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CLIMATE INNOVATION IN THE PRACTICE OF QUALITY MANAGEMENT OF ENTERPRISES IN INDUSTRY 4.0

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A B S T R A C T

The article is devoted to determining the role of climate innovation for the practice of quality management of enterprises in industry 4.0. To do this, it conducts an empirical study of climate innovation in the international practice of quality management of enterprises of industry 4.0 in 2023, based on statistics by the end of 2022, using methods of regression, correlation and trend analysis, as well as variation analysis. As a result, the impact of innovation on product quality 4.0 from the standpoint of climate sustainbility has been identified and quantified. It has been established that ICT and infrastructure, staffing, organization of production and innovation funding for industry 4.0 determine the quality of 4.0 from the standpoint of climate sustainability to a much greater extent than the climate-related features of innovation in industry 4.0. The article reveals a pattern of changes in the impact of innovation on quality during neoindustrialization 4.0. This pattern is that innovation increasingly reduces quality 4.0 from the point of view of climate sustainbility in the course of neoindustrialization 4.0. The theoretical significance of the article lies in the fact that it has formed a new climate dimension of quality 4.0 in the "Decade of Action", embodied in the authors' concept of climate TQM 4.0 and taking into account the environmental properties of products 4.0 in determining and managing its quality. The practical significance of the article is related to the fact that the proposed authors' recommendations will improve the quality of 4.0 through climate optimization of innovation. The managerial significance of the article is that the developed new approach to quality management of enterprises in industry 4.0 with the help of climate innovation has rethought this management practice through the prism of the stages of the innovation process. The approach includes management measures of climate TQM 4.0 at each stage of the innovation process.

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1. INTRODUCTION

Climate change is an environmental threat that gradually loomed and manifested itself with the beginning of industrial revolutions, which received a wide public response in the XXI century. The growing concerns of ecologists in the second half of the last century and the alarming scientific forecasts, perceived for decades by manufacturers and consumers of industrial products as relating to the distant future, which can be avoided, unfortunately, have already come to life and have become a modern well-known reality.
Climatic conditions have already changed seriously and continue to change in all corners of the world, in most cases becoming less favorable for human habitation and health, to the functioning of ecosystems of the natural world, as well as for farming. In this regard, the time has come for unprecedented environmental responsibility of society, which is reflected in the global decarbonization initiative, enshrined in the Paris Agreement UN (2023) in 2015. In the same year, the Sustainable Development Goals (SDGs) were adopted, among which SDG13 is the goal of combating climate change.

In this regard, by the beginning of the “Decade of Action”, a new - climate dimention of product quality - had been institutionalized and finally entrenched in modern economic practice. This new dimension assumes the interpretation of product quality from the standpoint of its climate-related properties. In this new dimension, the more climate-friendly (safe) a product is, the higher its quality. The problem lies in the complexity of applying the noted new – climate dimension to the product quality of industry 4.0, which is found in the scientific literature in the succinct formulation “quality 4.0”.

The meaning of the problem is that the products of industry 4.0 are obviously less climate-friendly than similar products. When studying the quality of 4.0, it is advisable to consider it in the unity of the two components of “industry activity” (industry 4.0), identified by UNCTAD (2023) when determining the “readiness for frontier technologies index”. Первая составляющая: “high-technology manufactures”. The first component: “high-technology manufactures”. In comparison with low-tech industrial productions, high-tech ones are more energy-intensive, since they assume a more complete coverage of production by automation, as well as the use of more technically complex automation tools, in particular, industrial robots (Mavlyanova et al., 2015; (Vechkinzova et al., 2022).

The second component: “digitally deliverable services”. In comparison with less technically complex (non-digital) services, the services provided in industry 4.0 are much more energy-intensive, since they involve replacing human labor with machine labor (Borisova et al., 2015; Steblyakova et al., 2022). So, instead of human-provided consultations and call centers, artificial intelligence (AI)-based online consultants and chatbots are used. Electronic marketplaces (online trading platforms) are used instead of physical sales points. Instead of cash, digital means of payment are used along with mobile communication technologies (including 4G and 5G) and the Internet.

Innovation acts as a promising solution to the described problem. Innovative technologies and applied solutions for industry 4.0 can potentially be directed and can provide improved climate-related properties of products, thereby improving the quality of 4.0. However, it remains unclear from the existing scientific literature how fully this potential is used in modern economic practice, since this issue has not been studied in sufficient detail. This is a gap in the literature and causes a contradictory interpretation of the implications of innovation for quality 4.0.

On the one hand, many innovations are specifically created to improve the climate-related properties of products of industry 4.0, which is reflected in the corporate social responsibility reports of its manufacturers. On the other hand, the introduction of innovation for climate sustainbility requires special care in industry 4.0 in order to prevent its crisis. For example, a hasty transition to “clean” energy can cause interruptions in the energy supply of productions of industry 4.0 and, as a result, cause their shutdown and breakdown of expensive equipment (Turginbayeva et al., 2018).

Another example is the significant rise in the cost of industry 4.0 products with the introduction of innovation for climate sustainbility, which reduces the digital competitiveness of these products in high-tech markets and increases the risks of losses of enterprises in industry 4.0. Unlike industry 4.0, in low-tech industries and especially in the field of non-digital services, innovation for climate sustainbility are often less expensive and therefore increase the price competitiveness of their products (goods or services) compared to products of industry 4.0. This can both reduce the price affordability of products of industry 4.0 in the economy, and slow down the pace of industrialization 4.0.

This article aims to fill the identified gap in the literature by clarifying the described contradiction. The purpose of the article is to determine the role of innovation for climate sustainbility in the practice of quality management of enterprises in industry 4.0. In the fundamental part of this study, a literature review is conducted, during which the essence of total quality management (TQM) in industry 4.0 is revealed, a new climate dimension of quality 4.0 in the “Decade of Action” is justified as a challenge for TQM 4.0, a gap in the literature is identified, research questions (RQs) are posed and hypotheses are put forward.

The empirical part of this study examines the impact of innovation on product quality 4.0 from the standpoint of climate sustainbility. The pattern of change in the impact of innovation on quality is determined as neoindustrialization 4.0 progresses. The authors' recommendations on improving quality through climate optimization of developed, taking into account the stage of neo-industrialization 4.0. The authors propose a new approach to quality management of enterprises in industry 4.0 with the help of innovation for climate sustainbility.

2. LITERATURE REVIEW

2.1. Total quality management (TQM) in industry 4.0

The concept of total quality management (TQM) forms the theoretical basis of the research in this article (Anvari and Anvari, 2023; Yangailo, 2022). TQM is a progressive method of quality management in an organization, the features of which are, firstly, increased flexibility and continuous quality improvement (Kivrak and Say, 2022; Akpoviroro et al., 2019; Yangailo et al., 2023) and, secondly, complexity – improving not only the quality of products, but also also the quality of all organizational processes (Bisho and Sam, 2022; Cardoso et al., 2022).

