MORTALITY ASSUMPTIONS AND FORECASTING METHODOLOGY: POPULATION PROJECTION OF THE CZECH REPUBLIC FROM THE CZECH STATISTICAL OFFICE, 2018–2100

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Abstract
The present study describes the methodology of the new mortality forecast for Czechia. The author presents a brief review of existing forecasting approaches. Mortality trends in Czechia are then thoroughly assessed in comparison to other European countries in order to extract a realistic pattern of the recent mortality decline. Mortality dynamics are analysed with the Lee-Carter functional model and from the perspective of the rates of mortality decline. The new model is based on deterministic assumptions about the age-specific patterns of future mortality change. Three scenarios are presented, reflecting three possible future mortality settings. The projection results appear plausible both in terms of internal coherence (such as the gender gaps) and compared to other existing mortality forecasts for Czechia.

Keywords: mortality, forecast, projection, ageing, life expectancy. **Demografie,** 2019, **61: 261–280**

INTRODUCTION

The modelling and forecasting of future mortality trends are a common centre of interest among demographers, actuaries, and population economists. Mortality forecasts, an inherent part of population forecasting, are essential for making estimates of the expected rates of population ageing and future longevity risk (*De Waegenaere et al.,* 2010).

Increases in longevity have been the main drivers of the mortality trends observed in developed countries since the 1970s, starting with the process of the cardiovascular revolution, which established the new trajectory of a decline in old-age mortality and delayed the age of onset of fatal chronic circulatory conditions. Along with parallel improvements in lifestyles and increasing awareness in the domain of individual responsibility towards health status, improvements in other conditions have also been occurring, particularly among elderly populations, resulting in an increasing concentration of life-expectancy gains among elderly age groups.

The countries of Central and Eastern Europe have long stood outside of this trend. Unlike in western populations, life expectancy in the East stagnated or even deteriorated between the 1960s and the 1980s (*Meslé,* 2004). In the 1990s, however, a new stage

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of rapidly increasing life expectancy occurred, with Czechia being among the most notable examples thereof (*Rychtaříková*, 2004).

This uneven development, however positive, represents an issue when future mortality is to be predicted. In classical extrapolative approaches, mortality forecast arises from the observation of past trends. Should this trend be long and regular enough, future mortality can merely be estimated as a statistical extension of the observed trend, under the condition that the main features of the past trend are well captured by the model.

This study deals with the task of computing mortality forecast for the projection of the Czech Statistical Office. The results of this projection, which is updated every five years, are to be used in optimising the parameters of the future pension system. In order to serve this purpose, the mortality of all cohorts already born needs to be predicted, which requires extending the projection horizon to at least the year 2100. Thus the length of the predicted period by far exceeds the length of time during which the recent mortality improvements have been occurring and the task calls for a novel approach.

This paper will first discuss recent approaches to mortality forecasting along with their advantages and disadvantages. Then, based on analytical results, we will present the methodological rationale for the 2018 mortality forecast. In the next section, the model itself will be explained together with a description of how uncertainty was dealt with. Finally, main results of the mortality forecast will be presented.

AN OVERVIEW OF THE LITERATURE

Mortality forecasting has a long history and experience has shown that under stable conditions mortality trends tend to be quite predictable (*Booth*, 2006).

The empirical approaches used to forecast mortality can be roughly divided into those that start with a prediction of a synthetic indicator, such as life expectancy, followed by assumptions on age profiles (a top-down approach) and those that start with modelling and forecasting the stratified elements of a mortality curve, such as age patterns and cohort effects (a bottom-up approach). In the top-down approach, the target life expectancy is obtained by means of statistical extrapolation or by expert judgment. An age-specific pattern is then estimated to converge to the targeted aggregate levels. Such an approach has been used previously in the Czech Statistical Office's mortality forecasts.

The bottom-up types of approaches seek first to capture age-specific patterns, which are then used to compute future life tables. In the first step, the mortality age pattern is formalised into a representative model. The model can be based on experience from other countries, such as the so-called *model life tables* for different population types (*Coale and Demeny*, 1966). In *relational models*, a standard life table is modified based on observed point estimates of the death rates at given ages (*Brass* 1974). The Brass relational model is still widely used in mortality forecasting, especially in countries with a lower quality of mortality data. Another, alternative way to formalise and predict mortality age patterns is represented by the large family of *parametric models*, which impose a parsimonious mathematical relation between age and the force of mortality. These models include exponential (*Gompertz*, 1825; *Makeham*, 1860), logistic (*Thatcher et al.*, 1998) or polynomial relations, or their combinations (*Heligman and Pollard*, 1980). The main disadvantage of these models is that they cannot be fitted to a complete age scale, unless a large number of parameters are used. Since the 1990s *functional models* have been proposed, further developed, and widely applied (*Lee and Carter*, 1992; *Lee*, 2000; *Hyndman and Booth*, 2008). Functional models and their modifications are among the most widely used projection models in countries that have high-quality data. The most recent direction in mortality forecasting then employs Bayesian models, taking advantage of the possibility to estimate future mortality schedules along with their natural uncertainty (*Czado et al.*, 2005; *Girosi and King*, 2008, *Wiśniowski et al.*, 2015). The United Nations have used elements of Bayesian forecasting in the recent versions of the World Population Prospects series.

Other approaches have focused on patterns of mortality change rather than the mortality age pattern itself (*Haberman and Renshaw*, 2012). This group of models introduces a new variable, the mortality improvement rate, which, in a continuous setting, equals the first derivative of the force of mortality. According to *Hunt and Villegas* (2017), this approach is particularly appreciated among practitioners of mortality forecasting, where more attention is paid to the actual mortality change in specific age groups, typically seniors. The method of discrete mortality improvement rates (the annual percentage changes in death rates) was recently used in the ONS 2016 population forecast for the UK (*ONS,* 2017). The difficulty with estimating rates of improvement lies in their high yearly volatility and lack of empirically grounded assumptions about their past and future trends.

In addition to the age and period perspective, models are sometimes enhanced by adding a cohort component. Functional models with cohort components were proposed, as well as cohort-sensitive Bayesian models; cohort mortality improvement factors have been discussed, for example, in *Haberman and Renshaw* (2013). However, a study of the surface plots of the mortality improvement rates has shown that cohort effects had a negligible impact on mortality trends between 1950 and the present day in Czechia (*Rau et al*., 2018), where, like in other post-socialist countries, mortality change was almost entirely driven by period (and age) effects.

Age effects themselves were also rather irregular over time. In young age groups, mortality rates are currently approaching biological minimums, while the declines keep accelerating at higher ages. In mortality forecasting terminology, the coincidence of the deceleration of young-age mortality decline and the acceleration of old-age mortality decline is referred to as a 'rotation' and it is recommended that it be taken into account especially in long-term mortality projection models, as ignoring it may result in unrealistic mortality age patterns (*Li et al.,* 2013).

DATA

The core dataset used for the forecast consisted of life table death rates based on the new life table methodology introduced by the Czech Statistical Office in 2018. The new life table methodology uses non-parametric adaptive smoothing of death rates based on the *p*-spline method (*Eilers and Marx*, 1996) and applies logistic parametric model for the old-age mortality curve, with parameters computed using the maximum likelihood estimation procedure. The input life tables were available for 1-year age intervals (0–110+) for the period 1960–2017.

To compare the Czech mortality change with trends observed recently in other developed European countries, we retrieved population and mortality data from Human Mortality Database (www.mortality.org).

