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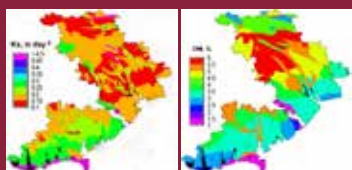
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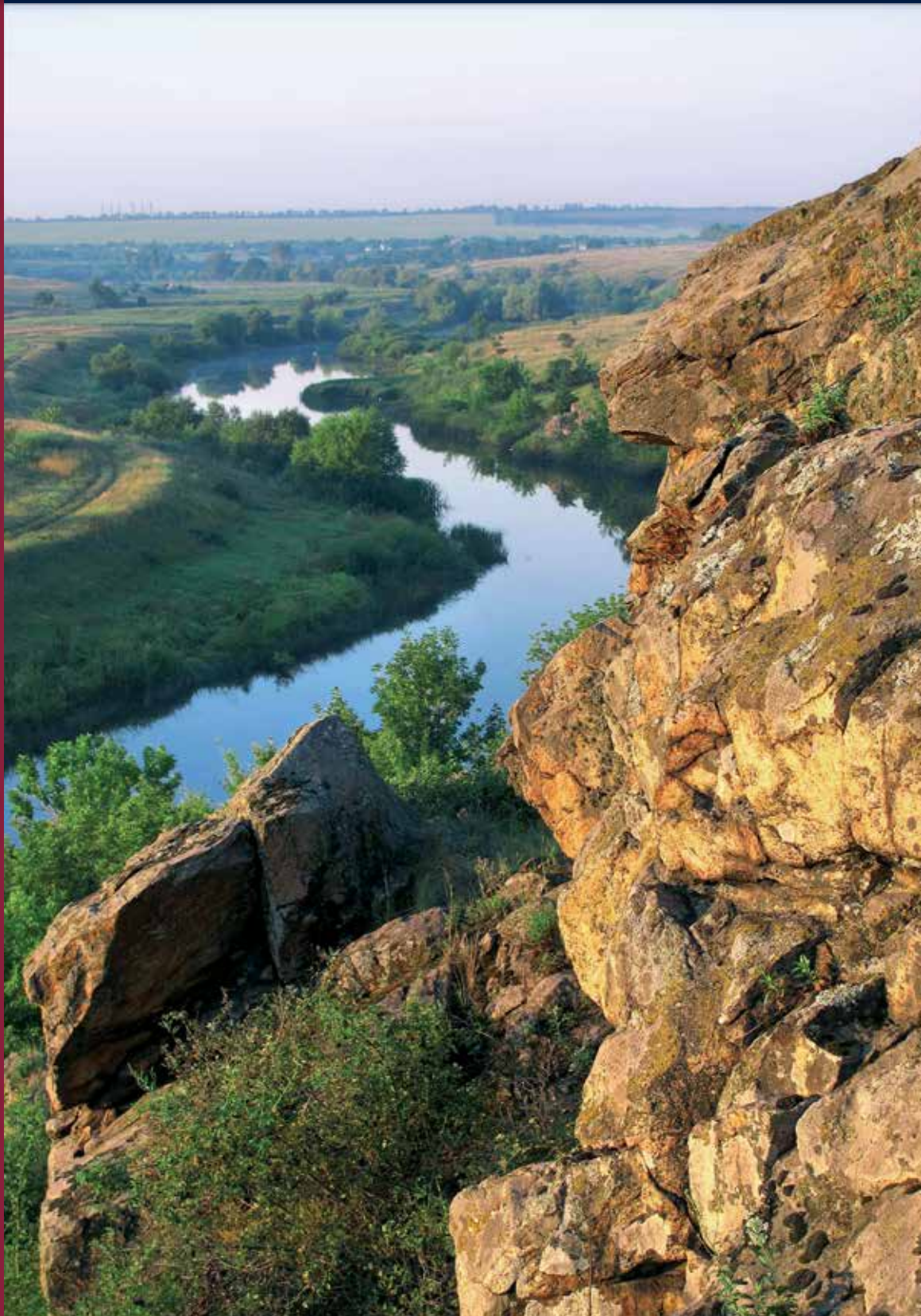
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E-mail: hydrogeology@karazin.ua,
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+38-098-089-3974

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Z.A.Temirov, M. Mamajonov, K.Q. Abdumalikov

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Modeling the average life expectancy of the population based on the Lee and Carter method (on the example of the population of the Fergana region, Uzbekistan)

Zokirjon A. Temirov, Mo'minjon Mamajonov, Khikmatillo Q. Abdumalikov

Andijan State University named after Zahiriddin Muhammad Babur, Andijan, Uzbekistan, zokirjon82@mail.ru