In industry 4.0, TQM is the most preferred and actively used, since this method enables to systematically increase the level of automation and integrate business processes to maximize product quality (Stefanović, 2019). This management practice can be called TQM 4.0, since quality management in industry 4.0 has its own specifics associated with the need to maximize to maximize the use of high technologies (Ibrahim, 2019).
Innovation is crucial for quality 4.0, as global digital competition is particularly high (Hervas-Oliver et al., 2021). Innovation allows both individually and jointly to improve the useful properties of industry 4.0 products, modernize its production, as well as optimize its implementation (Tirgil and Fındık, 2022). Innovation management using TQM 4.0 makes it possible not only to increase the technological complexity of products in industry 4.0, but also all related production and distribution processes (Palazzeschi et al., 2018). This creates a synergistic effect in the form of a significant improvement in the quality of 4.0 with a comprehensive modernization of the product and processes compared to their separate modernization (Robert et al., 2022).

2.2. New – climate dimension of quality 4.0 in the "Decade of Action": a challenge for TQM 4.0

A new climate dimension of quality 4.0 has taken shape in the "Decade of Action" (Popkova, 2022; Popkova and Shi, 2022). This new dimension needs in detailed and independent study, as it may conflict with other dimensions of quality 4.0. For example, products of industry 4.0 may have high technical complexity, but low climatic resilience Therefore, the climate dimension of quality is a serious challenge for TQM 4.0, requiring strong scientific and methodological support.

The advantage of TQM 4.0 to combat climate change in industry 4.0 is that this progressive method enables to comprehensively improve the climate sustainbility of both products and processes (Popkova and Sergi, 2023). The need for this is explained by the fact that products of industry 4.0 can have good climate-related properties - their consumption does not harm the environment, is characterized by low energy consumption (Popkova and Sergi, 2020), "clean" energy can be used in their production, and biodegradable packaging allows environmentally safe disposal of waste generated by the consumption of these products (Popkova et al., 2023).
At the same time, the production of the products considered in this example may be characterized by low climate sustainbility – is very energy-intensive, excludes the use of "clean" energy, as well as has a large amount of carbon emissions. This example shows that achieving carbon neutrality requires the systematic development of climate-responsible practices in both production and consumption, which can be facilitated by the use of TQM 4.0. To denote the practice of quality management 4.0 in its new – climate dimension using the TQM method, the term "climate TQM 4.0" is proposed in this article

Innovation is the driver of improving quality 4.0, which is confirmed by numerous sources of published literature. Nevertheless, it does not give a clear interpretation of the implications of innovation for quality 4.0 from the standpoint of climate sustainbility, which is a gap in the literature and raises the following research questions (RQs).

RQ_1: What aspects of innovation determine quality 4.0 from the standpoint of climate sustainbility? The available papers by Matt et al. (2021), Mubarak et al. (2021), Pasi et al. (2022) focus on the direct climate-related properties of the innovations themselves for industry 4.0. The logic is that innovation should initially be climate-responsible in order to make the greatest contribution to the fight against climate change. Recognizing the unconditional importance of the climate-related properties of innovations, it is worth presenting a critical point of view and noting that these properties themselves do not guarantee the desired effect from the introduction of innovation to combat climate change.

For example, the introduction of climate-responsible innovation with insufficient engineering support or savings may provide a limited beneficial effect to combat climate change or may not lead to the creation of this effect at all. In this regard, it is worth considering the whole range of potential factors of climate sustainbility of innovation noted in the available literature:

- ICT and innovation infrastructure in industry 4.0 (Rane and Narvel, 2021). Environmental and energy characteristics of infrastructure support largely determine these features of productions of industry 4.0 (Wang et al., 2020);
- Personnel support of the innovation process in industry 4.0 (Ma et al., 2023). The introduction of innovation for climate sustainbility in industry 4.0 requires "green" digital personnel who not only possess digital competencies, but also share environmental values and know the specifics of combating climate change through innovation (Bettiol et al., 2023);
- Climate-related properties of innovations in industry 4.0. They are discussed in detail above, so we will not dwell on them here (Anshari and Almunawar, 2022);
- Organization of production in industry 4.0. Production and distribution processes should be flexible and climate-adaptive, as well as capable of improving energy efficiency (Nimawat and Gidwani, 2022);
- Innovation funding for industry 4.0 (Chang et al., 2023). The adequacy of funding largely determines the opportunities for innovation, as well as the choice (or forced refusal) in favor of innovation for climate sustainbility, which are often the most costly (Zhang et al., 2022). "Green" investments create additional incentives for the introduction of innovation for climate sustainbility (Mhlanga, 2022).

Based on the provisions of the above scientific literature, the following hypothesis is put forward in this article. H_1: The quality of 4.0 in terms of climate sustainbility is more determined by ICT and infrastructure, staffing, production organization and innovation funding for industry 4.0 than by the climat-related properties of innovations in industry 4.0.

RQ_2: What impact does the degree of neoindustrialization 4.0 have on the implications of innovation for quality 4.0 from the standpoint of climate sustainbility? According to the available fragmentary evidence cited in the writings of Hsu et al. (2020), Hynes (2022), Lyu et al. (2023), the world's advanced economies that are in the locomotive of neoindustrialization 4.0 and leaders in the rankings of digital competitiveness, also demonstrate outstanding results in the field of "green" growth. Based on this, they believe that innovation increasingly improves quality 4.0 from the standpoint of climate sustainbility with the neoindustrialization 4.0.

In contrast to this position, Ding and Yang (2023), Hao et al. (2022), Shen et al. (2023) indicate that innovation increasingly reduces quality 4.0 from the standpoint of climate sustainbility as neoindustrialization 4.0 progresses. The logic is that the higher the level of development of industry 4.0, the more seriously it contradicts the environment and the more difficult it is to implement innovation for climate sustainbility. Based on this, the following hypothesis is put forward. H_2: as neoindustrialization 4.0 progressed, the contribution of innovation to improving quality 4.0 from the standpoint of climate sustainbility decreases.

To test the hypotheses put forward in this article, the authors study the modern practice of quality management of enterprises in industry 4.0 based on international experience, and also carry out econometric modeling of the climatic implications of this management. The mathematical apparatus of the research makes it possible to formulate the scientific provisions of climate TQM 4.0 most accurately, to determine and convincingly substantiate the role of innovation for climate sustainbility in its implementation.

3. MATERIALS AND METHODOLOGY

To fill the gap in the literature, this article conducts an empirical study of innovation for climate sustainbility in the international practice of quality management of enterprises in industry 4.0 In order to fully cover the global experience, a representative sample was formed, which included both developed and developing countries from all parts of the world. The total number of countries in the sample was 58. The criterion for including countries in the sample was the availability of the necessary statistical data. The time period of the study is 2023, based on the 2022 statistics. The empirical base of the study is attached to this article in a separate file.