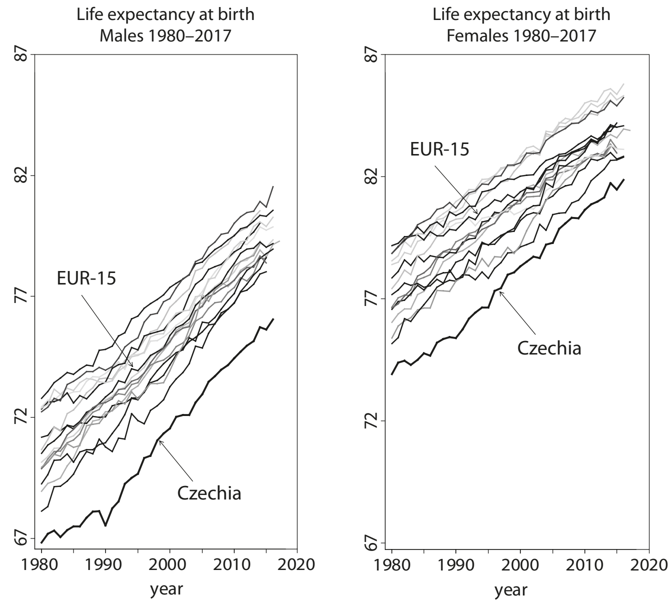
AN ANALYSIS OF RECENT MORTALITY TRENDS

For analytical purposes, a higher-level population was created based on the sums of population exposures and death counts in 15 developed West European countries. The countries were chosen to reflect diverse mortality experiences observed since 1980. The following countries were included: Austria, Belgium, Denmark, Finland, France, Great Britain, former West Germany, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden and Switzerland. In the text below, this population is referred to as the EUR-15.

The continuous increase in life expectancy at birth is the main feature of the mortality change in recent decades. This change is shown in Figure 1, where Czechia is placed next to the EUR-15 countries. All countries shift upwards at a similar pace. Among males, a slight homogenisation of life expectancy levels is observed among the EUR-15 countries. Regarding females, several countries (namely Denmark, Netherlands, and the UK) have experienced a slower life expectancy increase than others, resulting in them lagging behind the vanguards. Among both sexes, the trend observed for Czechia was roughly parallel to that in the EUR-15, while in terms of levels of life expectancy Czechia still lags two decades behind the most progressive Western countries.

As noted earlier, recent mortality improvements are not evenly distributed across ages. It is well known that the main toll of the mortality decline is progressively shifting to more older ages. Less is known about the role of premature and young age mortality in the present pattern of decline. In order to assess the shape of the mortality decline in Czechia and compare it with the EUR-15 population, we decomposed the mortality change into the effect of average levels, age-specific change, and the period effect using the Lee-Carter mortality model.

Figure 1 Life expectancy at birth in EUR-15 countries and in Czechia by sex between 1980 and 2017



Source: Human Mortality Database, 2018.
Note: EUR-15 includes Austria, Belgium, Denmark, Finland, France, Great Britain, former West Germany, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden and Switzerland. The countries are not labelled individually.

In the Lee-Carter model, the logarithm of age-specific mortality in the given year $ln(m_{x,t})$ is expressed as the following combination of vector parameters:

$$\ln\left(m_{x,t}\right) = \alpha_x + \beta_x \kappa_t + \varepsilon_{x,t},$$

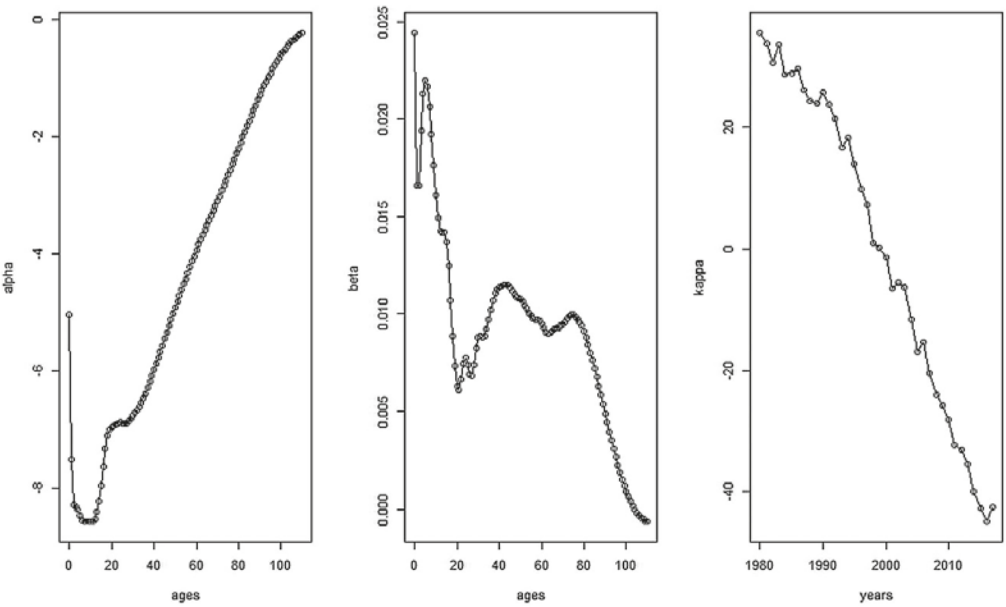
Where α represents a vector of the averaged death rate logarithms, β is the vector of the age-specific response to the mortality change, κ stands for the effect of the period, and ε adds an error term. The multiplicative terms β and κ are estimated by means of the singular value decomposition after the initial data matrix was subtracted with α. For estimation feasibility, the sum of β_x is forced to equal to 1 and the sum of κ_t is constrained to 0.

Figure 2 represents the results of the Lee-Carter model applied to Czech mortality data for the period 1980–2017. The left panel shows the average log-mortality pattern (α), the middle panel displays the age-specific mortality change (β), and the right panel visualises the parameter of time (κ). The time parameter is straightforward to interpret: the mostly unidirectional mortality decline occurred throughout the period of observation, with a slight acceleration in the 1990s. Regarding the age-specific pattern of this decline, the change was the most pronounced among infants and children and was observed least among the oldest-old (the improvements drop rapidly after age 80). Among males, important improvements took place in the 30–60 age group, pointing to the particular role played by the decline of male premature mortality in the recent mortality change in Czechia, especially in comparison with females.

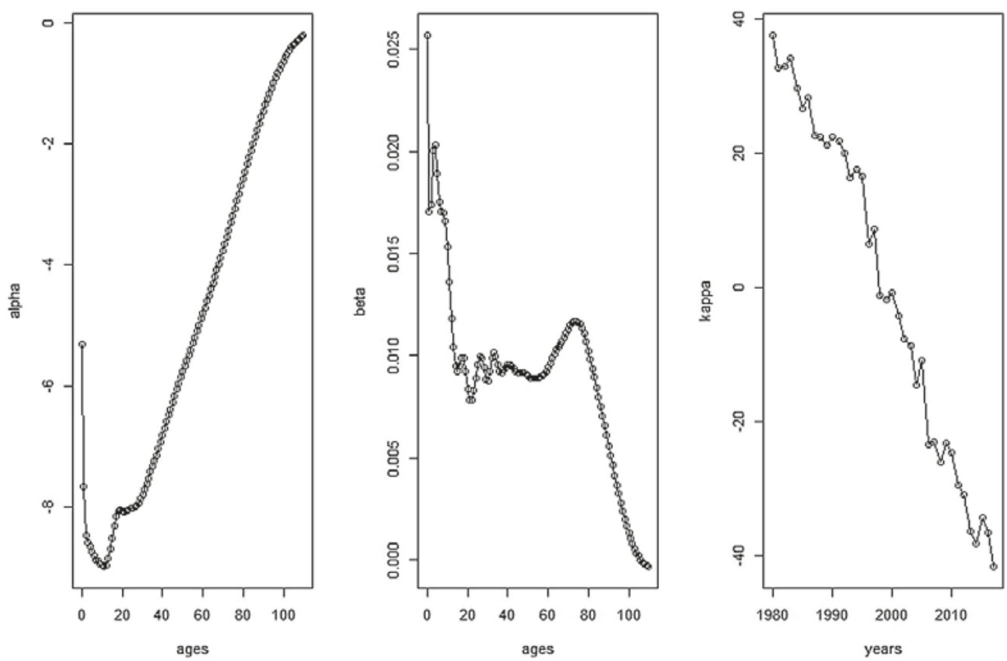
These results were then compared with the same model fitted to the aggregate EU-15 population for the 1980–2014 period (Figure 3). The tempo of the mortality decline, expressed as the kappa parameter, was similar as that in the case of Czechia. However, we do not see as much premature mortality improvement in the beta parameter among either of the sexes. We interpret this finding as a result of a compensational pattern of mortality decline observed in Czechia and we hypothesise that such a compensational pattern is temporary and will not be sustained in a long-term perspective. Instead, Czechia will more likely follow the European pattern of gradual mortality decline. However, transferring the European experience onto Czech data is not technically possible within the framework of the Lee-Carter model.

