emerging digital economies are at this stage. The target result of industrial and manufacturing engineering 4.0 is expressed quantitatively in increasing the number and growing production capacities of high-tech industries.

The most preferred management measures at this stage are: 1) measures of knowledge management aimed at the development of human potential through education, disclosure of talents, R&D; 2) measures of institutional management aimed at creating an enabling regulatory environment, financial support, development of ICT infrastructure.

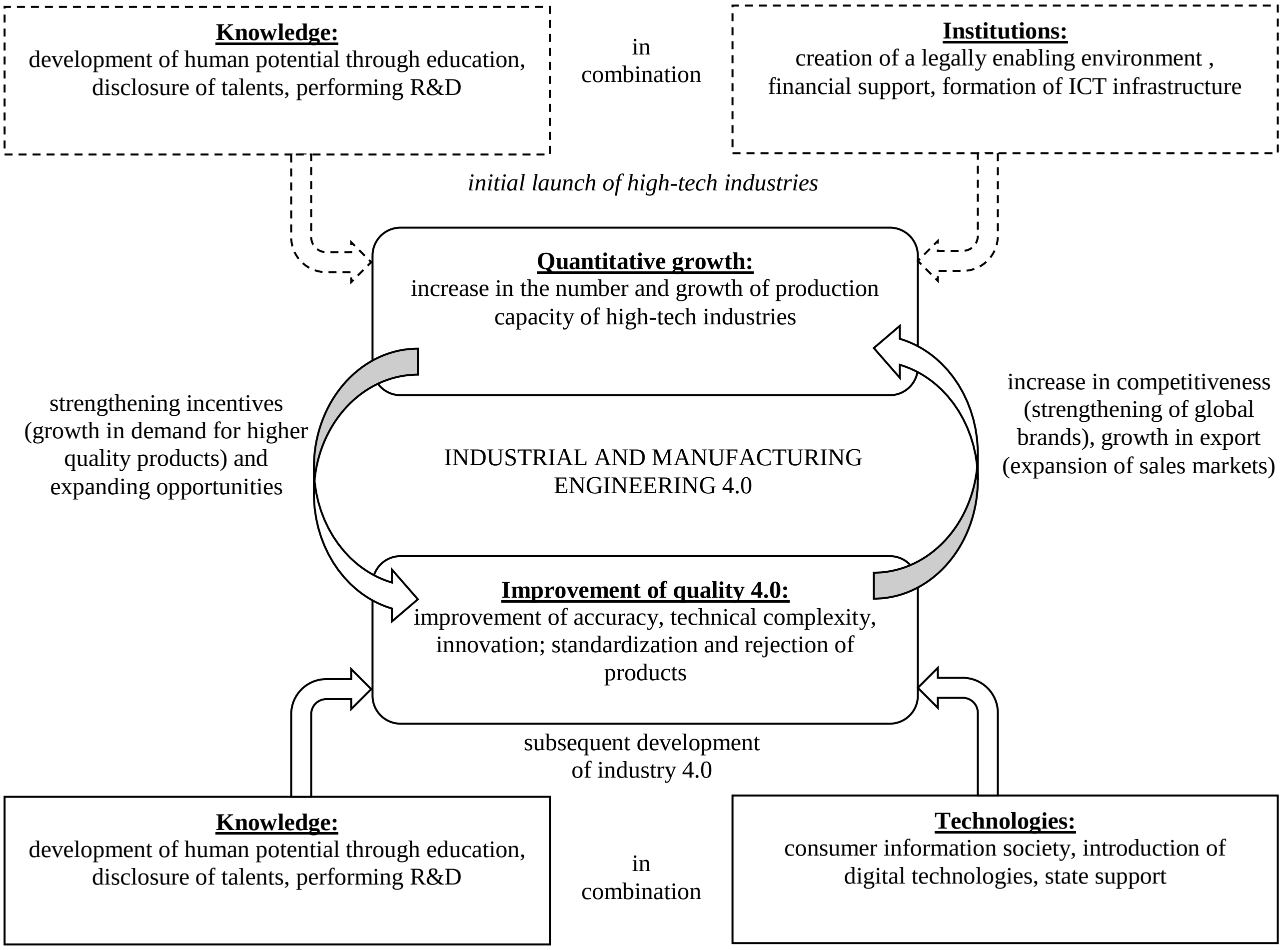

Figure 3. Cyclical model for the development of industry 4.0
Source: developed by the authors.