To find an answer to RQ_1 and clarify what aspects of innovation determine quality 4.0 from the standpoint of climate sustainbility, task 1 is set: to determine the impact of innovation on quality 4.0 from the standpoint of climate sustainbility. The task is solved using the regression analysis method. Mathematical modeling of the dependence of the components of the "Climate Change Performance Index 2023" (NewClimate Institute, 2023) on the potential factors of climate sustainbility of innovation identified by UNCTAD (2023) using the indicated method is carried out:

- ICT rank (it will be denoted as R_{ICT}) as an indicator of ICT and innovation infrastructure in industry 4.0, the value of which is determined by UNCTAD (2023) based on indicators such as "Internet users (per cent of population)" and "Mean download speed (Mbps)";
- Skills rank (it will be denoted as R_{SKL}) as an indicator of the personnel support of the innovation process in industry 4.0, the value of

which is determined by UNCTAD (2023) based on indicators such as "Expected years of schooling" and "High-skill employment (% of working population)";

- R&D rank (it will be denoted as $R_{R\&D}$) as an indicator of the climate-related properties of innovations in industry 4.0, the value of which is determined by UNCTAD (2023) based on indicators such as "Number of scientific publications on frontier technologies" and "Number of patents filed on frontier technologies";
- Industry rank (it will be denoted as R_{IND}) as an indicator of the organization of production in industry 4.0, the value of which is determined by UNCTAD (2023) based on such indicators as "High-technology manufactures exports (% of total merchandise trade)" and "Digitally deliverable services exports (% of total service trade)";
- Finance rank (it will be denoted as R_{FIN}) as an indicator of innovation funding for industry 4.0, the value of which is determined by UNCTAD (2023) based on such an indicator as "Domestic credit to private sector (% of GDP)".

All of these indicators are measured in places in the ranking (the less, the better). The dependent variables are the following: 1) "Greenhouse Gas Emissions", score 0-40 (it will be denoted as $ClSust_1$); 2) "Renewable Energy", score 0-20 (it will be denoted as $ClSust_2$); 3) "Energy Use", score 0-20 (it will be denoted as $ClSust_3$); 4) "Climate Policy", score 0-20 (it will be denoted as $ClSust_4$) (the values of the listed indicators, the more, the better) (NewClimate Institute, 2023). The research model takes the following form:

$$ClSust=a+b_{ICT}*R_{ICT}+b_{SKL}*R_{SKL}+b_{R\&D}*R_{R\&D}+ \\ +b_{IND}*R_{IND}+b_{FIN}*R_{FIN} \quad (1)$$

In model (1), the positive influence of factor variables on the dependent variable is indicated by the values of regression coefficients with a negative sign (below zero), and the negative influence is indicated by values with a positive sign (above zero). The statistical significance of variables in the model (1) is determined using the multiple coefficient of determination (R), standard errors for factor variables. To check the reliability of the model (1), Fischer's F-test is performed.

The hypothesis H_1 will be considered proven if, in the research model (1), the regression coefficients b_{ICT}, b_{SKI}, b_{IND} and b_{FIN} take smaller and negative values than the regression coefficient $b_{R\&D}$ (which can also take a positive value). This will provide scientific evidence that ICT and infrastructure (R_{ICT}), personnel support (R_{SKL}), production organization (R_{IND}) and innovation finance for industry 4.0 (R_{FIN}) determine quality 4.0 from the standpoint of climate sustainbility (ClSust) to a greater extent than the climate-related properties of innovations in industry 4.0 ($R_{R\&D}$).

To find an answer to RQ_2 and clarify what impact the degree of neoindustrialization 4.0 has on the implications of innovation for quality 4.0 from the standpoint of climate sustainbility, task 2 is set: to identify the pattern of changes in the impact of innovation on quality as neoindustrialization 4.0 progresses. In the sample frame according to the criterion "score group" in the "Frontier technologies readiness index", three sub-samples are distinguished: 1) High (high degree of neoindustrialization 4.0); 2) Upper middle (medium degree of neoindustrialization 4.0); 3) Lower middle (low degree of neoindustrialization 4.0).

The problem is solved using the method of correlation analysis. The authors calculate cross-correlation coefficients that mathematically describe the relationship between indicators of quality 4.0 (R) and indicators of climate sustainability of innovation (ClSust) in each of the three sub-samples of countries. The positive relationship of the variables is indicated by the values of the correlation coefficients with a negative sign (below zero), and the negative relationship is indicated by the values with a positive sign (above zero). The hypothesis H_2 will be considered proven if the arithmetic mean of the correlation coefficients in the "High" sub-sample takes a negative value and is less than the arithmetic mean of the correlation coefficients in the "Lower middle" sub-sample.

To ensure the practical significance of the study, task 3 is set: to make authors' recommendations for improving quality through climate optimization of innovation, taking into account the stage of neoindustrialization 4.0. Based on the research model (1) and the results of correlation analysis, the optimal combination of factor variables is selected for each subsample of countries to maximize the dependent variables. The increment of variables is estimated using the trend analysis method. Using the method of variation analysis, the implications of optimization for global inequality manifested at the country level are estimated – the variation of the components of the "Climate Change Performance Index 2023" among sub-samples in 2023 is compared with their variation among sub-samples during optimization. The positive impact of the authors' recommendations on global inequality, expressed in a reduction in the inequality between countries, is evidenced by a reduction in the coefficient of variation after optimization.

Task 4 is also set: to propose an approach to quality management of enterprises in industry 4.0 with the help of climate innovation. The approach is based on the generalized organizational structure of the enterprise of industry 4.0, includes the authors' recommendations for improving the order and specific measures for quality management of enterprises in industry 4.0 with the help of climate innovation. The approach reveals the essence of climate TQM 4.0.

4. RESULTS

4.1. The impact of innovation on quality 4.0 from the perspective of climate sustainability

In order to find the answer to RQ_1 and clarify which aspects of innovation determine the quality of 4.0 from the standpoint of climate sustainability, the first task of this study defines the impact of innovation on quality 4.0 from the standpoint of climate sustainability. For this purpose, the following regression equations were compiled using regression analysis in accordance with the research model (1) that mathematically describe the dependencies of the components of the “Climate Change Performance Index 2023” (NewClimate Institute, 2023) on the potential factors of climate sustainability of innovation identified by UNCTAD (2023). The function for Greenhouse Gas Emissions has the following form:

$$ClSust_1=22.7996+0.0175*R_{ICT}-0.0241*R_{SKL}+ +0.1007*R_{R\&D}-0.0476*R_{IND}-0.0322*R_{FIN} \quad (2)$$

Equation (2) indicates that Greenhouse Gas Emissions are reduced by 0.0241 points while the personnel support for the innovation process in industry 4.0 is improved by 1 place. Greenhouse Gas Emissions are reduced by 0.0476 points when the organization of production in industry 4.0 is improved by 1 place. Greenhouse Gas Emissions are reduced by 0.0322 points with an increase in the amount of innovation funding for industry 4.0 by 1 place. It is noteworthy that the improvement of the climate-related properties of innovations in industry 4.0 does not contribute to the reduction of Greenhouse Gas Emissions. Regression statistics for equation (2) are given in Table 1.

Table 1. Regression statistics of Greenhouse Gas Emissions dependence on factors of climate sustainability of innovation

Standard Error		-	df	SS	MS	Observed F	Significance F	Significance Level	Multiple R
R_{ICT}	0.0533	Regression	5	237.6396	47.5279	1.1173	0.3627	0.50	0.3115
R_{SKL}	0.0457	Residual	52	2211.9154	42.5368				
$R_{R\&D}$	0.0515	Total	57	2449.5550					
R_{IND}	0.0325								
R_{FIN}	0.0297								

Source: calculated and compiled by the authors.