Figure 2 Lee-Carter mortality model components for Czechia by sex, 1980–2017

a. Males



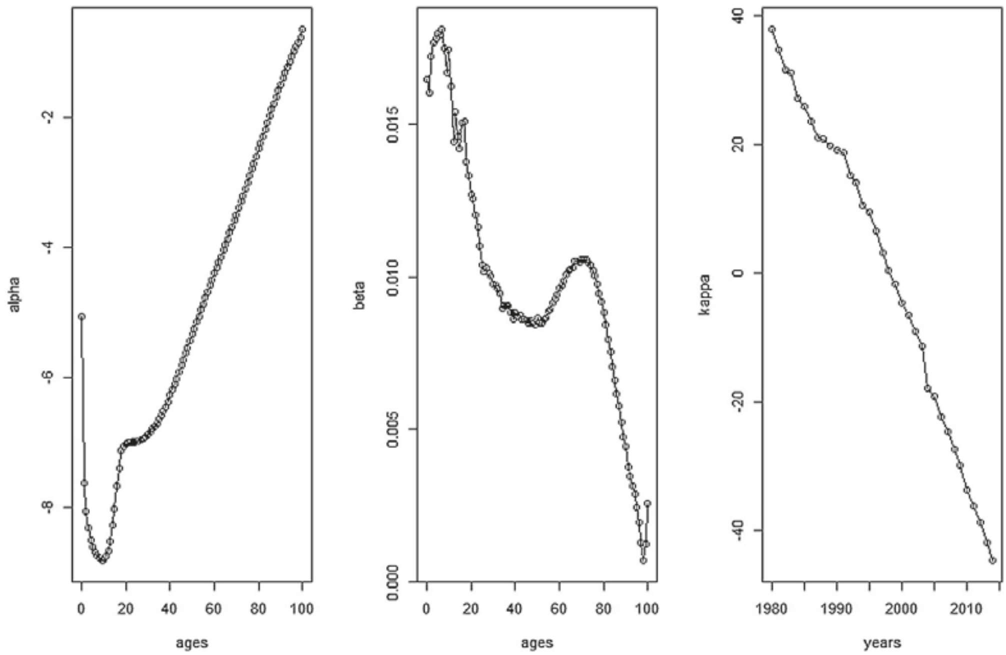
b. Females



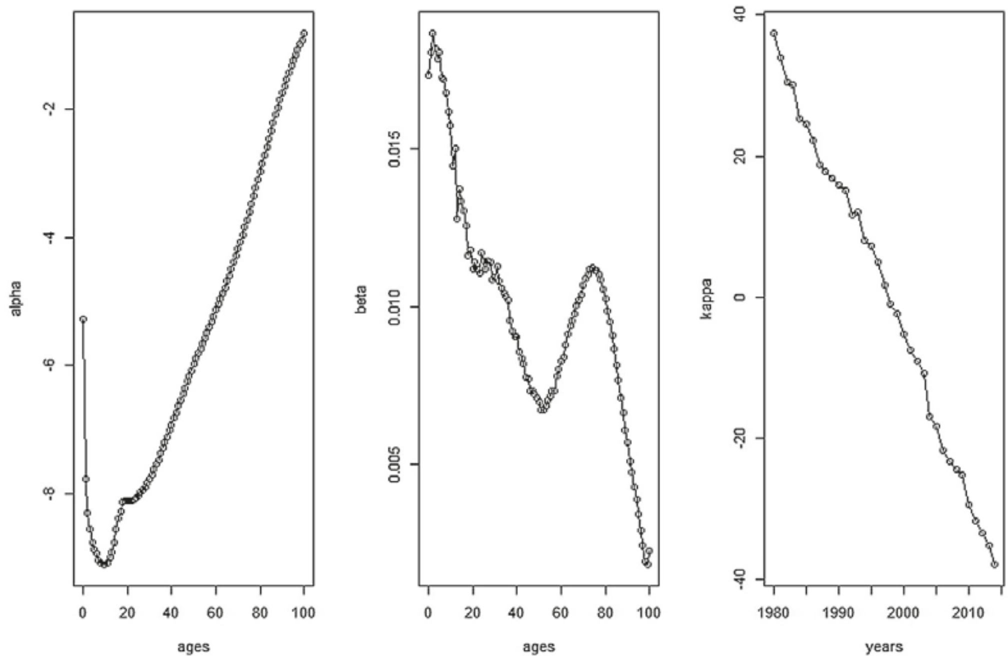
Source: Czech Statistical Office, 2018c.

Figure 3 Lee-Carter mortality model components for the EUR-15 population by sex, 1980–2014

a. Males



a. Females



Source: Human Mortality Database, 2018.

THE STOCHASTIC FORECAST OF LIFE EXPECTANCY

The fitted Lee-Carter model was then used to directly predict future Czech mortality rates using a random walk with drift as the estimation procedure for the kappa parameter. The primary and inherently subjective input in both the deterministic and the stochastic forecasting process is the choice of the base period, i.e. the period that is taken as the basis for model parameters estimation. In good forecasting practice, this period should be as long as possible, ideally at least as long as the predicted period. We performed an analysis of the sensitivity of the Lee-Carter model to the choice of base period in the particular demographic context of Czechia. We used base periods starting in 1960, 1970, 1980, and 1990. The results of this analysis expressed in terms of life expectancy at birth in 2100 (Table 1) point to the important impact of the chosen base period: male life expectancy derived from the Lee-Carter forecast based on 1960–2017 data differs by 6.5 years from the one derived from the base period 1990–2017. Even more apparent is the sensitivity of the model to the base period in the case of the sex difference in life expectancy at birth, which ranges from 4 years to less than 1 year in 2100. This result is not surprising given the above-mentioned irregularity of Czech mortality trends, characterised by substantial mortality turnaround in the late 1980s.

Although choosing the longest base period is justified in countries with a gradual mortality transition, in post-communist countries this period includes mortality experience based on conditions that are not likely to be reproduced in the future (such as the socialist health crisis followed by a rapid positive turnaround). For more recent but shorter time periods (such as 1980–2017), lack of robustness and volatility of the estimated parameters of the Lee-Carter model for Czechia (see Figure 2) significantly distorts the mortality age pattern if the prediction period extends over several decades. For these reasons, a purely stochastic approach was excluded as main forecasting methodology.

PROJECTION METHODOLOGY

The further search for an optimal mortality forecast method was driven by the wish to take into account the observations pointed out above and to allow for maximum flexibility in terms of future patterns of age-specific mortality change. These conditions are closely met by the projection model based on rates of mortality improvement. In this model, we first derived the age-specific rates of mortality change in the EUR-15 population, projected them for the whole period of prediction, and modified them in order to reflect three alternative mortality scenarios.

The rates of mortality improvement $r_{x,t}$ were defined in this setting as the annual prospective age-specific mortality-reduction coefficients:

$$r_{x,t} = \frac{m_{x,t}}{m_{x,t+1}},$$

Where $m_{x,t}$ and $m_{x,t+1}$ stand for two subsequent mortality rates at the given age x.

