

Quantitative estimation and mathematical modeling of demographic potential in Russia

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Abstract

The demographic problem in Russia remains relevant since the early 90s of the XX century and is caused by a number of reasons, including a low fertility rate over a long period of time and a high rate of premature mortality among youths and the working-age population, which lead, in particular, to an increase in the demographic burden, population aging, problems the imbalance in the labor market. As a result, this has a negative impact on the country's welfare, since demographic potential is an integral part of the country's human potential. This justifies the necessity to develop an approach to obtaining an integral indicator that objectively reflects the state and trends of demographic potential in Russia and its regions, which can be used both to conduct a comparative analysis of regions or in dynamics in order to identify the regions for targeted financing and support from the state, and to build multidimensional models, to assess the degree of influence of the characteristics of the socio-economic situation of Russia and its regions on the level of demographic potential. The results obtained on the basis of these models can be used to justify demographic policy measures aimed at leveling the demographic situation in the country and developing a strategy for the transition from depopulation to expanded reproduction. Currently, many approaches to quantifying Russia's demographic potential have been proposed in the scientific literature. The article analyzes the advantages and limitations of the most common models and methods for assessing demographic potential, based on various approaches to defining the concept of "demographic potential". Estimates of demographic potential based on the net reproduction rate, marginal growth rate and standardized growth rate are obtained. A comparative analysis of the results of assessing the level of Russia's demographic potential for the period from 1995 to 2022 based on integral indicators has been carried out.

Keywords demographic potential, econometric models, demographic models, net reproduction rate, marginal growth rate, standardized growth rate.

Introduction

The demographic decline, compounded by the low fertility rate, high rates of premature mortality, and, as a result, the aging of the population, has remained one of the most acute problems in Russia over the past few decades [1-6]. The problem becomes particularly relevant given the fact that in the general structure of the population there is a decrease in the proportion of the population younger than the working age and working age, since these two age-specific groups form the demographic potential of the country and are the basis for its well-being.

To solve the above-mentioned problems, the state develops and implements a demographic policy aimed at overcoming depopulation, stimulating natural population growth, and maintaining the balance of labor resources [7]. In particular, the demographic policy is aimed to provide social support to families with children [8], reduce the level of premature mortality [9], including from socially significant causes of death, ensure access to high-tech medical care for the population, promote a healthy lifestyle, and create conditions for physical culture and sports [10], etc. However, despite all the measures taken and implemented within the framework of state programs, there is still a tendency to reduce the population in Russia [11-13]. This indicates the insufficient effectiveness of the existing demographic policy in the country [14].

To implement effective measures aimed at the transition from depopulation to expanded reproduction, it is necessary first of all to obtain objective and adequate estimates of the level of development of the country's demographic potential, on the basis of which it is possible to build econometric models that allow identifying factors that have the greatest impact on the level of the country's demographic potential, and therefore, demographic policy [15]. The complexity of obtaining such estimates is due to the multidimensional nature of the concept of "demographic potential" [16].

To date, many approaches have been developed for assessing the state of the demographic process, based on various principles of defining this term [17-18]. Existing methods for assessing the level of demographic potential of regions make it possible not only to record the current state, but also to make forecasts, considering the influence of various social, economic and environmental factors [19]. The development of digital technologies and the development of methods for processing and modeling big data bring to new opportunities for more accurate assessment and modeling of demographic processes [20].

In demographic research, the concept of potential is used to identify hidden resources contained in the population structure based on various demographic characteristics [21-22]. The analysis of existing methods for assessing demographic potential has shown that two main approaches are used in scientific practice: one is based on obtaining estimates of the volume of demographic potential (quantitative approach), and the other is based on assessing its quality [23].

Quantitative methods for assessing demographic potential

Quantitative approaches to assessing demographic potential allow us to analyze demographic processes and trends in population development through various statistical and mathematical tools. Demographic potential is most often associated with the influence of macroeconomic factors on capital accumulation, investment, employment, and projected population growth in a particular territory [24]. This takes into account the relationship of employment and labor surplus with financial policies and psychological factors of migration and natural growth through the concept of "expected income".