Regression statistics from Table 1 indicate that Fischer’s F-test has been passed at a significance level of 0.50. The change in Greenhouse Gas Emissions among the sample countries in 2023 by 31.15% is explained by the influence of factors of climate sustainability of innovation. The standard error is small for all factor variables: 0.0533 for R_{ICT}, 0.0457 for R_{SKL}, 0.0515 for $R_{R\&D}$, 0.0325 for R_{IND}, 0.0297 for R_{FIN}. The function for Renewable Energy has taken the following form:

$$ClSust_2=9.2854+0.0183*R_{ICT}-0.0442*R_{SKL}+ +0.0629*R_{R\&D}-0.0271*R_{IND}-0.0360*R_{FIN} \quad (3)$$

Equation (3) indicates that Renewable Energy increases by 0.0442 points with an improvement in the personnel support for the innovation process in industry 4.0 by 1 place. Renewable Energy increases by 0.0271 points with the improvement of the organization of production in industry 4.0 by 1 place. Renewable Energy rises by 0.0360 points with an increase in the amount of innovation funding for industry 4.0 by 1 place. It is noteworthy that the improvement of the climate-related properties of innovations in industry 4.0 does not contribute to the development of Renewable Energy. Regression statistics for equation (3) are given in Table 2.

Table 2. Regression statistics of the dependence of Renewable Energy on the factors of climate sustainability of innovation

Standard Error		-	df	SS	MS	Observed F	Significance F	Significance Level	Multiple R
R_{ICT}	0.0285	Regression	5	183.7836	36.7567	3.0301	0.0179	0.05	0.4750
R_{SKL}	0.0244	Residual	52	630.7785	12.1304				
$R_{R\&D}$	0.0275	Total	57	814.5620					
R_{IND}	0.0174								
R_{FIN}	0.0159								

Source: calculated and compiled by the authors.

Regression statistics from Table 2 shows that Fischer’s F-test has been passed at a significance level of 0.05. The change in Renewable Energy among the sample countries in 2023 by 47.50% is explained by the influence of factors of climate sustainability of innovation. The standard error is small for all factor variables: 0.0285 for R_{ICT}, 0.0244 for R_{SKL}, 0.0275 for

$R_{R\&D}$, 0.0174 for R_{IND}, 0.0159 for R_{FIN}. The function for Energy Use has taken the following form:

$$ClSust_3=9.9438-0.0053*R_{ICT}+0.0298*R_{SKL}+ +0.0473*R_{R\&D}-0.0205*R_{IND}+0.0072*R_{FIN} \quad (4)$$

Equation (4) indicates that Energy Use is reduced by 0.0053 points with the development of ICT and innovation infrastructure in industry 4.0 by 1 place. Energy Use is reduced by 0.0205 points with the improvement of the organization of production in industry 4.0 by 1 place. It is notable that the improvement of the climate-related properties of innovations in industry 4.0 does not contribute to the reduction of Energy Use. Regression statistics for equation (4) are given in Table 3.

Table 3. Regression statistics of the dependence of Energy Use on the factors of climate sustainability of innovation

Standard Error		-	df	SS	MS	Observed F	Significance F	Significance Level	Multiple R
R_{ICT}	0.0247	Regression	5	117.7492	23.5498	2.5769	0.0371	0.05	0.4456
R_{SKL}	0.0212	Residual	52	475.2108	9.1387				
$R_{R\&D}$	0.0239	Total	57	592.9601					
R_{IND}	0.0151								
R_{FIN}	0.0138								

Source: calculated and compiled by the authors.

Regression statistics from Table 3 indicate that Fischer's F-test has been passed at a significance level of 0.05. The change in Energy Use among the sample countries in 2023 by 44.56% is explained by the influence of factors of climate sustainability of innovation. The standard error is small for all factor variables: 0.0247 for R_{ICT}, 0.0212 for R_{SKL}, 0.0239 for $R_{R\&D}$, 0.0151 for R_{IND}, 0.0138 for R_{FIN}. The function for Climate Policy has taken the following form:

$$ClSust_4=10.9926+0.0442*R_{ICT}-0.0328*R_{SKL}+ +0.0261*R_{R\&D}-0.0308*R_{IND}-0.0552*R_{FIN} \quad (5)$$

Equation (5) shows that Climate Policy is improving by 0.0328 points with the improvement of the personnel support for the innovation process in industry 4.0 by 1 place. Climate Policy is improved by 0.0308 points with the improvement of the organization of production in industry 4.0 by 1 place. Climate Policy is improved by 0.005522 points with an increase in the amount of innovation funding for industry 4.0 by 1 place. It should be noted that the improvement of the climate-related properties of innovations in industry 4.0 does not contribute to the improvement of Climate Policy. Regression statistics for equation (5) are given in Table 4.

Table 4. Regression statistics of the dependence of Climate Policy on the factors of climate sustainability of innovation

Standard Error		-	df	SS	MS	Observed F	Significance F	Significance Level	Multiple R
R_{ICT}	0.0304	Regression	5	232.2218	46.4444	3.3655	0.0104	0.05	0.4945
R_{SKL}	0.0260	Residual	52	717.5992	13.8000				
$R_{R\&D}$	0.0293	Total	57	949.8209					
R_{IND}	0.0185								
R_{FIN}	0.0169								

Source: calculated and compiled by the authors.

Regression statistics from Table 4 indicate that Fischer's F-test has been passed at a significance level of 0.05. The change in Climate Policy among the sample countries in 2023 by 49.45% is explained by the influence of factors of climate sustainability of innovation. The standard error is small for all factor variables: 0.0304 for R_{ICT}, 0.0260 for R_{SKL}, 0.0293 for $R_{R\&D}$, 0.0185 for R_{IND}, 0.0169 for R_{FIN}.

Thus, in equations (2)-(5), the regression coefficients b_{ICT}, b_{SKI}, b_{IND} and b_{FIN} have smaller and negative values than the regression coefficient $b_{R\&D}$, which is positive in all equations. The systemic rethinking of the obtained results makes it possible to conclude that ICT and infrastructure (R_{ICT}), personnel support (R_{SKL}), production organization (R_{IND}) and innovation finance for industry 4.0 (R_{FIN}) determine the quality 4.0 from the standpoint of climate sustainability (ClSust) to a much greater extent than the climate-related properties of innovations in industry 4.0 ($R_{R\&D}$). Hence, the hypothesis H_1 is proved.

4.2. The pattern of changes in the impact of innovation on quality with the neoindustrialization 4.0

In order to find an answer to RQ2 and clarify what impact the degree of neo-industrialization 4.0 has on the implications of innovation for quality 4.0 from the standpoint of climate sustainability, the second task of this study is solved. To this end, the authors identify a pattern of changes in the impact of innovation on quality as neo-industrialization 4.0 progresses.

To solve problem 2, cross-correlation coefficients, which mathematically describe the relationship between quality indicators 4.0 (R) and indicators of climate sustainability of innovation (ClSust) in each of the three sub-samples of countries (Table 5), have been calculated.

The arithmetic averages of the correlation coefficients for each indicator of quality 4.0 (R) are calculated and reflected in Fig. 1 in the context of the formed sub-samples of countries.

As shown in Fig. 1, ensuring the climate sustainability of innovation in countries with a low degree of neoindustrialization 4.0 is facilitated by: ICT and innovation infrastructure in industry 4.0 (correlation: -60.82%), personnel support for the innovation process in industry 4.0 (-23.30%), climate-related properties of innovations in industry 4.0 (-57.55%) and the organization of production in industry 4.0 (-39.30%).