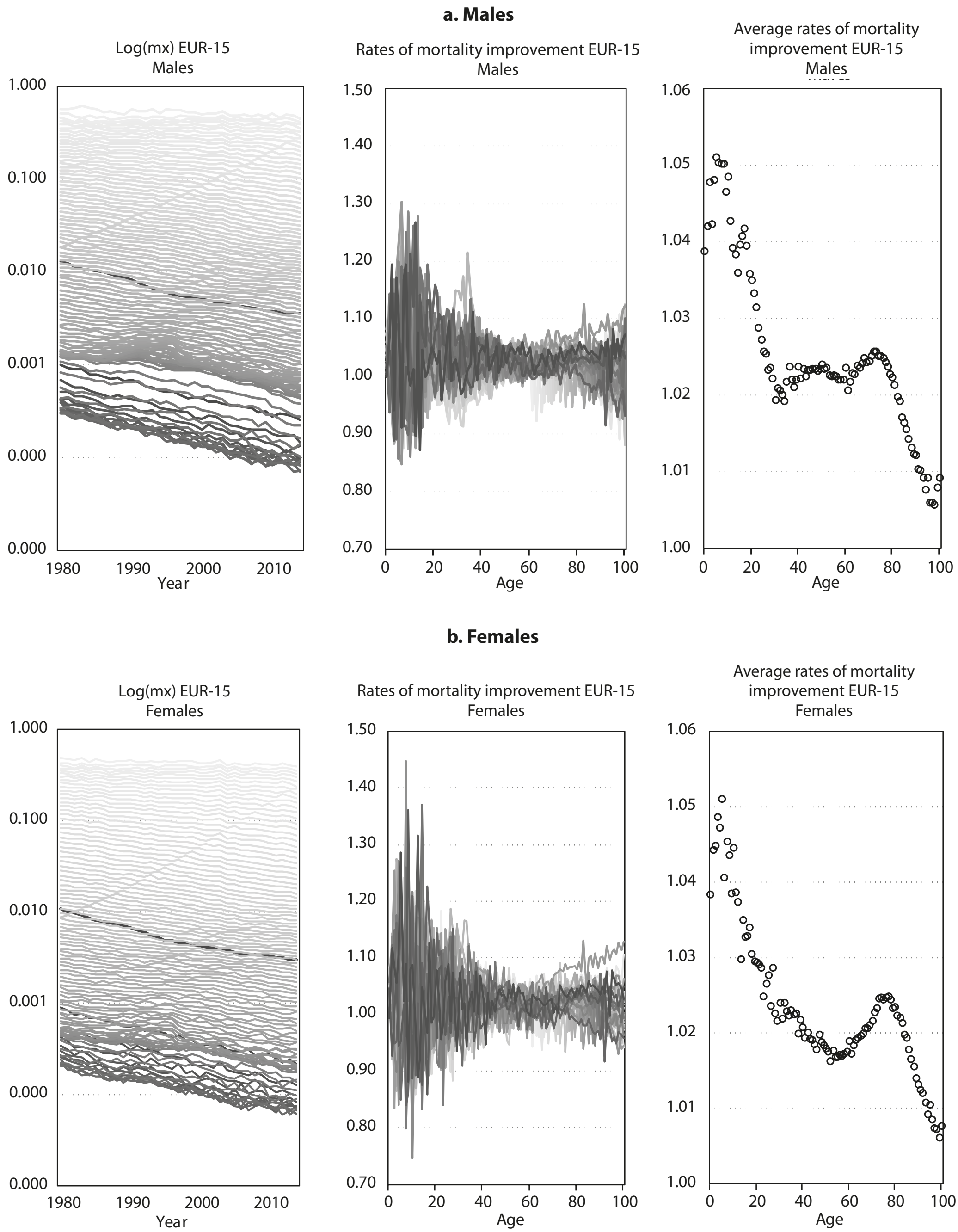
In Figure 4, the EUR-15 mortality rates, the rates of mortality improvement, and their averages are displayed in the left, middle, and right panels, respectively. The left panels show the surface of the age-specific mortality rates and their change in time (each line represents one single-year age group between 0 and 100). The middle panels show the rates of mortality improvement and their volatilit

Table 1 Sensitivity of the Lee-Carter life expectancy at birth forecasts by sex (for year 2100) to the choice of the base period in the Czech Republic

Base period	1960–2017	1970–2017	1980–2017	1990–2017
Life expectancy at birth in 2100:				
Male	85.07	88.23	90.12	91.47
Female	89.06	90.94	92.27	92.35
Sex difference	3.99	2.71	2.15	0.88

Source: Source: Czech Statistical Office, 2018c; author's calculations.

Figure 4 Age-specific mortality rates (left), rates of mortality improvement (middle), and average rate of mortality improvement (right) for the EUR-15 population by sex, 1980–2014



Source: Human Mortality Database, 2018.
Note: EUR-15 aggregates Austria, Belgium, Denmark, Finland, France, Great Britain, former West Germany, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden and Switzerland.

(each line represents the age-specific mortality change in a given calendar year). The variation is extremely high at young ages where mortality is low. However, when these rates are averaged over time (the right panel), the resulting pattern of age-specific mortality improvement comes out as more systematic and is similar to the beta parameter of the Lee-Carter model shown previously. Once again we observe increased mortality dynamics among males aged 30–60 years, which is explained by the relative stagnation of premature male mortality in the 1980s followed by a recovery since the 1990s (see age-specific rates in the left panel). The HIV/AIDS epidemic is the likely cause of this peculiar trend (*Valdes,* 2013), and once again, this trend is not likely to be repeated in the near future.

The projection model

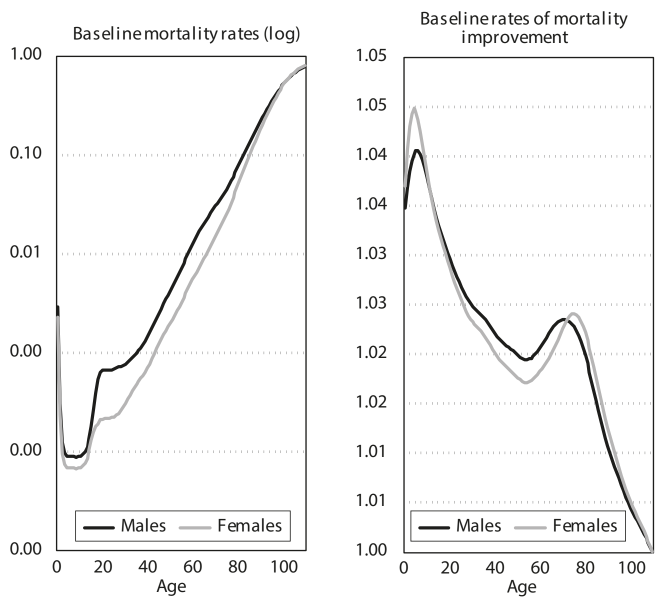
The projection model based on the observed rates of mortality improvement was created in the following steps:

- Define the baseline mortality pattern
- Define the baseline rates of mortality improvement
- Formulate assumptions about future patterns of mortality change
- Predict future death rates

The baseline mortality pattern differs from the last observed data year. Because of the relatively small size of the Czech population and the scarcity of deaths or exposures at young and old ages, the observed data cannot directly serve as a projection basis. In the present approach, the baseline mortality curve was estimated as the latest five-year average of the age-specific mortality rates numerically adapted to the linear extrapolation of life expectancy in 2018 based on the last five years (the 2018 life expectancy at birth was estimated as 76.19 years for males and 82.03 years for females). Baseline mortality curves for males and females are shown in Figure 5 (left panel).

The baseline rates of mortality improvement were based on the arithmetically averaged EUR-15 $r_{x,t}$. Slight modifications were adopted: the excess rates of improvement among adult males were removed; the male and female patterns of change were thus made more similar, while still allowing for slightly bigger reductions among males aged 30–60. The rates were finally smoothed using locally weighted

Figure 5 Medium scenario of the baseline mortality age-pattern and baseline rate of mortality improvement in the Czech Republic by sex, 2018



Source: Czech Statistical Office, 2018b.

regression (loess with 0.1 bandwidth). The resulting rates of improvement are displayed in the right panel of Figure 5.

Accounting for uncertainty

The forecast was designed in three scenarios reflecting the limits of the future mortality change as expected according to observed trends and related hypotheses. The scenarios are labelled 'low', 'medium', and 'high', in conformity with both with the predicted levels of life expectancy and with the predicted population size. In the very first year of the projection (2018), the low and high scenarios were defined as increasing or decreasing the baseline mortality estimate by 2.5% at every age.

The three main scenarios of expected mortality decline are shown in Figure 6. In the 'medium' and most likely scenario (middle panel), it is assumed that mortality reductions will initially follow the baseline rates of mortality improvement. Over time, the rates of improvement will decline and this decline will be more pronounced among younger ages. This scenario thus reflects the concept of a rotation of the mortality-reduction age pattern.