Statistical, econometric, and demographic methods are among the most common quantitative approaches to studying demographic potential. Statistical methods are useful for describing and monitoring demographic trends, econometric methods are useful for identifying factors and making forecasts, and demographic models are useful for studying the age structure and reproduction of the population. These models allow us to identify patterns, predict trends, and develop measures to stimulate the fertility rate, reduce mortality, and regulate migration flows. To form a comprehensive understanding of these approaches, it is necessary to study in detail their advantages and limitations.

Statistical methods are widely used in the analysis of demographic processes, as they are based on the processing of empirical data. Statistical methods allow us to study the demographic potential by constructing tables of births, deaths, marriages, and divorces and calculating the probabilities of corresponding events. Traditionally, demographic grids (grids) are used, which were improved in the XX century and were used in domestic research to analyze typical demographic events. Modern three-dimensional technologies allow reflecting demographic data about a person's life cycle, including place and ethnicity.

The existing method of combined demographic tables allowed researchers to predict changes in family types, which was used to develop social programs, especially in the field of housing construction in large Russian cities and urban agglomerations [25]. These tables also allow you to calculate mortality and life expectancy based on marital status.

According to the statistical approach, the key factor in assessing the level of demographic potential is the fertility rate. In international practice, the Cole approach is widely used, but its upper limit on the fertility rate is controversial for Russia, since the fertility rate in the most fertile Hutterite communities, which reached 12 children per married woman during her entire life in a prosperous social environment, is taken as a basis [26]. In this regard, an alternative method of the hypothetical minimum natural fertility rate was invented, applicable to the conditions of life in the USSR. The method is based on an analysis of the fertility of Uzbek female aged 20-24 years who lived in conditions of natural fertility. They demonstrated the highest possible fertility rate in real Soviet conditions without the intervention of birth control factors [27]. However, this method has become obsolete due to the shift in the average age of mothers to 30-34 years in large cities, and the model of reproductive activity has also changed – they marry later, use contraception more.

As improved statistical methods in the scientific literature, it is proposed to use standardized total fertility, mortality and migration rates to assess the current demographic situation in the regions of the Russian Federation. It

allows you to get a standardized indicator of depopulation and is characterized by the ease of using spreadsheets [28-29].

Limitations of statistical methods include the fact that they focus on retrospective analysis, which means that they do not always accurately predict future changes, since they do not take into account informal factors that have a significant impact on demographic trends.

Econometric methods involve the construction of regression models, which can be used to determine the impact of various factors on the level of fertility, migration, or mortality, which is necessary when developing strategies for the socio-economic development of regions. Spatial econometrics models take into account the influence of neighboring territories, which makes it possible to assess interregional differences and the spread of demographic trends. Thus, the method of spatial autocorrelation analysis allows us to identify clusters of regions with a high or low level of demographic development.

Econometric methods provide an opportunity not only to analyze the current state of demographic potential, but also to build forecasts based on the identified patterns, which can be obtained on the basis of time series analysis, which allows you to track changes in such demographic indicators: fertility rate, mortality and life expectancy, in the time perspective. In particular, the time-series analysis technique makes it possible to identify long-term trends in demographic development. Correlation and regression analysis reveals relationships between socio-economic factors and demographic characteristics, such as the level of urbanization, the level of income of the population, and the quality of medical care. Based on this method, it was proved that the unemployment rate and the availability of medical services significantly affect the fertility rate. Multidimensional statistical analysis, which includes methods of factor and cluster analysis, makes it possible to group regions by similarity of demographic characteristics, allowing you to form rational and reasonable recommendations for regulating demographic processes.

Panel data models are also a useful tool for considering the dynamics of demographic processes. They allow you to find and analyze changes not only in time, but also in space, which is of particular importance in interregional analysis.

However, the above approach also has a number of limitations. In particular, econometric models require significant amounts of data and computational resources, which can make it difficult to apply them in the context of limited statistical information. Also, the accuracy of the model is strongly influenced by the correct selection and choice of explanatory variables.

Demographic models are used to analyze the age structure of the population and its reproduction. In particular, cohort models allow us to study changes in age groups of the population over a long period of time, which is especially important when predicting future changes in the number of working-age people. Demographic balance models also estimate population growth and decline, taking into account migration flows, fertility rates, and mortality, which makes them useful for developing demographic policies.

Microsimulation models are one of the most promising analysis tools, as they allow you to model individual behavior of people depending on various factors, such as income level, education, or health status.