Table 5. Cross-correlation of quality indicators 4.0 (R) with indicators of climate sustainability of innovation (ClSust), %

Sub-sample	Cross-correlation, %	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
High	Greenhouse Gas Emissions, score	-34.78	-47.05	24.87	3.50	-0.93
	Renewable Energy, score	-11.85	-24.92	33.58	11.10	-8.11
	Energy Use, score	-0.12	-0.05	0.30	0.05	0.21
	Climate Policy, score	-11.74	-40.39	-14.07	-15.41	-41.04
Upper middle	Greenhouse Gas Emissions, score	5.45	21.78	3.30	-57.49	-21.60
	Renewable Energy, score	-21.71	-24.82	-4.08	-18.20	-21.10
	Energy Use, score	15.18	32.88	15.16	-58.52	-1.34
	Climate Policy , score	13.43	42.50	-9.48	-19.64	-45.24
Lower middle	Greenhouse Gas Emissions, score	-62.53	-97.53	-27.69	25.19	96.09
	Renewable Energy, score	-10.28	84.94	-47.76	-85.89	-87.86
	Energy Use, score	-83.17	-86.31	-55.41	-5.21	83.24
	Climate Policy, score	-87.28	5.70	-99.34	-91.30	-11.47

Source: calculated and compiled by the authors.

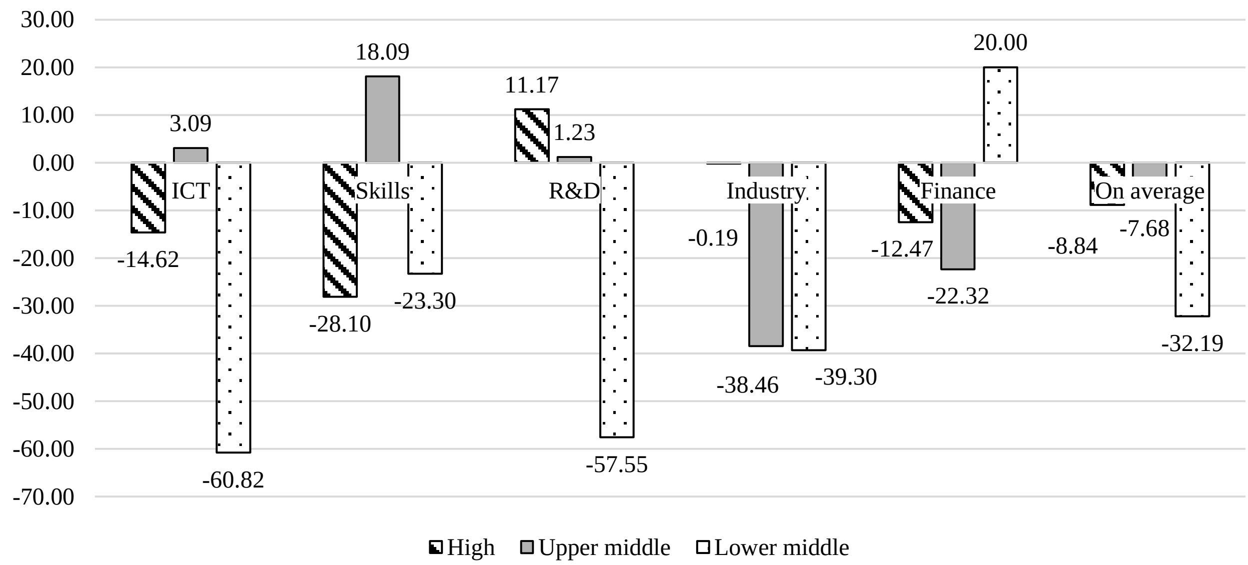

Figure 1. Arithmetic averages of correlation coefficients for each indicator of quality 4.0 in the context of the formed sub-samples of countries.
Source: calculated and compiled by the authors.

In countries a medium degree of neoindustrialization 4.0, the organization of production in industry 4.0 (-38.46%) and innovation funding for industry 4.0 (-22.32%) contribute to ensuring the climate sustainability of innovation. In countries with a high degree of neoindustrialization 4.0, the following factors contribute to ensuring the climate sustainability of innovation: ICT and innovation infrastructure in industry 4.0 (-14.62%), personnel support for the innovation process in industry 4.0 (-28.10%), organization of production in industry 4.0 (-0.19%) and innovation funding for industry 4.0 (-12.47%).

Thus, the systemic rethinking of the obtained results enables us to conclude that the arithmetic mean of the correlation coefficients in the sub-sample “High” has a negative value (-8.84%), but it is greater than the arithmetic mean of the correlation coefficients in the sub-sample “Lower middle” (-32.19%). This means that innovation increasingly reduces quality 4.0 from the standpoint of climate sustainability as neoindustrialization 4.0 progresses. Hence, the hypothesis H2 is proved.

4.3. Recommendations for improving quality through climate optimization of innovation, taking into account the stage of neoindustrialization 4.0

In order to ensure the practical significance of the research within the framework of solving its third task, the authors have developed recommendations for improving quality through climate optimization of innovation, taking into account the stage of neoindustrialization 4.0. Based on econometric models (2)-(4) and the results of correlation analysis (Table 5), the optimal combination of factor variables has been selected for each sub-sample of countries to maximize the dependent variables. The increment of variables has been estimated using the trend analysis method (Fig. 2-4).

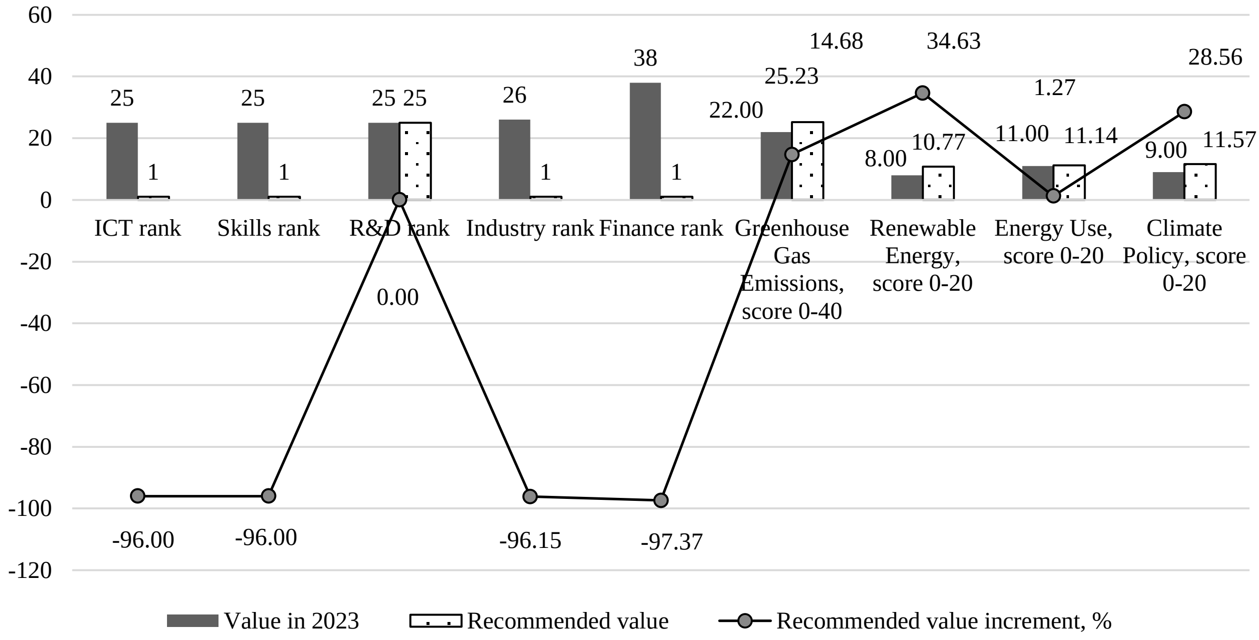

Figure 2. Recommendations for improving quality 4.0 through climate optimization of innovation in countries with a high degree of neoindustrialization 4.0
Source: calculated and constructed by the authors.