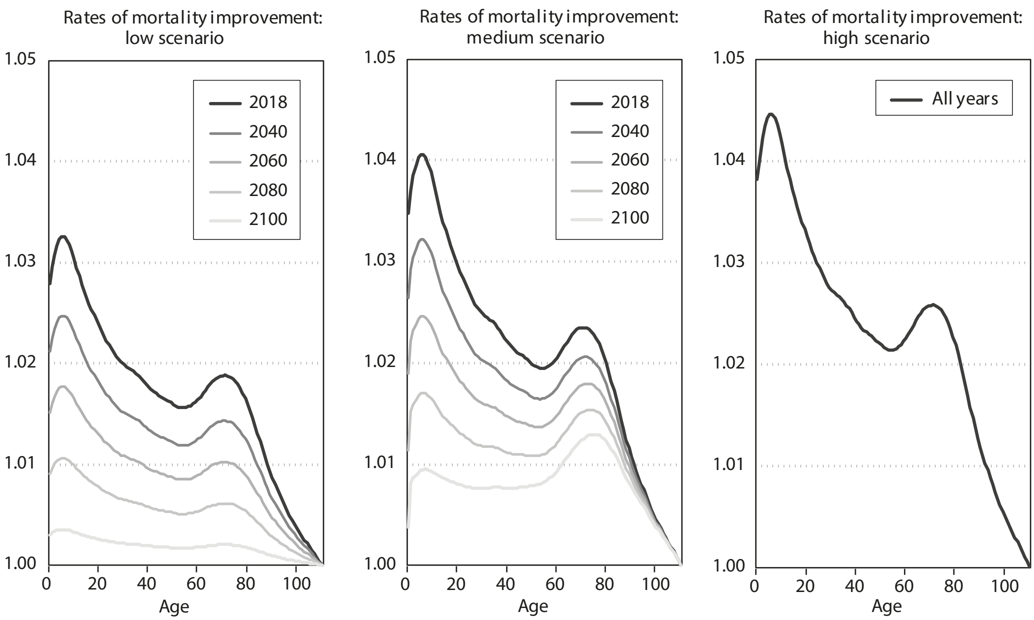
In the 'low' scenario (left panel), the initial mortality decline is set below the baseline levels and is projected to cease in 2150 (the rates of improvement gradually converge to 1). This scenario takes into account the possible eventual depletion of the biological and social reserves underlying further mortality improvements.

The 'high' scenario (right panel) considers a higher than baseline mortality improvement, which will be sustained in every year of the projection. This scenario represents the hypothesis that mortality decline will continue uninterrupted into the future, which is the scenario closest to the stochastic projections based on recent favorable mortality trends.

With the exception of the baseline year 2018, the mortality rates for every age and year $m_{x,t+1}$ were computed as ratios of the death rate observed in the preceding year $m_{x,t}$ and the respective predicted rate of improvement $r_{x,t}$:

$$m_{x,t+1} = \frac{m_{x,t}}{r_{x,t}}$$

Figure 6 Projected rates of mortality improvement in Czechia, males, low, medium, and high scenarios, 2018–2100



Source: Czech Statistical Office, 2018b.

RESULTS

Table 2 summarises the main results of the 2018 mortality forecast: life expectancy at birth according to different scenarios and the resulting sex difference. In 2100, life expectancy in the medium scenario is projected to reach 87.66 years among males and 91.22 years among females. The range between the low and the high scenario estimate equals 7 years in 2100. Compared to the stochastic forecasts presented in Table 1, the actual forecast results in higher but still decreasing sex differences in mortality (a drop to 3.56 years expected in 2100 in the medium scenario, and to only 3.03 years in the high scenario).

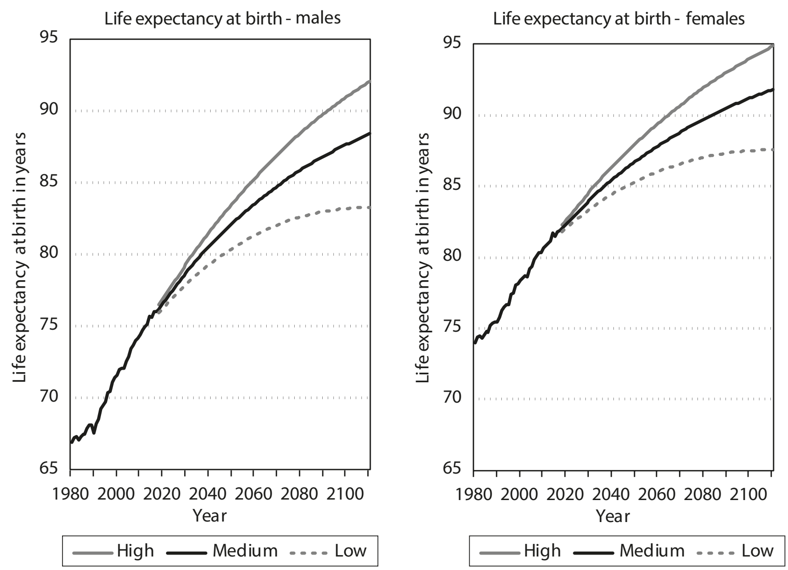
A more detailed outlook on the projected life expectancy can be seen in Figure 7, where the annual figures are presented for all the projected years and

Table 2 Life expectancy at birth by sex in 2017 (observed) and 2018–2100 (projected), Czechia, low, medium, and high scenarios

Year	Males			Females			Sex difference		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
2017	-	76.01	-	-	81.84	-	-	5.83	-
2018	75.93	76.19	76.47	81.80	82.03	82.25	5.87	5.84	5.78
2020	76.28	76.64	76.96	82.09	82.38	82.66	5.81	5.74	5.70
2030	77.90	78.71	79.32	83.36	84.02	84.59	5.46	5.31	5.27
2040	79.27	80.53	81.50	84.44	85.46	86.36	5.17	4.93	4.86
2050	80.40	82.14	83.49	85.32	86.73	87.97	4.92	4.59	4.48
2060	81.33	83.55	85.31	86.04	87.86	89.43	4.71	4.31	4.12
2070	82.05	84.79	86.95	86.61	88.86	90.75	4.56	4.07	3.80
2080	82.60	85.87	88.44	87.04	89.74	91.95	4.44	3.87	3.51
2090	82.98	86.83	89.77	87.34	90.52	93.02	4.36	3.69	3.25
2100	83.21	87.66	90.97	87.51	91.22	94.00	4.30	3.56	3.03

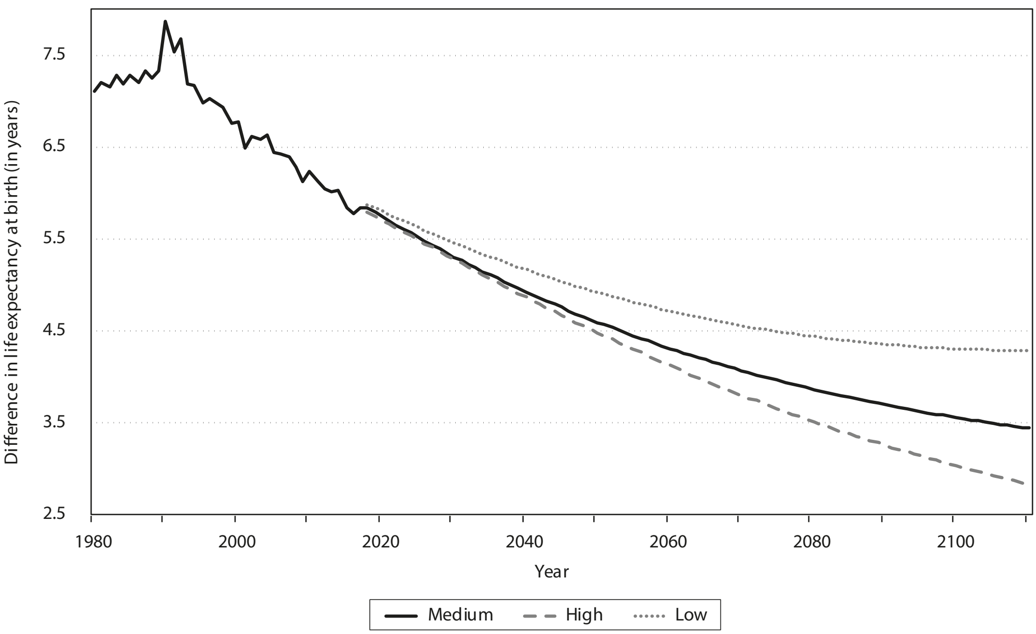
Source: Czech Statistical Office, 2018a and 2018b.