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Abstract. The economic and social development of countries around the world, improvements in social infrastructure, and rising living standards play a significant role in increasing life expectancy. Improvements in healthcare, improved food security, and other factors are also crucial. On the other hand, increased life expectancy leads to an increase in the proportion of elderly people in the population, which consequently increases the burden on pension and healthcare systems, as well as exacerbates problems such as labor shortages. Therefore, many countries conduct population and life expectancy projections, assess future demographics, and plan priority areas for future development. Various mathematical and statistical models are used to forecast population size and life expectancy. Extrapolation, cohort-component models, and logistic growth models help predict future population changes (Abdurakhmanov, 2011). The Cairns-Blake-Dowd (CBD) model (Cairns, Blake, Dowd, 2006, Safitri, Mardiyati, Malik, 2019), the Gompertz-Makeham model (Cohen, Bohk-Ewald, Rau, 2018), the Heligman-Pollard model (Emilidha, Danar-dono, 2017), and the Lee-Carter models (Lee, Carter, 1992, Booth, Maindonald, Smith, 2002, Booth, Hyndman, Tickle, Jong, 2006, Renshaw, Haberman, 2006) are also used to study the forecasting of population life expectancy. The Lee-Carter model is also widely used to forecast life expectancy. This model has been tested in many countries and is an important tool for long-term forecasts with stable results. The model describes complex demographic processes using a small number of parameters. The Lee-Carter model is one of the most widely used statistical demographic models for projecting life expectancy. Since its inception, the Lee-Carter model has been tested in many countries and regions, and various modifications have been developed. In a comprehensive review, Basellini, Camarda, and Booth (2023) analysed the 30-year history of the model's development and assessed it as one of the most important methodological approaches in forecasting. In recent years, numerous studies have been conducted to expand the model's ability to predict age-specific mortality rates, ensure the consistency of forecasts, and account for mortality dynamics (Liu and Shi, 2023). New modifications to the Lee-Carter model to account for extreme mortality shocks caused by the COVID-19 pandemic have also been proposed and tested in nine European countries (Schnürch et al., 2023). Recent studies have also assessed the model's stability when incorporating new data, the accuracy of its forecasts, and its performance compared to other mortality models (Mok et al., 2024). Furthermore, the Lee-Carter model has been successfully used to project age-specific mortality rates and life expectancy in Kazakhstan, Japan, the United Kingdom, the United States, and other countries, demonstrating its high adaptability to various demographic conditions. Therefore, this model is considered one of the most reliable and practical approaches to developing long-term population projections. The model is also flexible across different countries and regions, providing high accuracy in long-term forecasts. This article developed a life expectancy forecast using the Lee and Carter method based on mortality rates by age group in the Fergana region of Uzbekistan (Andijan, Namangan, and Fergana regions) for 1991–2015. The forecast results for 2015–2024 were compared with official statistics, and important conclusions were drawn.

proportion of elderly people in the population, which consequently increases the burden on pension and healthcare systems, as well as exacerbates problems such as labor shortages. Therefore, many countries conduct population and life expectancy projections, assess future demographics, and plan priority areas for future development. Various mathematical and statistical models are used to forecast population size and life expectancy. Extrapolation, cohort-component models, and logistic growth models help predict future population changes (Abdurakhmanov, 2011). The Cairns-Blake-Dowd (CBD) model (Cairns, Blake, Dowd, 2006, Safitri, Mardiyati, Malik, 2019), the Gompertz-Makeham model (Cohen, Bohk-Ewald, Rau, 2018), the Heligman-Pollard model (Emilidha, Danar-dono, 2017), and the Lee-Carter models (Lee, Carter, 1992, Booth, Maindonald, Smith, 2002, Booth, Hyndman, Tickle, Jong, 2006, Renshaw, Haberman, 2006) are also used to study the forecasting of population life expectancy. The Lee-Carter model is also widely used to forecast life expectancy. This model has been tested in many countries and is an important tool for long-term forecasts with stable results. The model describes complex demographic processes using a small number of parameters. The Lee-Carter model is one of the most widely used statistical demographic models for projecting life expectancy. Since its inception, the Lee-Carter model has been tested in many countries and regions, and various modifications have been developed. In a comprehensive review, Basellini, Camarda, and Booth (2023) analysed the 30-year history of the model's development and assessed it as one of the most important methodological approaches in forecasting. In recent years, numerous studies have been conducted to expand the model's ability to predict age-specific mortality rates, ensure the consistency of forecasts, and account for mortality dynamics (Liu and Shi, 2023). New modifications to the Lee-Carter model to account for extreme mortality shocks caused by the COVID-19 pandemic have also been proposed and tested in nine European countries (Schnürch et al., 2023). Recent studies have also assessed the model's stability when incorporating new data, the accuracy of its forecasts, and its performance compared to other mortality models (Mok et al., 2024). Furthermore, the Lee-Carter model has been successfully used to project age-specific mortality rates and life expectancy in Kazakhstan, Japan, the United Kingdom, the United States, and other countries, demonstrating its high adaptability to various demographic conditions. Therefore, this model is considered one of the most reliable and practical approaches to developing long-term population projections. The model is also flexible across different countries and regions, providing high accuracy in long-term forecasts. This article developed a life expectancy forecast using the Lee and Carter method based on mortality rates by age group in the Fergana region of Uzbekistan (Andijan, Namangan, and Fergana regions) for 1991–2015. The forecast results for 2015–2024 were compared with official statistics, and important conclusions were drawn.

Keywords: Lee & Carter, life expectancy, mortality rates, population age group, prognosis, life table, Fergana region.

Моделювання середньої тривалості життя населення на основі методу Лі та Картера (на прикладі населення Ферганської області)

Зокірджон А. Теміров, Момінджон Мамаджонов, Хікматілло К. Абдумаліков

Андижанський державний університет імені Захїрїддіна Мухаммада Бабура, Андижан, Узбекистан, zokir-jon82@mail.ru

Анотація. Економічний та соціальний розвиток країн світу, покращення соціальної інфраструктури та підвищення рівня життя відіграють значну роль у збільшенні тривалості життя. Покращення охорони здоров'я, підвищення продовольчої безпеки та інші фактори також мають вирішальне значення. З іншого боку, збільшення тривалості життя призводить до збільшення частки людей похилого віку в населенні, що, як наслідок, збільшує навантаження на пенсійну систему та систему охорони здоров'я, а також загострює таку проблему, як нестача робочої сили. Тому багато країн проводять прогнози чисельності населення та тривалості життя, оцінюють майбутню демографічну ситуацію та планують пріоритетні напрямки майбутнього розвитку. Для прогнозування чисельності населення та тривалості життя використовуються різні математичні та статистичні моделі. Екстраполяція, когортно-компонентні моделі та логістичні моделі зростання допомагають прогнозувати майбутні зміни чисельності населення. Для дослідження прогнозування тривалості життя населення також використовуються моделі Кернса-Блейка-Дауда (CBD). Модель Лі-Картера також широко використовується для прогнозування тривалості життя. Ця модель була випробувана в багатьох країнах і є важливим інструментом для довгострокових прогнозів зі стабільними результатами. Модель описує складні демографічні процеси з використанням невеликої кількості параметрів. Модель також є гнучкою для різних країн та регіонів, що забезпечує високу точність довгострокових прогнозів. У цій статті розроблено прогноз тривалості життя за методом Лі та Картера на основі показників смертності за віковими групами у Ферганській області Узбекистану (Андижанська, Наманганська та Ферганська області) за 1991–2015 роки. Результати прогнозу на 2015–2024 роки порівнювалися з офіційною статистикою.