Due to the effect of the transition from quantity to quality, incentives are strengthened (growth in demand for higher-quality products) and opportunities are expanded, which contributes to the launch of the second stage. At the second stage, the subsequent development of the already formed industry 4.0 is carried out. Developed digital economies are at this stage. The target result of industrial and manufacturing engineering 4.0 is expressed qualitatively in increasing accuracy, technical complexity, innovation, standardization, as well as in product rejection.

The most preferred management measures at this stage are: 1) measures of knowledge management aimed at the development of human potential through education, the disclosure of talents, R&D; 2) measures of technology management aimed at the development of the consumer information society, the introduction of digital technologies and government support for the development of industry 4.0.

The improvement of quality 4.0 ensures an increase in competitiveness (strengthening of global brands) and a growth of high-tech exports, that is, the expansion of sales markets for domestic high-tech industries. This generates the effect of transition from quality to quantity, expressed in the fact that the improvement of quality 4.0 contributes to the quantitative growth of high-tech industry enterprises. Then the described cycle repeats many times, which transfers industry 4.0 to an ever higher level of development.

5. DISCUSSION

The contribution of the article to the literature is achieved through the development of scientific provisions of the concept of industrial and manufacturing engineering 4.0 through clarifying the cause-effect relationships of the implementation of management measures and the development of industry 4.0. The scientific novelty of the research lies in the development of a new cyclical model of the development of industry 4.0, a comparative analysis of which with the existing (linear) model is carried out in Table 7.

Table 7. Comparative analysis of the existing (linear) and proposed new (cyclical) models of the development of industry 4.0

RQs	Development model of Industry 4.0			
	Linear model		Cyclical model	
	Characteristics of the model	Sources of literature	Characteristics of the model	Confirmation of the characteristics
RQ$_1$: Which management measures of industrial and manufacturing engineering 4.0 are most effective?	• measures of knowledge management ("knowledge", KN);	(Gharieb, 2021; Miao et al., 2020; Rawashdeh et al., 2021; Surjanti et al., 2019)	• at the stage of the initial launch of high-tech production; • at the stage of the subsequent development of industry 4.0.	• Qtity4.01 is 56.35% determined by the influence of KN (+), TN (+) and FR (-); • Qtity4.0$_1$ is 59.15% determined by the influence of KN (+), TN (+) and FR (-); • Qlity4.0$_1$ is 64.98% determined by the influence of KN (+), TN (-) and FR (+).
	• measures of institutional management ("technology", TN);	(Meyer et al., 2023; Papathomas and Konteos, 2023; Prud'homme et al., 2021; Zhang and Chen, 2023)	• at the stage of the initial launch of high-tech production.	
	• measures of technology management ("future readiness", FR).	(Greco et al., 2019; Hrabovskyi et al., 2022; Jilledi et al., 2021; Rainatto et al., 2021).	• at the stage of the subsequent development of industry 4.0.	
RQ$_2$: How does industry 4.0 develop?	• through the transition from quantity (productions: Qtity4.0$_1$ and export: Qtity4.0$_2$) to quality (Qlity4.0);	(Franzosi, 2021). (Rao et al., 2022). (Chen et al., 2023)	• through a repeated transition from quantity to quality, from quality to quantity.	• Qlity4.0 is 41.35% determined by the influence of Qtity4.0$_1$ and Qtity4.0$_2$;
	• through the transition from quality (Qlity4.0) to quantity (productions: Qtity4.0$_1$ and export: Qtity4.0$_2$).	(Peng et al., 2023). (Rahmanzadeh et al., 2022). Krebish and Berberoglu, 2020)		• Qlity4.0 determines Qtity4.0$_1$ by 38.85% and determines Qtity4.0$_2$ by 30.73%.

Source: developed by the authors.

As can be seen from Table 7, in support of the position of researchers such as Gharieb (2021), Miao et al. (2020), Rawashdeh et al. (2021), Surjanti et al. (2019), it has been proven that measures of knowledge management ("knowledge", KN) are effective and appropriate for implementation at both stages of the development process of industry 4.0. In contrast to Meyer et al., (2023), Papathomas and Konteos (2023), Prud'homme et al. (2021), Zhang and Chen (2023) it has been justified that measures of institutional management ("technology", TN) are effective and appropriate to implement only at the stage of the initial launch of high-tech industries.