Figure 7 Life expectancy at birth by sex between 1980 and 2017 (observed) and for 2018–2100 (projected), Czechia, low, medium, and high scenarios



Source: Czech Statistical Office, 2018b and 2018c.

Figure 8 Sex difference in life expectancy at birth, 1980–2017 (observed) and 2018–2110 (projected), Czechia, low, medium, and high scenarios



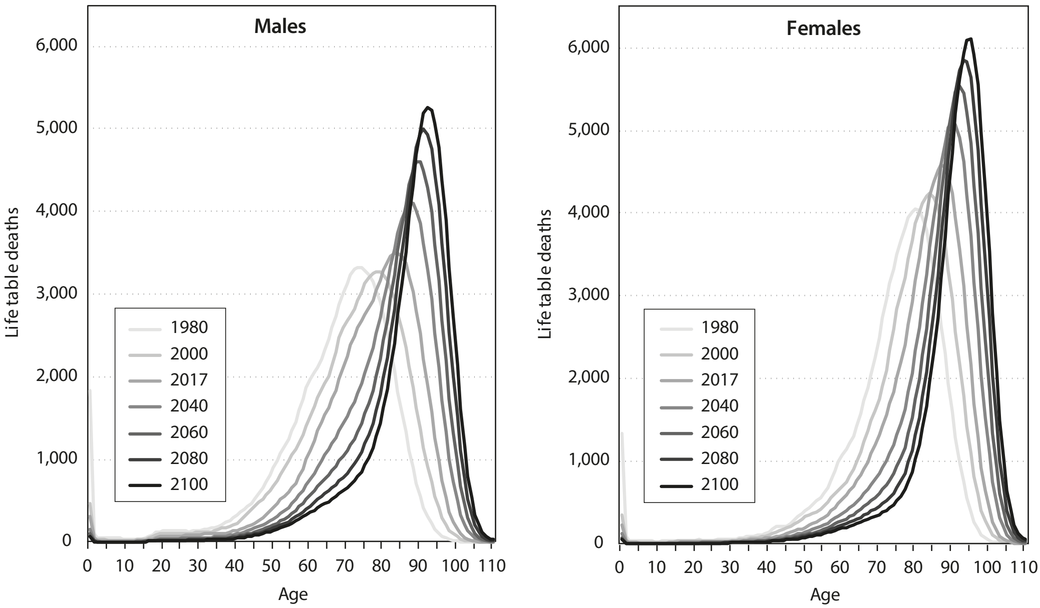
Source: Czech Statistical Office, 2018b and 2018c.

for the three mortality improvement scenarios. In the medium scenario, life expectancy increases continuously throughout the entire projected period; however, the pace of increase declines with time (due to the incorporated assumption of a decrease in and the rotation of mortality improvements). In the low scenario, the increase in life expectancy slows down even more rapidly and from 2080 the progress becomes negligible. In the high scenario, life expectancy increases the most rapidly as a result of the conservative pattern of mortality improvement, but even here, the increase is not linear, which suggests that even if the rates of improvement remain constant, the life expectancy increase will decelerate in the long run.

Figure 8 depicts the observed and predicted levels of sex difference in life expectancy at birth for each of the three scenarios. The assumptions applied in the scenarios produce different trajectories of sex differentials. In general, it is assumed and accepted that sex mortality differences will decrease in the future. The second half of the 20th century was a period of exceptionally high excess male mortality in both the East and the West, and Figure 8 confirms that this was also the case in Czechia, where sex differences reached a maximum in the late 1990s and have rapidly declined since then. If the mortality improvement rates were fixed in the future for both sexes (the high scenario), the sex difference would eventually drop to 3 years in 2100. This result is due to the fact that mortality improvement rates are derived from the base period that is characterised by more rapid declines in male mortality, especially at adult ages. The medium and low scenarios assume slower declines in adult mortality, which leads to higher sex differences.

Figure 9 shows how the expected mortality changes will affect the distribution of life table deaths (the d_x function of a life table). As a result of further reductions in premature mortality and the shift in deaths to older ages, the modal age at death will move upwards and deaths will be increasingly concentrated around it, i.e. the variance of age at death will decline. This phenomenon is referred to as the compression of mortality (*Myers* and *Manton,* 1984).

Figure 9 Distribution of life table deaths by sex in Czechia (dx): 1980–2017 (observed) and 2018–2110 (projected), medium scenario



Source: Czech Statistical Office, 2018b and 2018c.

The modal age at death (also called the normal length of life and derived as the age at which the maximum life table deaths occur) will increase in the medium scenario by 8 years among both sexes between 2017 and 2100. As Table 3 shows, in 2100 men will most likely die at the age of 92 years while the typical age of death for women will be 95 years. The sex difference in the modal age at death is lower than that of life expectancy: in 2017 only a sex difference of only 3 years is observed, and this difference will go unchanged over the projected period.

Figure 10 displays the curves of life table survivors by age, according to the medium scenario. The survival curves provide additional insight into the shape of future mortality patterns. As the number of life table births is constant (100,000), survival curves allow us to directly read the quantiles of the length of life (e.g. the age at which 50,000 of life-table born are still alive is called the median length of life). In 1980, the median length of life was 70 years for men and 77 years for women. In 2017, the median length of life increased to 78 years for men and 84 years for women. In 2100, 50% of the population will live to at least 90 years of age (men) or 93 years (women). The increasing proportions of people surviving to increasingly older ages are visible in Figure 10 as the increasingly rectangular shape of the survival curve. This process of rectangularisation will slow down in the second half of the projected period.

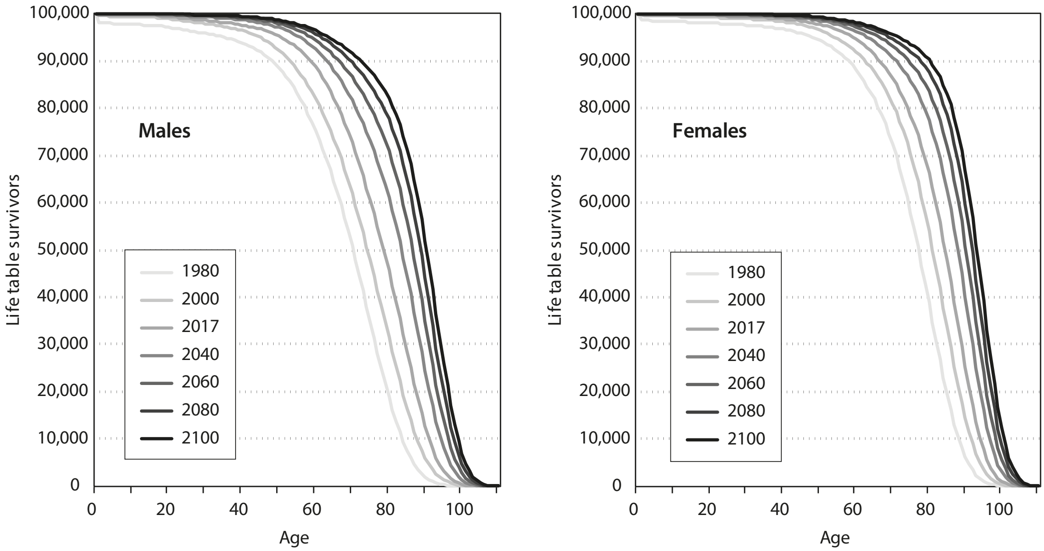
The probability of surviving up to the discussed threshold for the retirement age (65 years) is projected

Table 3 Modal age at death by sex in Czechia: 1980–2017 (observed) and 2018–2110 (projected), medium scenario

Year	1980	2000	2017	2040	2060	2080	2100
Males	73	78	84	87	90	91	92
Females	80	84	87	90	92	93	95

Source: Czech Statistical Office, 2018b and 2018c.