Recommendations on climate optimization of innovation for countries with a high degree of neoindustrialization 4.0 include:

- Development of ICT and innovation infrastructure in industry 4.0 by 96.00% (from 25th place in 2023 to 1st place);
- Improvement of the personnel support for the innovation process in industry 4.0 by 96.00% (from 25th place in 2023 to 1st place);
- Improvement of the organization of production in industry 4.0 by 96.15% (from 26th place in 2023 to 1st place);
- Increase in innovation funding for industry 4.0 by 97.37% (from 38th place in 2023 to 1st place).

The advantages of implementing the authors' recommendations for quality 4.0 from the standpoint of climate sustainability are related to:

- Reduction of greenhouse gas emissions by 14.68% (from 22.00 points in 2023 to 25.23 points);
- Development of renewable energy by 34.63% (from 8.00 points in 2023 to 10.77 points);
- Reduction of energy use by 1.27% (from 11.00 points in 2023 to 11.14 points);
- Improvement of climate policy by 28.56% (from 9.00 points in 2023 to 11.57 points).

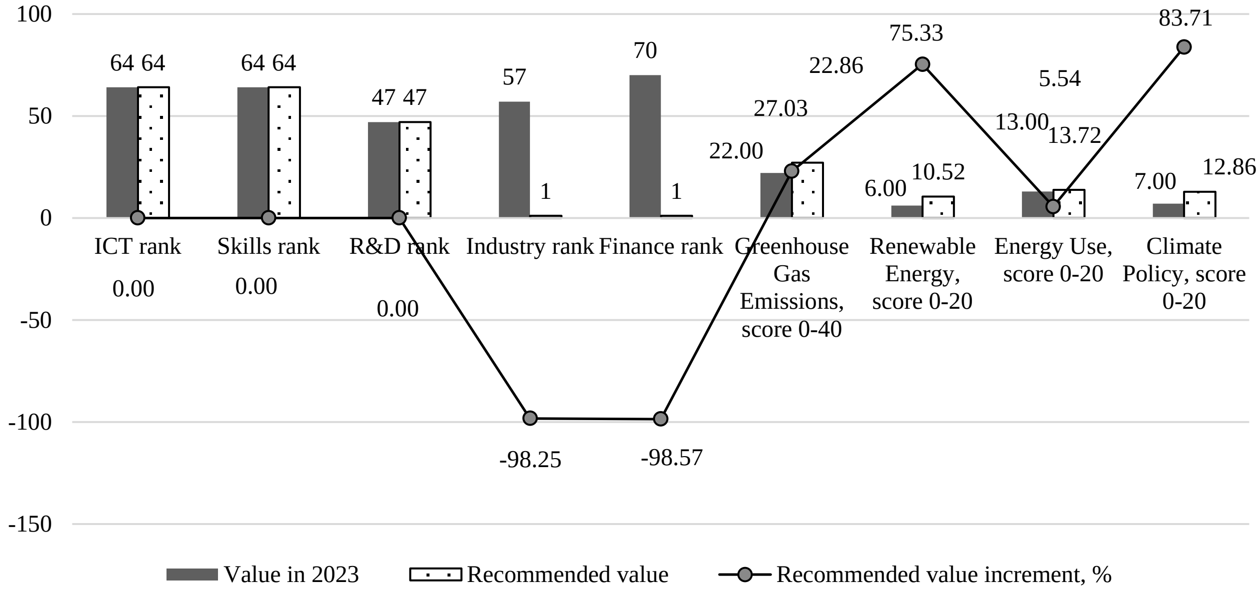

Figure 3. Recommendations for improving quality 4.0 through climate optimization of innovation in countries with an an medium degree of neoindustrialization

Source: calculated and constructed by the authors.

Recommendations on climate optimization of innovation for countries with an n medium degree of neoindustrialization 4.0 include:

- Improvement of the organization of production in industry 4.0 by 98.25% (from 57th place in 2023 to 1st place);
- Increase in innovation funding for industry 4.0 by 98.57% (from 70th place in 2023 to 1st place).
- The advantages of implementing the authors' recommendations for quality 4.0 from the standpoint of climate sustainability are related to:
- Reduction of greenhouse gas emissions by 22.86% (from 22.00 points in 2023 to 27.03 points);
- Development of renewable energy by 75.53% (from 6.00 points in 2023 to 10.52 points);
- Reduction of energy use by 5.54% (from 13.00 points in 2023 to 13.72 points);
- Improvement of climate policy by 83.71% (from 7.00 points in 2023 to 12.86 points).

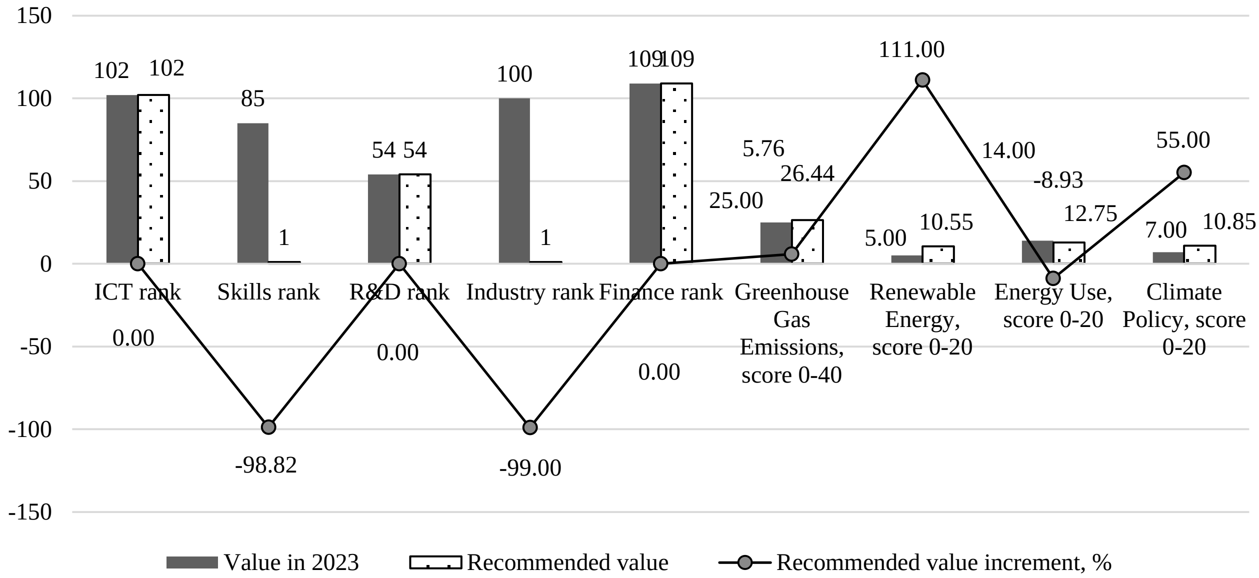

Figure 4. Recommendations for improving the quality of 4.0 through climate optimization of innovation in countries with a low degree of neoindustrialization 4.0

Source: calculated and constructed by the authors.