Unlike Greco et al. (2019), Hrabovskyi et al. (2022), Jilledi et al. (2021), Rainatto et al. (2021), it has been proven that measures of technology management ("future readiness", FR) are effective and appropriate to implement only at the stage of subsequent development of industry 4.0. The mathematical dependences of the following indicators established in the article serve as confirmation of the conclusions made (the received answer to RQ$_1$):

- at the stage of the initial launch of high-tech production: Qtity4.0$_1$ is 59.15% determined by the influence of KN (+), TN (+) and FR (-); Qlity4.0$_1$ is 64.98% determined by the influence of KN (+), TN (-) and FR (+);
- at the stage of subsequent development of industry 4.0: Qtity4.0$_1$ is 56.35% determined by the influence of KN (+), TN (+) and FR (-).

The authors have also received a new answer to RQ$_2$, which consists in the fact that the development of industry 4.0 occurs through a repeated transition from quantity to quality, from quality to quantity. The established mathematical dependencies of the indicators serve as confirmation of this conclusion:

- at the stage of the initial launch of high-tech industries: Qlity4.0 is 41.35% determined by the influence of Qtity4.0$_1$ and Qtity4.0$_2$, which proves the existence of a transition effect from quantity to quality (and confirms the position of Chen et al., 2023; Franzosi, 2021; Rao et al., 2022);
- at the stage of subsequent development of industry 4.0: Qlity4.0 determines Qtity4.0$_1$ by 38.85% and determines Qtity4.0$_2$ by 30.73%, which proves the existence of a transition effect from quality to quantity (and confirms the position of Peng et al., 2023; Rahmanzadeh et al., 2022; Krebish and Berberoglu, 2020).

The provided evidence confirms that the developed cyclical model more reliably describes and more deeply explains the essence and order of the development process of industry 4.0 than the existing linear model.

6. CONCLUSION

Therefore, the conducted research has achieved its purpose and has led to the following scientific results for each of the tasks set and successfully solved in the article. Firstly, the system vision of industrial and manufacturing engineering 4.0 has been formed in the unity of quality management and development of high-tech industrial enterprises, expressed in the structural equation model (SEM). The econometric model has drawn a parallel between the quantitative and qualitative results of the development of industry 4.0, proving that different management measures of industrial and manufacturing engineering 4.0 are needed to achieve them.

Secondly, the perspective of the development of high-tech industrial enterprises in Russia in the context of industry 4.0 through the improvement of quality management has been revealed. Based on the compiled structural equation model (SEM), using the example of Russia, it has been proven that in the developed digital economies, quality management 4.0 plays a central role in the development of high-tech industrial enterprises. A set of management measures for industrial and manufacturing engineering 4.0 has been proposed, the implementation of which will increase quality 4.0 by 41.36%. This will ensure an increase in medium and high-tech manufacturing value added by 99.02% and an increase in high-technology exports by 119.42%.

Thirdly, a cyclical model of the development of industry 4.0 has been developed, explaining the logical sequence and demonstrating the path of continuous development of industry 4.0. The novelty and value of the compiled cyclical model lies in the fact that it has proven for the first time the simultaneous existence of two previously considered alternative effects of industrial and manufacturing engineering 4.0: the effect of transition from quantity to quality and the effect of transition from quality to quantity.

The theoretical significance of the authors' conclusions is that they have clarified the role of quality management in the development of high-tech industrial enterprises in the context of industry 4.0. The compiled cyclical model of the development of industry 4.0 for the first time has structured the sequence of this process, dividing it into two stages: the first is the stage of the initial launch of high-tech industries and the second is the stage of the subsequent development of industry 4.0. The authors' model has demonstrated that quality management 4.0 plays a key role in the development of high-tech industrial enterprises at the second stage, while at the first stage the role of quality 4.0 is insignificant.

The practical significance is that the developed cyclical model has reflected and mathematically expressed the causal relationships of the development of industry 4.0, opening up opportunities for high-precise planning of this process, making it more predictable and manageable. Accordingly, the managerial significance is expressed in the fact that the reliance on the cyclical model of the development of industry 4.0 will improve the management efficiency of industrial and manufacturing engineering 4.0, selecting the most effective management measures at each of the identified two stages of the development of industry 4.0. Based on the proposed model, developed and emerging digital economies will be able to select the most appropriate management measures for industrial and manufacturing engineering 4.0, taking into account their specifics.

The significance for economic policy is due to the fact that the developed cyclical model of the development of industry 4.0 will enable emerging digital economies to successfully implement adopted national digitalization strategies and establish import substitution of high-tech industries. The practical implementation of the cyclical model of the development of industry 4.0 will reduce organizational and managerial barriers to entry of new players into the global high-tech markets This will increase international digital competition and ensure the demonopolization of global high-tech markets. The massive involvement of emerging digital economies in the Fourth Industrial Revolution will accelerate scientific and technological progress.

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