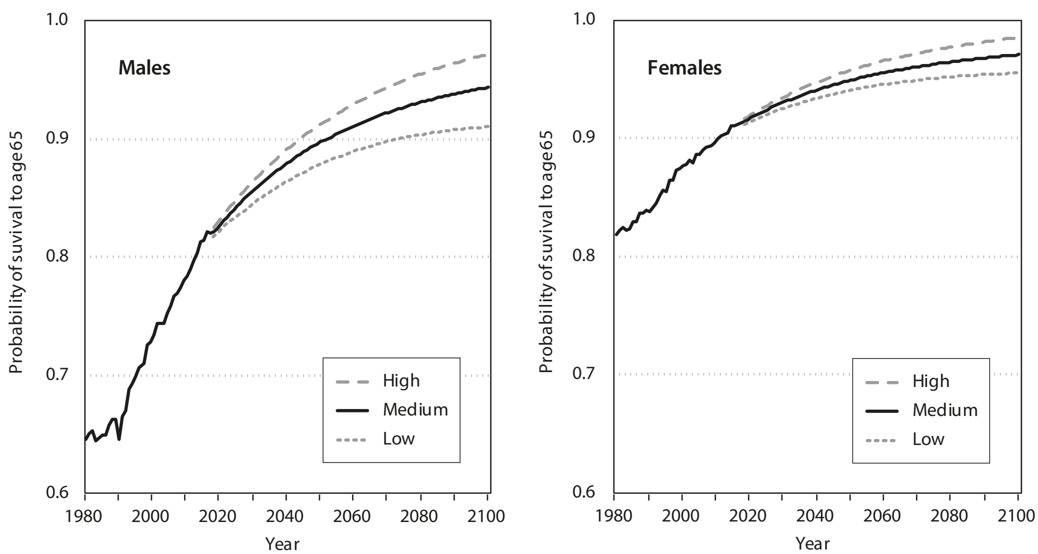
Figure 10 Distribution of life table survivors (lx) by sex in Czechia: 1980–2017 (observed) and 2018–2100 (projected), medium scenario



Source: Czech Statistical Office, 2018b and 2018c.

to further increase in all three scenarios and this increase will be more pronounced in the population of males due to the greater reductions in male premature mortality (Figure 11). Male chances of living to the age of 65 already increased steeply between 1980 and 2017 (from 0.65 to 0.82), and a further increase to 0.94 is expected by 2100. Among females, the chance of surviving to the age of 65 was already 0.91 in 2017 and will increase to 0.97 in 2100, suggesting that almost every woman will survive to this age.

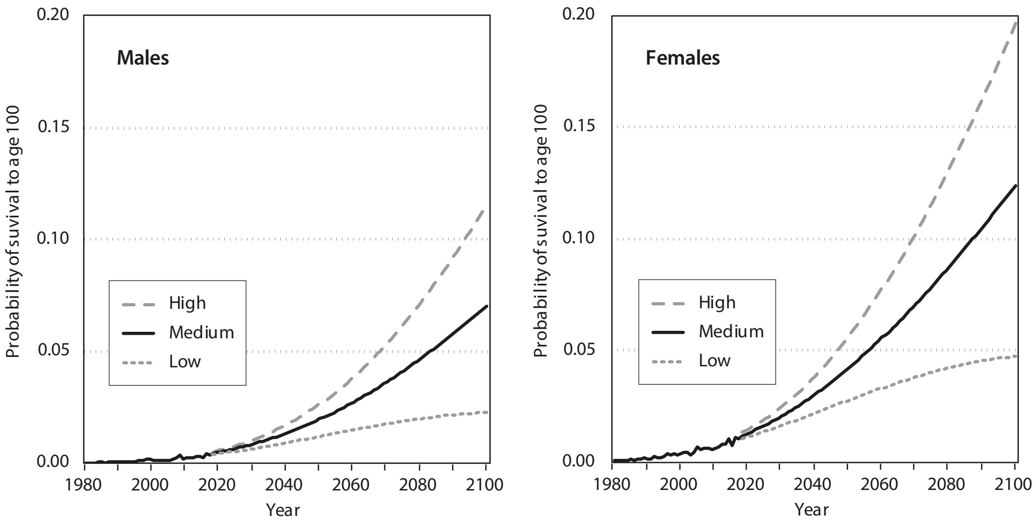
Figure 11 Probability of survival to age 65 by sex in Czechia, 1980–2017 (observed) and 2018–2100 (projected)



Source: Czech Statistical Office, 2018b and 2018c.

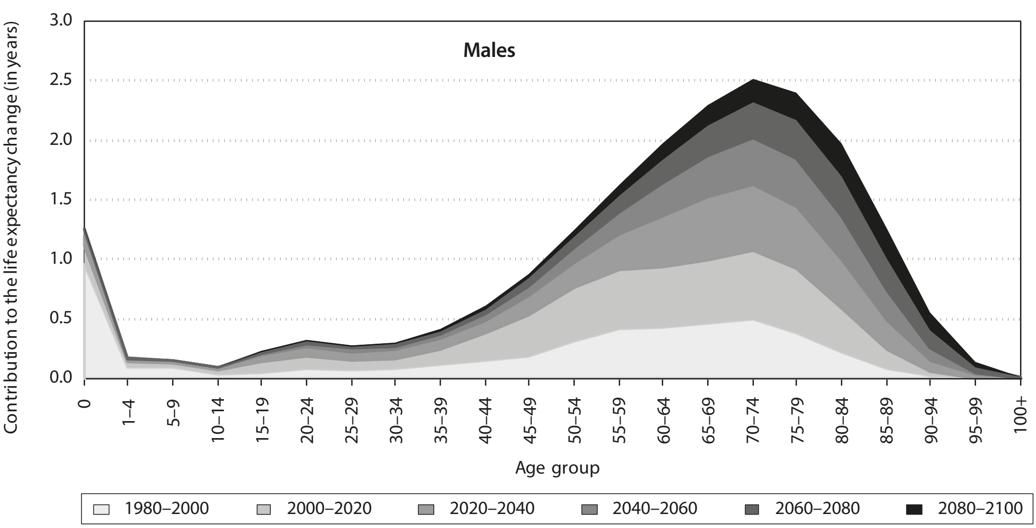
Figure 12 shows the trend in longevity, operationalised here as the chances of becoming a centenarian. Between 1980 and 2017, the chance of living to the age of 100 increased from almost zero to 0.004 in men and to 0.011 in women. Survival to age 100 will, however, improve at increasing rates and is expected to reach 0.07 and 0.12 in 2100 for men and women, respectively (7% of men and 12% of women born in 2100 will live to the age of 100 or more according to the 2100 period life table estimate, i.e. under the assumption that mortality conditions remain constant to the year of the predicted life table).

Figure 12 Probability of survival to age 100 by sex in Czechia, 1980–2017 (observed) and 2018–2100 (projected)



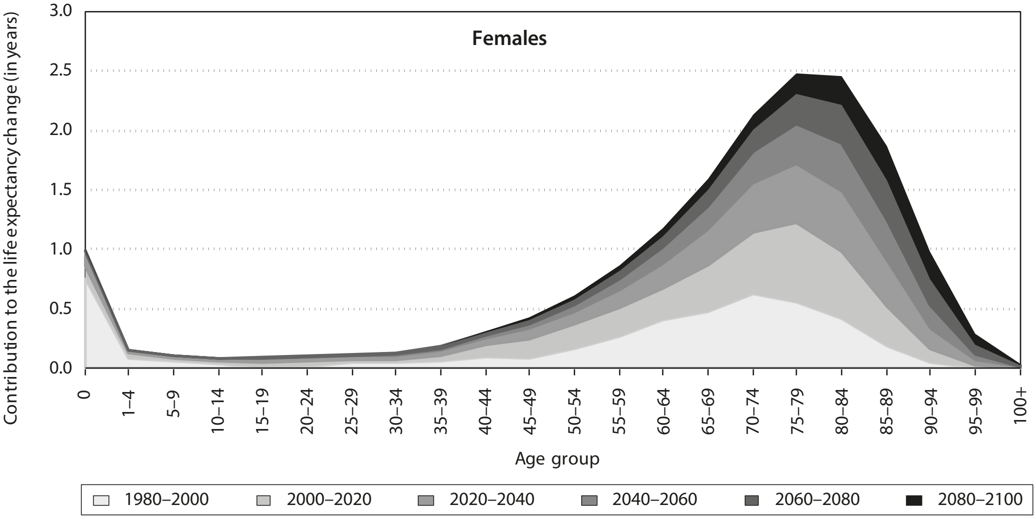
Source: Czech Statistical Office, 2018b and 2018c.