Ключові слова: Лі та Картер, тривалість життя, показники смертності, вікова група населення, прогноз, таблиця життя, Ферганська область

Introduction

Today, the average life expectancy of the population varies in different countries and regions of the world. Life expectancy is influenced by the lifestyle of the population, living conditions, sanitary and hygienic conditions, the level of medical services, the geo-ecological situation of the regions and other factors, and is mainly higher in economically developed countries and lower in developing countries.

Since independence, Uzbekistan has seen an increase in life expectancy (www.stat.uz). A key factor in this is the development of a legal framework for comprehensive measures in healthcare, social policy, and improving living standards, as well as the implementation of reforms (Decree of the President of the Republic of Uzbekistan dated December 7, 2018, No. PF-5590 “On comprehensive measures to radically improve the healthcare system of the Republic of Uzbekistan”). Uzbekistan has set priority objectives to increase the average life expectancy to 78 years by 2030 (Decree of the President of the Republic of Uzbekistan dated February 16, 2026, No. PF-21 “On additional measures to consistently continue reforms within the framework of priority areas of country development until 2030”). In this regard, it is important to study the average life expectancy of the population and its forecast, as well as to plan future tasks.

Interest in studying the average life expectancy of a population arose in the early 17th century, when John Graunt first developed a life table in London (Connor, 2024). Later, scholars such as Abraham de Moivre, Benjamin Gompertz, and William Makeham refined this table (Makeham, 1860). Research into life expectancy prediction began in the late 20th century. The first to undertake such research were Ronald Lee

and Lawrence Carter (Lee, Carter, 1992). Today, Lee and Carter's method is used in many economically developed countries.

This method has been used in Kazakhstan by A.Knykova (Akzharkyn, Azat, 2017), I.A.Lakman, R.A.Askarov, V.B.Prudnikov, Z.F.Askarova, V.M.Timiryanova (Lakman, Askarov, Prudnikov, Askarova, Timiryanova, 2021), and in Russia and Bashkortostan, scientific research has been conducted on the Lee & Carter method. In Uzbekistan, a number of scientists have been engaged in population forecasting and life tables. In particular, scientists such as Z.N.Tojiev (Tojiev, 2010), Q.Abdurakhmanov (Abdurakhmanov, 2011), N.J.Muhammedova (Muhammedova, 2019), R.B.Kodirov (Kodirov, Temirov, 2021) and Z.A.Temirov (Temirov, 2022) have conducted scientific research. Direct Lee & Carter method forecasts have not been implemented to date. In this article, for the first time in Uzbekistan, a life expectancy forecast using the Lee & Carter method is implemented.

The purpose of this research is to develop a life expectancy at birth forecast using the Lee & Carter method for the Fergana Valley regions. To achieve this goal, the tasks were set to develop a life expectancy forecast for the Fergana region by age group based on mortality rates for 1991–2015 using the Lee & Carter method until 2030, and to develop a life expectancy forecast for 2016 to 2030 based on data for 1991–2015, and to compare the Lee & Carter method forecast for 2015–2024 with official statistical data.

Material and methods

The Lee–Carter model parameters and related calculations were estimated using Microsoft Excel 2013

(Version 15.0.4569.1504; Microsoft Corporation, Redmond, WA, USA).

The Lee-Carter method was developed by Ronald Lee and Lawrence Carter in 1992 and is primarily aimed at predicting future mortality rates by age group. The main goal of the method is to identify changes in mortality rates over time and project them into the future.

The basic formula of the method is expressed as follows:

$$\ln(m_{x,t}) = a_x + b_x \cdot k_t + \varepsilon_{x,t}, \quad (1)$$

here, $m_{x,t}$ – mortality rate in age group x and period t ; a_x – age-specific logarithmic mean mortality rate, b_x – age sensitivity coefficient, k_t – time-varying coefficient, $\varepsilon_{x,t}$ – error component.

The methodology is implemented in the following stages:

1. For each age group, the population size and the number of deaths are determined. The mortality rate $m_{x,t}$ is calculated using the following formula: $m_{x,t} = d_{x,t} / p_{x,t}$, where $d_{x,t}$ is the number of deaths in age group x , and $p_{x,t}$ is the population size in this age group.
2. Logarithmic indices are calculated. In this case, the natural logarithms of the obtained $m_{x,t}$ values are taken, that is, $\ln(m_{x,t})$. This step helps to determine the main mortality trend by age group.
3. In determining the average age coefficients, (a_x) is the average of the $\ln(m_{x,t})$ values for each age group. This is the a_x coefficient, which represents the age-specific mortality rate.
4. Next, the trend is determined (b_x and k_t). In this case, the differences in mortality rates by age and time are given by $Z_{x,t} = \ln(m_{x,t}) - a_x$. This difference is used to calculate the coefficients b_x and k_t . b_x represents the age sensitivity, and k_t represents the overall mortality trend over time. The coefficient k_t is usually normalized, that is, its sum is set to 0.
5. Using the determined coefficients a_x , b_x , and k_t , mortality rates are projected for future years. This allows the population's average life expectancy, life table, and mortality probabilities by age group to be calculated in the future.
6. At the end of the study, the forecast results are compared with official statistical data and the accuracy of the method is assessed. This stage ensures the reliability of the methodology.