However, the construction of demographic models requires significant computational resources and careful calibration of parameters, which can complicate their practical application. Moreover, forecasts based on these models are subject to a certain degree of uncertainty, as they depend on a large number of variables and assumptions.

In recent years, more and more attention has been paid to hybrid approaches to assessing demographic potential, which combine the advantages of statistical, econometric and demographic models. Hybrid models provide more accurate estimates of demographic potential, taking into account a wide range of factors, which is especially important when developing effective demographic policy measures.

Methods for assessing the quality of demographic potential

The accelerating pace of technological progress is accompanied by increased requirements for the qualitative characteristics of the population. This has led to the need to develop approaches that are focused on assessing the qualitative potential of the population and its correlation with socio-economic conditions. The question of optimal population size in global, regional and national dimensions has become more relevant than ever. The idea of a demographic optimum – a state in which the size and structure of the population are in harmony with the resource capabilities of society – comes to the fore.

The key methodological difficulty in the framework of the demographic optimum concept is the formalization of the "optimal equilibrium" criterion. This approach involves the development of models in which the

population is considered as a subsystem of society. One possible tool is balance equations that reflect the relationship between fertility rate, mortality, migration, and population quality characteristics [29].

The formula for the overall demographic quality balance can be expressed as follows:

$$Q = f(B, D, M) \quad (1)$$

где Q – an integral indicator of the quality of the population; B – the fertility rate; D – the death rate; M – migration balance; H – the level of human capital (education, health, qualifications, etc.).

Today, there are many approaches to qualitative assessment of the population, each offering its own vision of the relationship between individual, social and structural characteristics of the population. These approaches form the methodological basis on which modern demographic research is based, and allow us not only to interpret current processes, but also to predict their development in the context of social transformations. The main approaches can be divided into 5 groups [30]:

1. The homeostatic approach assumes that the population size and structure have the ability to stabilize under the influence of external and internal factors. Researchers believe that society tends to reach an equilibrium state, where the fertility rate and mortality are balanced, as is observed in the late stages of demographic transition.

2. The axiological approach is based on recognizing the importance of individual values and needs, such as the desire to start a family, have children, maintain health, and change your place of residence. These factors act as regulators of demographic behavior and affect such indicators as marriage, fertility, and migration activity.

3. The valeological approach is a special case of the axiological approach, but it focuses on the problems of self-preservation behavior, especially among young people. It is used in social and pedagogical research and covers the topics of prevention of deviant behavior, healthy lifestyle and sustainable personal development.

4. The gender approach is used to study differences in the demographic behavior of male and women. The influence of gender on reproductive attitudes, migration preferences, and life expectancy is taken into account. This approach is important for the formation of effective social policies, especially in terms of equality and equal opportunities.

5. The human capital approach is based on ideas about the relationship between education, health, labor activity and the quality of life of the population. Various researchers have considered the population as a carrier of a valuable resource that determines economic and social development. Formally, this approach is based on human development indices (HDI) calculated by the formula [31]:

$$HDI = \sqrt[3]{I_{le} \cdot I_{ed} \cdot I_{in}} \quad (2)$$

где I_{le} – health index (based on life expectancy); I_{ed} – education index. I_{in} – index of income per capita.

The above approaches to studying the potential of population quality provide a comprehensive picture of the deep processes taking place in the population system. They are used to develop social and demographic strategies that allow adjusting policies in the areas of health, education, employment, and migration. In addition, the assessment of the population's qualitative potential is becoming a key tool in developing measures to overcome depopulation, stimulate the fertility rate and improve living standards. However, these approaches allow us to assess only the current quality of the population and do not take into account the potential of its reproduction. Also, the application of these approaches is associated with the problem of finding and collecting statistics necessary for analysis.

Integrated indicators of demographic potential

To date, the most widespread approach is based on the construction of integral indicators for assessing demographic potential, since it is based on obtaining a single quantitative assessment of the level of development of demographic potential, taking into account not only the characteristics of the state of the demographic process, but also the potential for its development.

One of these indicators was proposed by the French researcher L. Henri, who developed a method for estimating the intensity of generational replacement based on calculating the net reproduction rate. This method allows us to estimate the average number of daughters that a woman can give birth to in her lifetime, taking into account the age-related fertility and mortality rates based on the following expression [32]:

$$NRR = \sum_x l_x \cdot f_x \cdot p_f \quad (3)$$

где l_x – percentage of female who live to the age of x (from the mortality table); f_x – the age coefficient of the total fertility rate of all children; P_t – share of girls among newborns (approximately 0.488).