Figure 13 Contributions to the change in life expectancy at birth in Czechia between 1980 and 2100, medium scenario, males



Source: Czech Statistical Office, 2018b and 2018c.

Figure 14 Contributions to the change in life expectancy at birth in Czechia between 1980 and 2100, medium scenario, females



Source: Czech Statistical Office, 2018b and 2018c.

Past and expected gains in life expectancy were further decomposed into the contributions of 5-year age groups. Figures 13 and 14 depict these contributions for six twenty-year periods of time covering the total period of 1980–2100. The lower and lighter areas in the graphs show the improvements already achieved (1980–2020), while the darker shades of grey display future contributions to life expectancy change by age (2020–2100). Two main structural features are apparent: life expectancy gains will become increasingly concentrated among older age groups and will diminish with time.

Table 4 Contributions of selected age groups to the observed and projected life expectancy at birth change by sex in Czechia, 1980–2100, medium scenario

Period	1980–2000	2000–2020	2020–2040	2040–2060	2060–2080	2080–2100	Total
Age group	*Males*						
0	0.96	0.15	0.10	0.04	0.02	0.01	1.27
1–64	2.11	2.64	1.52	0.99	0.65	0.42	8.33
65–79	1.34	1.65	1.56	1.19	0.86	0.61	7.22
80+	0.33	0.57	0.72	0.79	0.79	0.75	3.96
All ages	**4.74**	**5.01**	**3.90**	**3.02**	**2.32**	**1.79**	**20.78**
	Females						
0	0.75	0.11	0.08	0.04	0.02	0.01	1.00
1–64	1.35	1.25	0.76	0.49	0.32	0.21	4.39
65–79	1.65	1.59	1.17	0.83	0.57	0.39	6.21
80+	0.66	1.03	1.06	1.04	0.97	0.87	5.63
All ages	**4.41**	**3.99**	**3.08**	**2.40**	**1.88**	**1.48**	**17.23**

Source: Czech Statistical Office, 2018b and 2018c.

The main numerical results of the decomposition are presented in Table 4. In total, a gain of almost 21 years of life expectancy is expected by 2100 compared to 1980 for men and 17 years for women. For both sexes, the life expectancy gains achieved between 1980 and 2020 are similar (in size) to those expected between 2020 and 2100. The age pattern of past and future development is, however, different. In 1980–2000, a major role in life expectancy improvement was still played by infant mortality, followed (among males) by ages below 65. With time, the importance of infant mortality in life expectancy falls to almost zero and the contributions of ages below 65 decrease steadily. For both sexes, life expectancy gains are increasingly determined by mortality at ages 80 and above (as of 2080, ages 80 and over will be the most important drivers of life expectancy change for both sexes).

A COMPARISON WITH OTHER PROJECTIONS

The results of the 2018 forecast were compared to alternative mortality forecasts published recently for Czechia. To our knowledge, these include the Eurostat population projection 2017 (based on 2015 data), the United Nations World Population prospects 2017, the population forecast created by the Department of Demography and Geodemography of Charles University in Prague published in 2018 (*Bleha et al.* 2018), and the previous CZSO forecast from 2013 (Table 5). All of the cited forecasts are based on deterministic cohort-component methods. The Eurostat projection uses the top-down approach: life expectancy in each member country is assumed to converge to a predefined target and the speed of this convergence differs according to the determined scenario. The Charles University forecast employs expert judgement assumptions about the change in future life expectancy, as does the previous CZSO 2013 projection.

In 2060, which is the last year covered by all the alternative forecasts, the life expectancy estimates differed by less than 0.5 years between each other for males, while more variation was observed for females. The highest estimates of life expectancy were given by the previous CZSO 2013 forecast. For the year 2100 we can only compare the CZSO 2018 results to the UN WPP and the CZSO 2013. The male life expectancy estimate in 2100 is almost identical to the UN WPP, while the CZSO 2018 projection estimates higher life expectancy for females, resulting in higher estimates

Table 5 Projected life expectancy at birth by sex for Czechia – a comparison of medium-scenario projections, 2017–2100

Year	Eurostat 2017		WPP 2017**		B&K 2017***		CZSO 2013		CZSO 2018	
	Males	Females	Males	Females	Males	Females	Males	Females	Males	Females
2017*	75.4	81.5	75.59	81.47	76.08	81.78	76.25	82.05	76.01	81.84
2020	76.8	82.6	76.51	82.10	76.78	82.37	77.01	82.76	76.64	82.38
2030	78.6	84.1	78.40	83.33	78.93	84.08	79.51	85.13	78.71	84.02
2040	80.3	85.5	80.33	84.51	80.73	85.51	81.26	86.55	80.53	85.46
2050	82.0	86.8	82.10	85.65	82.36	86.81	83.00	87.98	82.14	86.73
2060	83.5	88.1	83.46	86.77	83.73	87.93	83.72	88.61	83.55	87.86
2070	84.9	89.3	84.66	87.88	-	-	84.44	89.24	84.79	88.86
2080	86.20	90.40	85.74	88.99	-	-	85.15	89.88	85.87	89.74
2090	-	-	86.83	90.07	-	-	85.87	90.50	86.83	90.52
2100	-	-	87.65	90.91	-	-	86.59	91.13	87.66	91.22

* or latest available
** WPP estimates were interpolated to fit the required years
*** Projection by B. Burcin and T. Kučera, as published in Bleha et al. (2018)

of life expectancy difference. This result is linked to the fact that the UN forces gender-specific coherence in their forecasts – male mortality is estimated as a function of female mortality to assure a reasonable gender gap even in the long run.

DISCUSSION AND SUMMARY

The presented study proposed a bottom-up deterministic model of future mortality change. The model takes into account the age-specific profile of mortality change and its tempo, both based on observations from developed countries in the recent period, assuming that Czechia will follow a similar trajectory. The proposed model is based on a prediction of the annual discrete change in age-specific mortality rates. The uncertainty is expressed in scenarios of a differential pattern of distribution of the tempo of mortality decline across ages and time.

Implementation of the proposed method is straightforward. As the dynamic input variable is derived from the higher-order external population, the results are insensitive to the choice of the base period in the country of interest. Keeping the dynamic component stratified by age and period enables flexibility in terms of assumptions and scenarios. The method does not distort the age-specific mortality profile and even in a very long horizon of 100 years yields results that prove realistic in terms of different life table measures, such as life expectancy, life table deaths, probabilities, and survivors. Given the universality of the assumptions, the scenarios derived from this projection can be directly applied to sub-populations such as regions and can be easily adapted to new trends.

The projection is deterministic in nature and therefore prone to subjectivity and errors in expert judgement. However, we believe that the subjectivity is partially reduced by a thorough analysis of international patterns of mortality change. As for other deterministic projections, it is not possible using the applied method to directly compute uncertainty measures. However, in the horizon of 100 years, the stochastic uncertainty of a mortality forecast for a population of 10 million inhabitants with only a short series of consistent mortality trends would not be very informative.

According to the medium scenario, life expectancy will further increase by 11.7 years for men and by 9.4 years for women to 2100. Unlike recent improvements, the future life expectancy change will be dominated by mortality improvements in the elderly population groups. The chances of surviving to the age of 65 years will increase to 94% for men and 97% for women, i.e. almost everyone will be able to live to retirement age. By the end of the projection period, men would most typically die at the age of 92 years while women at the age of 95 years. These profound shifts in the age pattern of mortality will further intensify population ageing in Czechia.

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