The Lee-Carter methodology provides highly accurate forecasts and analyzes trends in mortality rates across age groups.

Results and discussion

According to the formula, it is necessary to determine the mortality rate data for a given age group in a given year, $m_{x,t}$.

In this formula, a_x is the average age-specific logarithm, and the mortality rate is determined using the following formula:

$$a_x = \frac{1}{T} \sum_{t=1}^T \ln(m_{x,t}), \quad (2)$$

here $m_{x,t}$ is the mortality rate for age x and period t (for example, the rates for each age group in 1990, 1991, 1992, etc., 2015), which is determined by first using statistical data on the population size and the number of deaths by age group. $m_{x,t}$ is obtained by dividing the number of deaths in a given age group and year by the number of population in the same age group and is determined using the following formula:

$$m_{x,t} = d_{x,t} / p_{x,t}, \quad (3)$$

here: $d_{x,t}$ – number of deaths by age group;

$p_{x,t}$ – population by age group.

In this research, the population and death toll data for the Fergana region (Andijan, Namangan, and Fergana regions) for 1991-2015 were used, and one example was given as a sample, and the remaining indicators were presented in tabular form. For example:

$$m_{x,t} = d_{x,t} / p_{x,t} = d_{0-1, 1991} / p_{0-1, 1991} = 6865:378761 = 0.01812 \approx 0.018125$$

The number of deaths in the Fergana region aged 0-1 in 1991 divided by the population, that is, the mortality rate was 0.018125 (Table 1).

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

Based on the formula, the next step is to determine the age-dependent average logarithm – a_x , the mortality rate. It is determined using the following formula:

$$a_x = \frac{1}{T} \sum_{t=1}^T \ln(m_{x,t}), \quad (4)$$

here: T – number of years observed;

$m_{x,t}$ – mortality rate by age group;

$\ln(m_{x,t})$ – natural logarithm.

Table 1 above presents the data on mortality rates ($m_{x,t}$) by age group for the years 1991-2015. According to it, $\ln(m_{x,t})$ is first determined.

$$\ln(m_{x,t}) = \ln(m_{0-1, 1991}) = \ln 0.018125 = -4.010463078.$$

In this way, the $\ln$ of the data presented in the table was determined and is given in table below (Table 2).

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

Note: To keep the table size small, only data for the 0-1 age group is presented.

In Table 2 above, $\ln(m_{x,t})$ was determined. This table only includes data for the 0-1 age group. It is necessary to determine a_x according to the formula. In this case, it is also calculated separately for each age group and is calculated as follows:

$$a_x = \frac{1}{T} \sum_{t=1}^T \ln(m_{x,t}) = a_{0-1} = \frac{1}{T} \sum_{t=1}^T \ln(m_{0-1}),$$

here: T – indicates the number of years, and in our example, it is 1991 – 2015, i.e. T=25.

$$a_{0-1} = \frac{1}{T} \sum_{t=1}^T \ln(m_{0-1}) =$$

$$a_{0-1} = \frac{(-4.01047) + (-3.9358) + (-4.14433) + (-4.25508) + \dots + (-5.11433)}{25} = \frac{-118.01255}{25} = -4.720502$$

In the above example, the average value of $\ln(m_{x,t})$ for the 0-1 age group in 1991, 1992... and 2015

was determined. In this way, the average value of $\ln(m_{x,t})$ for the other 0-4, 5-9 and other age groups is also determined and is given in the table below (Table 3).

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

In Table 3, the a_x of the population of the Fergana region in all age groups for 1991-2015 was determined. This indicator helps to determine b_x in the formula.

B_x means an increase or decrease in the mortality rate in age group x during the period. Here b_x and k_t are related in the form of a product and are determined together. They cannot be determined separately. B_x and k_t are determined using the following formulas:

Table 1. Mortality rates by age groups in the Fergana region, 1991-2015

Age group	1991	1995	2000	2005	2010	2015
0-1	0.018125	0.013418	0.009010	0.008002	0.006105	0.006010
1-4	0.003871	0.005566	0.003012	0.001870	0.001239	0.001346
5-9	0.000601	0.000588	0.000445	0.000391	0.000402	0.000306
10-14	0.000551	0.000561	0.000462	0.000375	0.000378	0.000391
15-19	0.000844	0.000850	0.000761	0.000555	0.000484	0.000606
20-24	0.001152	0.001173	0.001133	0.000877	0.000665	0.000720
25-29	0.001266	0.001528	0.001386	0.001355	0.000989	0.000906
30-34	0.001710	0.001874	0.001768	0.001608	0.001407	0.001265
35-39	0.002267	0.002450	0.002004	0.002159	0.001712	0.001786
40-44	0.003469	0.003743	0.003221	0.002841	0.002507	0.002292
45-49	0.006012	0.005275	0.004819	0.004405	0.003542	0.003500
50-54	0.009384	0.010045	0.007997	0.007654	0.005976	0.006042
55-59	0.013553	0.014545	0.014514	0.011907	0.011080	0.009969
60-64	0.020769	0.024259	0.021370	0.022953	0.018723	0.017533
65-69	0.025308	0.033986	0.036972	0.035076	0.034884	0.027139
70-74	0.041057	0.044529	0.051098	0.057595	0.053255	0.049998
75-79	0.064568	0.071573	0.072017	0.079917	0.085619	0.075580
80-84	0.092944	0.110383	0.114424	0.096789	0.120102	0.132783
85+	0.166127	0.232935	0.210438	0.150602	0.112675	0.127934