Recommendations on climate optimization of innovation for countries with a low degree of neoindustrialization 4.0 include:

- Improvement of the personnel support of the innovation process in industry 4.0 by 98.82% (from 85th place in 2023 to 1st place);
- Improvement of the organization of production in industry 4.0 by 99.00% (from 100th place in 2023 to 1st place).

The advantages of implementing the author's recommendations for quality 4.0 from the standpoint of climate sustainability are related to:

- Reduction of greenhouse gas emissions by 5.76% (from 25.00 points in 2023 to 26.44 points);
- Development of renewable energy by 111.00% (from 5.00 points in 2023 to 10.55 points);
- Improvement of climate policy by 55.00% (from 7.00 points in 2023 to 10.85 points).

Nevertheless, optimization does not allow reducing and even maintaining energy use at the level of 2023, which will increase by 8.93% (from 14.00 points in 2023 to 12.75 points). Using the method of variation analysis, the implications of optimization for global environmental inequality manifested at the country level are estimated – the variation of the components of the "Climate Change Performance Index 2023" among the sub-samples in 2023 is compared with their variation among the sub-samples during optimization (Table 6).

Table 6. Variation analysis to determine the implications of optimization for global environmental inequality

Value type	Indicators	Values of indicators for sub-samples of countries, score			Arithmetic average, score	Standard deviation, score	Coefficient of variation, %
		High	Upper middle	Lower middle			
Actual values	Greenhouse Gas Emissions	22	22	25	23.12	1.73	7.47
	Renewable Energy	8	6	5	6.57	1.47	22.35
	Energy Use	11	13	14	12.97	1.54	11.89
	Climate Policy	9	7	7	7.81	0.84	10.78
Recommended values	Greenhouse Gas Emissions	25.23	27.03	26.44	26.23	0.92	3.50
	Renewable Energy	10.77	10.52	10.55	10.61	0.14	1.29
	Energy Use	11.14	13.72	12.75	12.54	1.30	10.39
	Climate Policy	11.57	12.86	10.85	11.76	1.02	8.66

Source: calculated and compiled by the authors.

The positive impact of the authors' recommendations on global inequality, expressed in a reduction in the inequality between countries, is evidenced by a reduction in the coefficients of all variations after optimization. Thus, the coefficient of variation of greenhouse gas emissions decreases from 7.47% to 3.50%, the coefficient of variation of renewable energy reduces from 22.35% to 1.29%, the coefficient of variation of energy use drops from 11.89% to 10.39%, the coefficient of variation of climate policy lowers from 10.78% to 8.66%.

Thus, the proposed recommendations make it possible to fully unlock the potential for improving quality through climate optimization of innovation at each stage of neoindustrialization 4.0, as well as to reduce global environmental inequality (the climate gap among the countries of the world).

4.4. The approach to quality management of enterprises of industry 4.0 using climate innovation

To solve the fourth task of this study, a new approach to quality management of enterprises in industry 4.0 with the help of climate innovation has been developed. The approach is based on the generalized organizational structure of the enterprise of industry 4.0, includes the authors' recommendations for improving the order and specific measures for quality management of enterprises of industry 4.0 with the help of climate innovation. The approach reveals the essence of climate TQM 4.0 and is presented in Fig. 5.

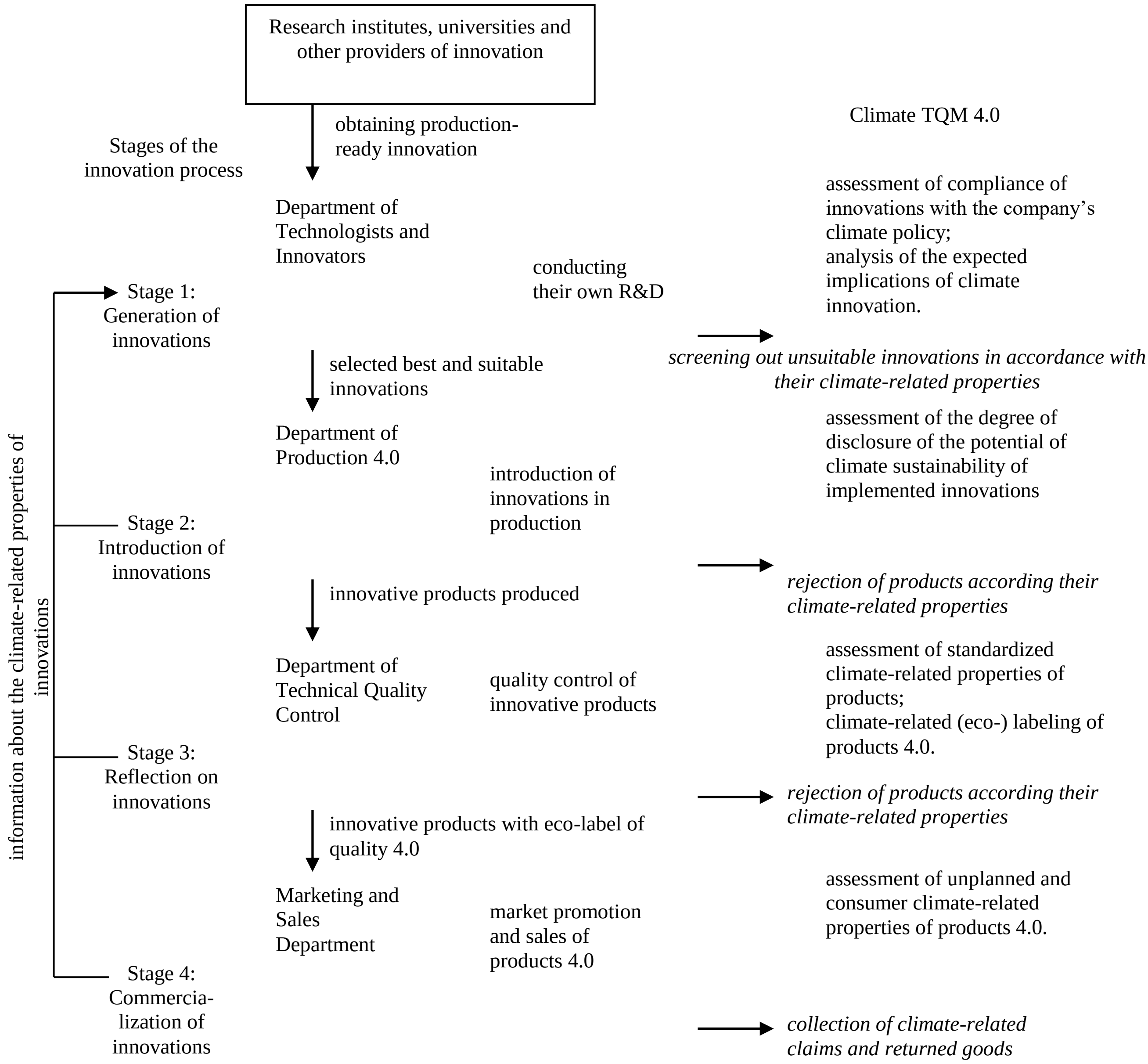

Figure 5. Approach to quality management of enterprises of industry 4.0 with the help of climate innovation
Source: developed by the authors.