If NRR is equal to one, which means that each generation of female completely replaces itself, ensuring the stability of the population. A value above one indicates population growth; if below one, it indicates population decline.

In addition to the net reproduction rate, demographic research uses two other key indicators-gross and net reproduction rates, which allow us to analyze the process of generational change with a stable natural reproduction of the population. The gross coefficient reflects the average number of girls born to a woman who has lived to the end of the reproductive period, but the impact of age-related mortality is not taken into account.

In contrast, the net coefficient takes into account mortality in different age groups and shows how many of the girls born, on average, live to the age of their mother [22]. According to experts in the field of demography, it is the net coefficient that more accurately characterizes the patterns of population reproduction. To increase the population size, these coefficients must exceed one, which means that on average there are more than one daughter per woman. If these indicators do not reach one, this indicates a tendency to reduce the population.

The intensity of natural growth is proposed to be estimated using the marginal growth rate based on the following vector-matrix equation:

$$\bar{x}(t+1) = A \cdot \bar{x}(t) \quad (4)$$

где $\bar{x}(t)$ – the initial vector of the population's gender and age composition in a year t ; A – a matrix formed from the fertility rate and life expectancy.

The value of this indicator is calculated on the basis of a characteristic equation composed exclusively of coefficients describing the natural movement of female at the fertile age. The equation is formed using matrix elements and has the form [20]:

$$\lambda^t - \sum_{i=m+1}^r \lambda^{t-i} b_{i1} \prod_{j=1}^{i-1} p_{j1} = 0 \quad (5)$$

где b_{i1} – the fertility rate of girls among female belonging to age group i ; λ – root of the characteristic equation of the matrix A ; p_{j1} – survival rate (transition to the next age group) of female of the i -th age group [24].

The maximum possible population growth rate is determined by the largest eigenvalue of the matrix, which is also called the Apron root. If the value of this indicator is greater than one, it indicates a tendency to increase the population. If it is less than one, we are talking about a reduction in the number, that is, depopulation. Note that the net coefficient corresponds to the sum of the coefficients for the variable λ in equation (5). If there is population growth, the corresponding inequality holds:

$$b_{m+1} p_{11} \cdots p_{m1} + b_{m+2} p_{11} \cdots p_{m+1,1} + \cdots + b_r p_{11} \cdots p_{r-1,1} > 1 \quad (6)$$

Among the key limitations inherent in both the net reproduction rate and the marginal rate of population growth, we can highlight the narrowness of coverage of demographic characteristics. These indicators are calculated exclusively on the basis of data on the natural movement of female of childbearing age, mainly under 50 years of age. They do not reflect demographic processes related to the male population, older women, and do not take into account the sex structure of newborns. In addition, the net coefficient allows you to judge only the intensity of reproduction, but does not give an idea of its actual speed.

Standardized demographic indicators, in particular standardized growth and population growth rates, can partially overcome these shortcomings. Unlike traditional coefficients, these indicators are calculated using an age structure reduced to a single model, which eliminates the influence of the age composition of a particular population. For example, the standardized growth rate over a given time interval is defined as the difference between the standardized total fertility rate and the corresponding death rate. In the case of a five-year period and groups formed by the five-year age of male and female, the calculation is based on a special expression:

$$SNP_t = \sum_{i=4}^{10} \sum_{k=1}^2 b_{ik}^t z_{ik} - \sum_{i=4}^M \sum_{k=1}^2 q_{ik}^t z_{ik}, \quad (7)$$

где SNP_t – standardized total natural population growth rate in year t ; b_{ik}^t – values of age-specific fertility rates of girls ($k=1$) and boys ($k=2$) in year t by female of the i -th five-year-age group, indices $i = \overline{4,10}$ characterize five-year

age groups of female from 15 to 49 years; q_{ik}^f – values of age-related mortality rates for female and male in five-year groups, starting from the first and ending with the last one with the M index; z_{ik} – standardized proportion of the i -th age group of female ($k=1$) and male ($k=2$) in the population.