Table 2. Logarithmic indicators of the population of the Fergana region by age group 0-1 in 1991-2015

1991	1992	1993	1994	1995
-4.01047	-3.9358	-4.14433	-4.25508	-4.31116
1996	1997	1998	1999	2000
-4.50460	-4.584	-4.53723	-4.59097	-4.70942
2001	2002	2003	2004	2005
-4.71276	-4.7831	-4.78059	-4.76147	-4.82806
2006	2007	2008	2009	2010
-4.84115	-4.84406	-5.01555	-5.06261	-5.09865
2011	2012	2013	2014	2015
-5.16047	-5.10819	-5.16047	-5.15803	-5.11433

$$b_x = \frac{\sum_t z_{x,t} * k_t}{\sum_t k_t^2} \text{ and } k_x = \frac{\sum_t z_{x,t} * b_t}{\sum_t b_t^2}, \quad (5)$$

In the above formula, $z_{x,t}$ is the deviation from the trend of increasing or decreasing mortality rates, which is the difference between the mortality rate ($\ln(m_{x,t})$) for each age and year from the mean, and is determined by the following formula:

$$Z_{x,t} = \ln(m_{x,t}) - a_x, \quad (6)$$

To determine b_x and k_t given in the formula, it is first necessary to determine $Z_{x,t}$. It is calculated according to the given formula:

$$Z_{x,t} = \ln(m_{x,t}) - a_x = Z_{0-1, 1991} = \ln(m_{0-1, 1991}) - a_x = -4.01046 - (-4.5289424) = 0.5184824$$

In this way, $Z_{x,t}$ was developed for all years and age groups (Table 4).

The $Z_{x,t}$ we need has been determined. Now we need to determine b_x . As is known, b_x and k_t were determined together. Here k_t was normalized using the Lee Carter method, that is, the sum of k_t was taken equal to 0. The study studied the data for 1991-2015, that is, 25 years. In this case, $k_{1991} = -12$, $k_{1992} = -11$, $k_{1993} = -10$, ..., $k_{2003} = 0$ va $k_{2015} = 12$.

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

According to the formula, b_x is determined. This is based on the data in Table 3.

$$b_x = \frac{\sum_t z_{x,t} * k_t}{\sum_t k_t^2}$$

$$b_{0-1} = \frac{0.71004 * (-12) + 0.7847 * (-11) + \dots + (-0.0601) * 0 + (-0.4097) * 1 + \dots + (-0.03938) * 12}{(-12)^2 + (-11)^2 + \dots + (-1)^2 + 0^2 + 1^2 + \dots + 11^2 + 12^2} = \frac{-62.3623}{1300} = -0.04797099$$

The b_x to be determined was developed for the age group 0-1. The remaining age groups were calculated in the same way and the results are presented in Table 5.

Table 3. Population age group indicators of the Fergana region for 1991-2015

Age group	$\sum \ln_{(mx,t)}$	a_x
0-1	-118.01255	-4.720502
1-4	-150.21547	-6.0086188
5-9	-192.4332	-7.697328
10-14	-194.09625	-7.76385
15-19	-183.01344	-7.3205376
20-24	-174.43565	-6.977426
25-29	-167.47769	-6.6991076
30-34	-161.05222	-6.4420888
35-39	-155.08179	-6.2032716
40-44	-146.22906	-5.8491624
45-49	-135.17558	-5.4070232
50-54	-122.5009	-4.900036
55-59	-109.57178	-4.3828712
60-64	-96.55036	-3.8620144
65-69	-85.48965	-3.419586
70-74	-74.84418	-2.9937672
75-79	-64.87416	-2.5949664
80-84	-54.94537	-2.1978148
85+	-45.4554	-1.818216

Table 4. Population indicators of the Fergana region by age groups z_x for the period 1991-2015

Age group	1991	1995	2000	2005	2010	2015
0-1	0.71004	0.409342	0.011082	-0.10756	-0.37815	-0.39383
1-4	0.45438	0.817539	0.203469	-0.27320	-0.68483	-0.60200
5-9	0.28041	0.258548	-0.02011	-0.14947	-0.12173	-0.39460
10-14	0.26007	0.27806	0.083900	-0.12473	-0.11677	-0.08295
15-19	0.24318	0.250268	0.139658	-0.17600	-0.31289	-0.08809
20-24	0.21117	0.229236	0.194536	-0.06157	-0.33829	-0.25883
25-29	0.02722	0.215308	0.117778	0.095158	-0.21971	-0.30736
30-34	0.07083	0.162409	0.104179	0.009329	-0.12421	-0.23059
35-39	0.11397	0.191602	-0.00934	0.065162	-0.16682	-0.12451
40-44	0.18527	0.261292	0.111102	-0.01444	-0.13951	-0.22917
45-49	0.29302	0.162243	0.071833	-0.01800	-0.23604	-0.24797
50-54	0.23129	0.299356	0.071346	0.027506	-0.21996	-0.20898
55-59	0.08172	0.152361	0.150231	-0.04776	-0.11974	-0.22541
60-64	-0.01228	0.143044	0.016244	0.087704	-0.11599	-0.18166
65-69	-0.25704	0.037776	0.121996	0.069346	0.063856	-0.18719
70-74	-0.19902	-0.11784	0.019757	0.139447	0.061107	-0.00200
75-79	-0.14507	-0.04207	-0.03588	0.068196	0.137116	0.012406
80-84	-0.17795	-0.00599	0.029975	-0.13741	0.078405	0.178775
85+	0.02322	0.361216	0.259656	-0.07489	-0.36503	-0.23802

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

According to the Lee & Carter formula, the sum of the b_x indicators should be equal to 1. According to the calculations, the sum of b_x is -0.4027. To make the result equal to 1, b_x was normalized (Table 5).