As shown in Figure 5, the authors' approach involves conducting its own R&D by the department of technologists and innovators and/or obtaining production-ready innovations from research institutes, universities and other innovation suppliers at the innovation generation stage. Climate TQM 4.0 at this stage includes an assessment of the compliance of innovations with the company's climate policy, as well as an analysis of the expected effects of innovations on the climate. The result of the stage is the screening out unsuitable innovations in accordance with their climate-related properties, as well as the selection of the best and most suitable (from the standpoint of climate sustainability) innovations.

At the second stage, they are introduced by the Department of Production 4.0 into the company's activities. Climate TQM 4.0 at this stage includes the assessment of the degree of disclosure of the potential of climate sustainability of implemented innovations. The result of the stage is the rejection of products according their climate-related properties, as well as the transfer of manufactured innovative products to quality control.

At the third stage, the technical control department conducts quality control of innovative products. Climate TQM 4.0 at this stage includes the assessment of standardized climate-related properties of products, as well as climate-related (eco-) labeling of products 4.0.

The result of the stage is the rejection of products according their climate-related properties, as well as the transfer to the implementation of innovative products with eco-label of quality 4.0. продукции с эко-маркировкой качества 4.0.

At the fourth stage, the marketing and sales department promotes and sells products 4.0 on the market. Climatic TQM 4.0 at this stage includes the assessment of unplanned and consumer climate-related properties of products 4.0. The result of the stage is the collection of climate-related claims and returned products from consumers. Information about the climate-related properties of innovations collected at each stage is transmitted to the department of technologists and innovators. Thus, the described process is cyclical, which ensures continuous improvement of quality 4.0 from the standpoint of climate sustainability.

5. DISCUSSION

The increment of scientific knowledge in this article is that it complements the concept of TQM with new scientific provisions of climate TQM 4.0. The scientific provisions of climate TQM 4.0, substantiated in this article, are reflected in Table 7 in contrast with the existing literature.

Table 7. Scientific provisions of climate TQM 4.0, which are justified in this article and contradict the existing literature

Aspects of scientific knowledge that contradict the positions established by RQs	Existing provisions of the TQM concept		Scientific provisions of climate TQM 4.0, justified in this article
	The essence of the provisions	Literature sources	
RQ_1: What aspects of innovation determine quality 4.0 from the standpoint of climate sustainbility?	The direct climate-related properties of the innovations themselves for industry 4.0	Anshari and Almunawar, (2022), Matt et al. (2021), Mubarak et al. (2021), Pasi et al. (2022)	• ICT and innovation infrastructure in industry 4.0; • Personnel support for the innovation process in industry 4.0;0; • Organization of production in industry 4.0; • Innovation funding for industry 4.0.
RQ_2: What impact does the degree of neoindustrialization 4.0 have on the implications of innovation for quality 4.0 from the standpoint of climate sustainbility?	With the neoindustrealization of 4.0, the contribution of innovation to improving quality 4.0 from the standpoint of climate sustainability increases	Hsu et al. (2020), Hynes (2022), Lyu et al. (2023)	With the neo-industrialization 4.0, innovation increasingly reduces quality 4.0 from the standpoint of climate sustainability

Source: developed by the authors.

As shown in Table 7, in contrast to Anshari and Almunawar, (2022), Matt et al. (2021), Mubarak et al. (2021), Pasi et al. (2022) a new answer to RQ_1 has been received: it has been proved that quality 4.0 from the standpoint of climate sustainability is determined not so much by the climate-related properties of the innovations themselves for industry 4.0, as by the ICT and innovation infrastructure in industry 4.0 (in support of Rane and Narvel, 2021; Wang et al., 2020); the personnel support for the innovation process in industry 4.0 (in support of Bettiol et al., 2023; Ma et al., 2023), the organization of production in industry 4.0 (in support of Nimawat and Gidwani, 2022), as well as innovation funding for industry 4.0 (in support of Chang et al., 2023; Mhlanga, 2022; Zhang et al., 2022).

In contrast to Hsu et al. (2020), Hynes (2022), Lyu et al. (2023), the new answer to RQ_2 has been found: it has been proved that innovation does not increase, but increasingly reduces quality 4.0 from the standpoint of climate sustainability as 4.0 neoindustrialization progresses (in support of Ding and Yang, 2023; Hao et al., 2022; Shen et al., 2023).

6. CONCLUSION

Therefore, the conducted research has made it possible to substantiate the significant but contradictory role of climate innovation in the practice of quality management of enterprises in industry 4.0, depending on the stage of neoindustrialization 4.0, which is the main conclusion of this article. In particular, the following results have been obtained:

1. The impact of innovation on the quality of 4.0 products from the standpoint of climate sustainability has been identified and quantified. It has been found that ICT and infrastructure, personnel support, organization of production and innovation funding for industry 4.0 determine quality 4.0 from the standpoint of climate sustainability to a much greater extent than the climate-related properties of innovations in industry 4.0 (the hypothesis H_1 has been proved);
2. The authors have identified the pattern of changes in the impact of innovation on quality as neoindustrialization 4.0 progresses, which consists in the fact that during neoindustrialization 4.0 innovation increasingly reduces quality 4.0 from the standpoint of climate sustainability Thus, in countries with a low degree of neoindustrialization 4.0, the relationship (correlation modulo) of indicators of quality 4.0 (R)

with indicators of climate sustainability of innovation was 32.19%, and in countries with a high degree of neoindustrialization 4.0 – only 8.84% (the hypothesis H2 has been proved).

The theoretical significance of the article lies in the fact that it has formed a new climate dimension of quality 4.0 in the “Decade of Action”, embodied in the authors’ concept of climate TQM 4.0 and taking into account the environmental properties of products 4.0 in determining and managing its quality. This new vision has made it possible to give a clear interpretation of the implications of innovation for quality 4.0 from the standpoint of climate sustainability, related to the reduction of greenhouse gas emissions, the transition to renewable energy, the reduction of energy use and the improvement of climate policy.

The practical significance of the article is related to the fact that the proposed authors’ recommendations will improve the quality of 4.0 through climate optimization of innovation. The set of recommendations includes: development of ICT and innovation infrastructure in industry 4.0; improvement of the staffing of the innovation process in industry 4.0; improvement of the organization of production in industry 4.0; increasing innovation funding for industry 4.0. The advantage of the authors’ recommendations is that for the first time they take into account the specifics of each stage of neoindustrialization 4.0.

The managerial significance of the article is that the developed new approach to quality management of enterprises in industry 4.0 with the help of climate innovation has rethought this management practice through the prism of the stages of the innovation process. In contrast to the existing approach, which is limited to a single stage of generation of innovation, a four-stage approach has been proposed that includes management measures of climate TQM 4.0 at each stage of the innovation process and therefore systemically increases the climate stability of both 4.0 products and related business processes.

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