Set of values z_{ik} satisfies the following relation:

$$\sum_{i=1}^M \sum_{k=1}^2 z_{ik} = 1. \quad (8)$$

To compare population growth rates between different time periods, regions, or countries, any age structure corresponding to the previously described conditions can be used. In particular, we are talking about observing the principle of decreasing proportions of the population as the age increases for each gender group.

The calculation of generalized standardized population growth and growth rates is based on age models that reflect natural extinction – that is, the structure formed on the basis of the age-related mortality rates of a particular population.

Standardized population growth rate in the interval $(t, t+1)$ it can be evaluated based on the following expression:

$$SPG_t = 1 + SNP_t. \quad (9)$$

Assessment of the demographic potential of Russia and its regions

For the purpose of conducting a comparative analysis, the author obtained five-year estimates of the net reproduction rate, as well as the maximum (λ) and standardized growth rates for Russia and its regions for the period from 1995 to 2022, based on the statistics of fertility and mortality rates provided by official authorities for five-year age groups of male and female [33-35].

The results presented in Figure 1 show that after a certain decline from 2000 to 2017, there was a process of increasing the values of all indicators of demographic reproduction, indicating a decrease in the intensity of depopulation of the population. During this period, the five-year marginal growth rate increased by approximately 0.07, and the standardized growth rate increased from 0.962 to 0.991. In turn, the net reproduction rate increased from 0.564 to 0.853. However, in the period from 2017 to 2022, the values of indicators decreased.

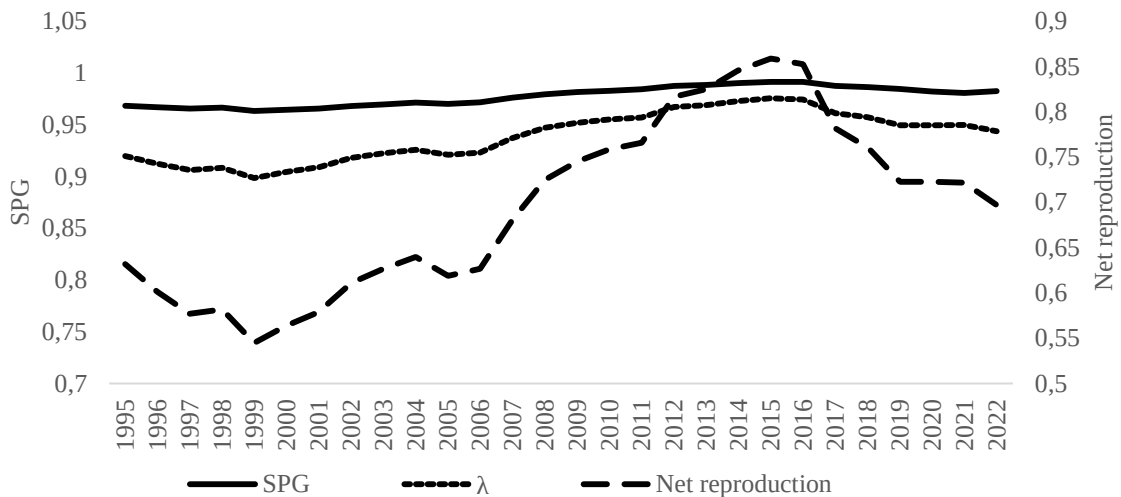


Fig. 1. Dynamics of indicators of Russia's demographic potential in 1970-2022, dimensionless

Analysis of the dynamics showed that all indicators showed positive changes on average over the year in the period 1995-2022: the marginal growth rate increased by 0.014, the standardized growth rate by 0.011, and the net reproduction rate by 0.018. This indicates a steady improvement in the demographic situation, especially in terms of reproductive behavior of the population. Although the changes appear to be moderate, even small increases can be strategically important in a long-term demographic downturn. The increase in the coefficients indicates some progress in social policies aimed at supporting the fertility rate, but the remaining difference between them underlines the need for a comprehensive approach to stimulating population reproduction.

The low values of the marginal growth rate in comparison with its standardized counterpart for Russia in the period from 1995 to 2022 can be explained by differences in the methods of calculating them, due to the different content of these indicators. As already mentioned, the marginal growth rate reflects the intensity of demographic reproduction in the long term, provided that the birth and death rates remain constant. This value is defined as the largest eigenvalue of the matrix of parameters of natural population movement, taking into account only female under 50 years of age. At the same time, smaller eigenvalues of this matrix are not taken into account, although their influence on the estimate of the growth rate in the short term may be significant, but over time their value tends to zero.