The b_x given in the formula was determined and k_t was derived based on b_x and k_t were derived in a dependent manner. In Table 4 above, Z_x and b_x were given in Table 5. Then, according to the formula:

$$k_{1991} = \frac{\sum_t z_{x,t} * b_t}{\sum_t b_t^2} = \frac{0.71004 * 0.11912 + (0.45438 * 0.176624) + \dots + (0.02322 * 0.083156)}{0.11912^2 + 0.176624^2 + \dots + 0.083156^2} = \frac{0.30361555}{0.09451803} = 3.21225$$

According to the analysis, $k_{1991} = 3.21225$, thus k_x for all years is also determined (Table 6).

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

The final step of the Lee & Carter model is given by $\varepsilon_{x,t}$. This residual, or how well the model explains the observed logarithmic mortality rate, is given by the following formula:

$$\varepsilon_{x,t} = \ln m_{x,t}^{real} - (a_x + b_x * k_t) \quad (7)$$

$$\varepsilon_{x,t} = \ln m_{x,t}^{real} - (a_x + b_x * k_t) = \varepsilon_{0-1,1991} =$$

Table 5. Population indicators of the Fergana region by age groups b_x for the period 1991-2015

Age group	b_x	Normalized b_x
0-1	-0.04797099	0.11912
1-4	-0.07112875	0.176624
5-9	-0.03111268	0.077258
10-14	-0.02700616	0.067061
15-19	-0.02836599	0.070437
20-24	-0.02967023	0.073676
25-29	-0.02280496	0.056628
30-34	-0.01630662	0.040492
35-39	-0.01548001	0.038439
40-44	-0.02360726	0.058621
45-49	-0.02479793	0.061577
50-54	-0.02482939	0.061655
55-59	-0.01814438	0.045055
60-64	-0.01103774	0.027408
65-69	-0.00122724	0.003047
70-74	0.008400829	-0.02086
75-79	0.008699358	-0.0216
80-84	0.007165516	-0.01779
85+	-0.03348779	0.083156

$$= -4.01047 - (-4.720502 + 0.11912 * 3.21225) = -4.01047 - (-4.720502 + 0.38264322) = -4.01047 - (-4.33786) = 0.32739.$$

$\varepsilon_{x,t}$, that is, the error, that is, how much it differs from the real situation, was determined. This indicator was calculated for each year and age group, and the average indicators can be seen in table below (Table 7).

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

According to the data in the table, this model has high accuracy. The average error across age groups and years is 0.03533. This is a very small error. However, in some years, the errors in some age groups are slightly larger. This indicates that there are some shortcomings in the statistical data.

The main part of the Lee Carter model is the forecast of the age-specific mortality rate, m_{nx} , in the coming years. The following formula is used:

$$\check{k}_t = \alpha + \beta \cdot t, \quad (8)$$

here:

$\check{k}_t$ – k_t 's projected year;

Table 6. Population and demographic indicators k_x of the Fergana region in 1991-2015

Years	$k_{x, New}$
1991	3.21225
1992	4.14320
1993	4.53562
1994	4.70372
1995	4.02623
1996	3.17007
1997	2.40657
1998	2.68623
1999	1.95086
2000	1.27403
2001	0.73485
2002	0.19794
2003	-0.25222
2004	-1.27883
2005	-1.03187
2006	-1.37942
2007	-1.21679
2008	-2.49909
2009	-3.13573
2010	-3.54270
2011	-3.41725
2012	-3.67442
2013	-3.91643
2014	-4.23964
2015	-3.45719
Total	0
Average	0

α – the starting point of the regression line in the Lee–Carter model;

β – this is the trend coefficient, which shows how much the value of k_t changes each year;

t – this time or year.

According to the formula, β is initially determined as follows:

$$\beta = \frac{\sum(t_i - \bar{t}) * (k_t - \bar{k})}{\sum(t_i - \bar{t})^2}, \quad (9)$$

here:

t – year (1991, 1992, 1993,2015);

k_t – the k_t value for that year;

$\bar{t}$ – annual average;

$\bar{k}$ – k_t average.

According to the formula, the following table was initially developed (Table 8)

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

$$\beta = \frac{\sum(t_i - \bar{t}) * (k_t - \bar{k})}{\sum(t_i - \bar{t})^2} = \frac{-523.52707}{1300} = -0.40271.$$

In the next step, α was determined.

$$\alpha = \bar{k} - \beta * \bar{t}$$

Here:

$\bar{k}$ – k_t average;

β – regression trend (shows how k_t changes each year);

$\bar{t}$ – annual average.

Based on the data from 1991-2015, k_t was determined and the results are given in Table 6. Based on the data in Table 6, the average k_t was determined:

$$\bar{k} = \frac{3.2122 + 4.14320 + 4.53562 + \dots + (-4.23964) + (-3.45719)}{25} = \frac{0}{25} = 0.0$$

$\bar{t}$ – when determining t , year1 is taken as follows:

1991 – 1, 1992 – 2, 1993 – 3, 1994 – 4,2015 – 25.

$$\bar{t} = \frac{1 + 2 + 3 + \dots + 24 + 25}{25} = \frac{325}{25} = 13$$

$$\alpha = \bar{k} - \beta * \bar{t} = 0 - (-0.4027) * 13 = 5.2351.$$

The mortality rate is determined for future years, and based on this, the mortality rate $m_{x,t}$ for the forecast year, or the age-specific mortality rate, is calculated. We use the following formula:

$$\bar{k}_{2016} = \alpha + \beta * t = k_{2016} = -5.2351 + (-0.4027) * 26 = -5.2351 + (-10.4702) = -15.7053.$$

$\bar{k}$ – the results of the remaining years of the forecast are given in table below (Table 9).

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

The k_t for the forecast years has been determined. The $m_{x,t}$ is determined by age group for the forecast period. The formula for the forecast year $m_{x,t}$ is as follows:

$$m_{x,t} = \exp(a_x + b_x * k_t) \quad (10)$$

According to the formula, we find $m_{0-1,2016}$ then:

Table 7. Average indicators of e_x by age group of the population of the Fergana region in 1991-2015

Age group	Average by age group	Years	Ex – average	Years	Ex – average
0-1	0.000000047	1991	-0.007600	2004	0.030629
1-4	0.022694488	1992	0.0766270	2005	0.075848
5-9	0.022730725	1993	0.1368210	2006	0.032356
10-14	0.031897109	1994	0.183069	2007	0.013291
15-19	0.046755517	1995	0.150312	2008	-0.02105
20-24	0.060771000	1996	0.1403940	2009	-0.06689
25-29	0.053889696	1997	0.0961500	2010	-0.06283
30-34	0.042431842	1998	0.14604900	2011	-0.06845
35-39	0.044410729	1999	0.1064650	2012	-0.09536
40-44	0.072302579	2000	0.1356510	2013	-0.12863
45-49	0.079086518	2001	0.1121260	2014	-0.15969
50-54	0.080998985	2002	0.1246610	2015	-0.17896
55-59	0.059547535	2003	0.112333	Average	0.03533
60-64	0.035947631				
65-69	0.003840503				
70-74	-0.025431394				
75-79	-0.025141743				
80-84	-0.019841151				
85+	0.084431147				
Average annual	0.03533				

Table 8. Fergana region population age group β determination table for 1991-2015

Years	k_x	$t-t'$	$kt-k'$	$(t-t')*(kt-k')$	$(t-t')^2$
1991	3.21225	-12	3.21225	-12*3.21225=-38.547	-12 ² =144
1992	4.14320	-11	4.14320	-45.5752	121
1993	4.53562	-10	4.53562	-45.3562	100
1994	4.70372	-9	4.70372	-42.33348	81
1995	4.02623	-8	4.02623	-32.20984	64
1996	3.17007	-7	3.17007	-22.19049	49
1997	2.40657	-6	2.40657	-14.43942	36
1998	2.68623	-5	2.68623	-13.43115	25
1999	1.95086	-4	1.95086	-7.80344	16
2000	1.27403	-3	1.27403	-3.82209	9
2001	0.73485	-2	0.73485	-1.4697	4
2002	0.19794	-1	0.19794	-0.19794	1
2003	-0.25222	0	-0.25222	0	0
2004	-1.27883	1	-1.27883	-1.27883	1
2005	-1.03187	2	-1.03187	-2.06374	4
2006	-1.37942	3	-1.37942	-4.13826	9
2007	-1.21679	4	-1.21679	-4.86716	16
2008	-2.49909	5	-2.49909	-12.49545	25
2009	-3.13573	6	-3.13573	-18.81438	36
2010	-3.54270	7	-3.54270	-24.7989	49
2011	-3.41725	8	-3.41725	-27.338	64
2012	-3.67442	9	-3.67442	-33.06978	81
2013	-3.91643	10	-3.91643	-39.1643	100
2014	-4.23964	11	-4.23964	-46.63604	121
2015	-3.45719	12	-3.45719	-41.48628	144
Total	0.00	0	0	-523.52707	1300

Table 9. Fergana region population by age group for 2016-2035 $\tilde{k}$ table

Years	$\tilde{k}$
2016	-5.2351
2017	-5.6378
2018	-6.0405
2019	-6.4432
2020	-6.8459
2021	-7.2486
2022	-7.6513
2023	-8.0540
2024	-8.4567
2025	-8.8594
2026	-9.2621
2027	-9.6648
2028	-10.0675
2029	-10.4702
2030	-10.8729
2031	-11.2756
2032	-11.6783
2033	-12.081
2034	-12.4837
2035	-12.8864

$m_{x,t} = \exp(a_x + b_x \cdot k_t) = m_{0-1,2016} = \exp(a_x + b_x \cdot k_{2016})$. We have a_x and b_x as given in Table 7 above.

$$m_{0-1,2016} = \exp(-4.720502 + 0.11912 * (-5.2351)) = \exp(-4.720502 + (-0.623605)) = \exp-5.344107 = 0.004776.$$

This is how all years and age groups are calculated (Table 10).

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

The table above provides a forecast of the mortality rate of the population of the Fergana region for all age groups from 2016 to 2030. Based on this data, life expectancy at birth was determined using a life table (Table 11).

The table was developed by the author based on data from the Statistical Agency of the Republic of Uzbekistan.

According to the table, the life expectancy at birth developed by the Lee & Carter method differed only slightly from the official statistical data. The average difference from 2016 to 2024 was -0.14. This indicates that the method has a high accuracy.

Table 10. Table of mortality rate ($m_{x,t}$) forecast in the Fergana region by age groups for 2016-2030.