In turn, the standardized growth rates calculated on the basis of the observed data on the age and mortality of the Russian population, taking into account a certain age structure and relatively stable proportions of age groups, showed higher values compared to the marginal growth rate. However, if mortality among male of all ages and female over 50 years of age increases, the opposite situation may occur, when the standardized growth rate will be lower than the limit.

In the context of Russian regions, indicators of demographic potential show different degrees of differentiation (see Table 1). The greatest differentiation of regions is observed in terms of the net reproduction rate, which in 1995 was 20.9%, and in 2022-16.6%.

The marginal growth rate shows a significantly smaller spread across regions. In most cases, the coefficient of variation does not exceed 3%, which indicates a uniform demographic load and similar natural processes in different regions of the Russian Federation. The plotted trend graphs shown in Figure 1 also confirm our conclusions: the NCV curve shows more pronounced fluctuations, including temporary recessions and rises associated with economic crises and social policies. The lambda curve grows more smoothly, reflecting the slow recovery of natural growth rates.

Table 1. Comparative analysis of statistical characteristics of indicators of demographic potential of Russian regions

Year	Statistical characteristics	Marginal growth rate for 5 years	Net reproduction rate	Standardized growth rate for 5 years
1995	Mean	0.925	0.662	0.968
	Standard deviation	0.031	0.138	0.011
	Coefficient of variation, %	3.3	20.9	1.1
2022	Mean	0.939	0.680	0.979
	Standard deviation	0.023	0.113	0.009
	Coefficient of variation, %	2.4	16.6	0.9

The coefficient of variation calculated for the regions of Russia based on the standardized growth rate indicator is 1.1% in 1995 and 0.9% in 2022, which indicates extremely small differences between the values of the indicator by region.

Discussion

The limitations of the presented approaches include the need to collect large amounts of data on the population size and its gender and age structure, which is complicated when studying the demographic potential at the regional level. Given the fact that there is a certain time lag in the publication of data by state statistics bodies, due to the need to collect large amounts of data for all territorial units, difficulties arise when trying to quickly assess the level of demographic potential of the country and its regions.

You should also pay attention to the fact that with the development of technology, machine learning methods are becoming increasingly popular, which allow you to analyze large amounts of data and identify hidden patterns, without resorting to the need to perform intermediate calculations, which makes them especially useful for predicting demographic processes, since it significantly reduces the time for pre-processing data and obtaining results. In this regard, it can be generalized that the choice of a method for assessing demographic potential depends on the research objectives, data availability, and the required accuracy of forecasts.

Conclusion

The study showed that the indicators of demographic potential in Russia for the period 1995-2022 changed unevenly, while at the same time there are positive changes, but also risks associated with low fertility rates and high levels of premature mortality, in particular among the working-age population. At the national level, an increase in the natural growth rate and net reproduction is recorded, which indicates a partial improvement in the conditions for population reproduction. However, these improvements do not allow us to talk about overcoming demographic problems. The net reproduction remains below the level of simple reproduction, especially in most regions, which makes the issue of fertility and mortality still relevant in the context of state demographic policy.

The choice of an indicator of the level of demographic potential for Russia and its regions is complicated by the fact that existing approaches cannot fully characterize all the specifics of the demographic process in Russia. Thus, the net coefficient and marginal growth rate do not take into account the state and dynamics of the male population, but they allow us to assess the degree of differentiation of regions in terms of fertility and mortality, taking into account the age structure of the female population and the dynamics of these processes. In turn, the standardized growth rate takes into account the age structure of the fertility rate and mortality of the male population, but the estimates obtained on its basis are characterized by extremely low differentiation, which does not allow using this indicator to build models in order to identify factors that have the greatest impact on the demographic process in Russia and its regions.

However, all the above-mentioned indicators indicate that the population in Russia and its regions continues to decline, especially under the working-age and working-age groups. Thus, the considered indicators can be used by state bodies when taking targeted measures aimed at equalizing and establishing positive dynamics of the demographic process, taking into account the specifics of a particular region, since they will assess the effectiveness of the measures developed and implemented.

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