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
0-1	0.004776	0.004552	0.004339	0.004136	0.003942	0.003758	0.003582	0.003414	0.003254	0.003102	0.002956	0.002818	0.002686	0.00256	0.00244
1-4	0.000975	0.000908	0.000846	0.000787	0.000733	0.000683	0.000636	0.000592	0.000552	0.000514	0.000479	0.000446	0.000415	0.000387	0.00036
5-9	0.000303	0.000294	0.000285	0.000276	0.000268	0.000259	0.000251	0.000244	0.000236	0.000229	0.000222	0.000215	0.000209	0.000202	0.000196
10-14	0.000299	0.000291	0.000283	0.000276	0.000268	0.000261	0.000254	0.000248	0.000241	0.000235	0.000228	0.000222	0.000216	0.000211	0.000205
15-19	0.000458	0.000445	0.000432	0.00042	0.000409	0.000397	0.000386	0.000375	0.000365	0.000355	0.000345	0.000335	0.000326	0.000317	0.000308
20-24	0.000634	0.000616	0.000598	0.00058	0.000563	0.000547	0.000531	0.000515	0.0005	0.000486	0.000471	0.000458	0.000444	0.000431	0.000419
25-29	0.000916	0.000895	0.000875	0.000855	0.000836	0.000817	0.000799	0.000781	0.000763	0.000746	0.000729	0.000713	0.000697	0.000681	0.000666
30-34	0.001289	0.001268	0.001247	0.001227	0.001207	0.001188	0.001169	0.00115	0.001131	0.001113	0.001095	0.001077	0.00106	0.001043	0.001026
35-39	0.001654	0.001629	0.001604	0.001579	0.001555	0.001531	0.001507	0.001484	0.001461	0.001439	0.001417	0.001395	0.001374	0.001353	0.001332
40-44	0.002121	0.002071	0.002023	0.001976	0.00193	0.001884	0.001841	0.001798	0.001756	0.001715	0.001675	0.001636	0.001597	0.00156	0.001524
45-49	0.003249	0.003169	0.003092	0.003016	0.002942	0.00287	0.0028	0.002731	0.002664	0.002599	0.002535	0.002473	0.002413	0.002354	0.002296
50-54	0.005392	0.00526	0.005131	0.005005	0.004882	0.004763	0.004646	0.004532	0.004421	0.004312	0.004207	0.004103	0.004003	0.003905	0.003809
55-59	0.009865	0.009688	0.009514	0.009343	0.009175	0.00901	0.008848	0.008688	0.008532	0.008379	0.008228	0.00808	0.007935	0.007792	0.007652
60-64	0.018215	0.018015	0.017817	0.017622	0.017428	0.017237	0.017048	0.016861	0.016676	0.016493	0.016312	0.016133	0.015955	0.01578	0.015607
65-69	0.032208	0.032169	0.032129	0.03209	0.03205	0.032011	0.031972	0.031933	0.031893	0.031854	0.031815	0.031776	0.031737	0.031698	0.03166
70-74	0.055879	0.056351	0.056826	0.057306	0.057789	0.058276	0.058768	0.059264	0.059764	0.060268	0.060776	0.061289	0.061806	0.062328	0.062853
75-79	0.083586	0.084316	0.085052	0.085795	0.086545	0.087301	0.088064	0.088833	0.089609	0.090392	0.091182	0.091979	0.092782	0.093593	0.09441
80-84	0.121885	0.122761	0.123644	0.124533	0.125428	0.12633	0.127238	0.128153	0.129075	0.130003	0.130937	0.131879	0.132827	0.133782	0.134744
85+	0.105025	0.101566	0.098221	0.094986	0.091858	0.088833	0.085907	0.083078	0.080342	0.077696	0.075137	0.072663	0.07027	0.067955	0.065717

Table 11. Fergana region population life expectancy forecast for 2016-2030

Years	stat.uz data	By Lee Carter	The difference
2016	73.53	73.84	-0.31
2017	73.17	73.98	-0.81
2018	74.37	74.13	0.24
2019	74.83	74.27	0.56
2020	73.73	74.41	-0.68
2021	74.00	74.55	-0.55
2022	74.77	74.68	0.09
2023	74.97	74.81	0.16
2024	74.97	74.94	0.03
2025		75.07	
2026		75.19	
2027		75.32	
2028		75.44	
2029		75.56	
2030		75.67	

The results of this study showed that the Lee-Carter model has high forecasting accuracy for the Fergana region of Uzbekistan. The difference between the model and official statistics for 2016-2024 is -0.14 years, indicating the reliability of the method for long-term forecasting. Similar results were noted in studies conducted in Kazakhstan (Akzharkin, Azat, 2017), Russia and Bashkortostan (Lakman, Askarov, Prudnikov, Askarova, Timiryanova, 2021).

According to an analysis of mortality rates by age group, mortality in the 0-1 and 1-4 age groups decreased almost threefold between 1991 and 2015. This is explained by improved medical care and rising living standards. Mortality in the over-70 age group is also expected to decrease until 2030, indicating that population aging will continue.

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According to the Lee-Carter method, the projected average life expectancy in the Fergana region will reach 75.67 years by 2030. Decree No. PF-21 of the President of the Republic of Uzbekistan sets priority objectives for increasing life expectancy to 78 years by 2030. This indicates the need for additional measures in healthcare and social policy.

Conclusions

This article presents the first practical forecast using the Lee & Carter method. This forecast is considered to be of great importance due to its high accuracy.

According to the formula, $\varepsilon_{x,t}$ – indicates the model error. This study used data on the population and death rates of the Fergana region by age group for 1991-2015. The average value of the model error $\varepsilon_{x,t}$ – is 0.03533, which indicates that the model worked with high accuracy, but the error in some age groups in some years, i.e. $\varepsilon_{x,t} > 1$, indicates that there are some shortcomings in the statistical data and the need to conduct a population census.

The relative increase in the difference between the model and actual data in 2017 and 2020 is explained by the fact that the Lee-Carter model is based on the average dynamic trend and cannot fully reflect short-term demographic changes (the COVID-19 pandemic in 2020).

According to the Lee & Carter method, life expectancy at birth in the Fergana region is expected to reach 75.67 years by 2030. Also, the increase in life expectancy among the elderly population means that life expectancy will continue to increase in the future and the proportion of elderly people in the population will increase. This serves as an important source for drawing up future roadmaps.

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